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# Irrigation rate and timing effects on Arizona cotton yield, water productivity, and fiber quality

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ABSTRACT

Irrigated agriculture in the Arizona low desert faces multiple threats, including drought in the Colorado River basin, depletion of reservoirs supplying water to irrigation districts, competition from growing municipal and industrial sectors, and climate uncertainty. Improving irrigation water productivity is imperative for sustaining agricultural production in the region. The objective of the study was to measure responses of cotton yield, water productivity, and fiber quality to variable irrigation rates and timings for the 2016, 2017, and 2018 cotton growing seasons at Maricopa, Arizona. Four irrigation rates were used, including 60%, 80%, 100%, and 120% of recommended amounts from a scheduling tool. The four rates were administered differentially during two time periods: (1) squaring to peak bloom and (2) peak bloom to 90% open boll. The experimental design incorporated 16 irrigation treatments in a randomized block design with four replications, and irrigation was applied via an overhead lateral-move sprinkler system with commercial site-specific irrigation equipment. Linear mixed models could estimate cotton fiber yield, seasonal evapotranspiration, fiber micronaire, and fiber strength with root mean squared errors of cross validation (RMSECV) of 11.9%, 1.8%, 6.4%, and 3.6%, respectively. Variation in irrigation water productivity and several fiber quality metrics could be explained by water applied in the second irrigation period but not in the first, suggesting more opportunity in the early season for improving water productivity without sacrificing yield or fiber quality. Irrigation rates in the first period could be reduced up to 70 mm (6% of total water applied to the 100%–100% treatment) without sacrificing yield. During the second irrigation period, full irrigation was required to prevent yield losses and maintain high fiber quality. This study provides valuable guidance on opportunities for using sprinkler irrigation to improve water productivity while maintaining acceptable cotton yield and fiber quality in the Arizona low desert. Further effort is needed to clarify requirements for pre-plant irrigation, incorporate plant feedback data into in-season irrigation scheduling algorithms, and identify metrics to guide irrigation termination decisions.

## 1. Introduction

Improving the water productivity of agroecosystems is a primary objective globally, particularly in arid and semi-arid regions that require irrigation to supplement limited precipitation (Ali and Talukder, 2008; Brauman et al., 2013). For example, in the water-limited environment of the Arizona low desert, a number of factors increase the urgent need for water productivity improvements, including ongoing drought in the Colorado River basin (Prein et al., 2016), depletion of Lake Mead which supplies Colorado River water for local irrigation districts (Holdren and Turner, 2010), competition from municipalities and industries in metropolitan areas, and climate uncertainty (Cayan et al., 2010). Ali and Talukder (2008) described 18 techniques for improving the water productivity of agroecosystems, including various improvements to irrigation and fertilization management, plant breeding to increase harvest index or reduce transpiration, and other agronomic considerations. Similarly, Evans and Sadler (2008) described a variety of irrigation technologies with potential to improve water productivity, including scientific irrigation scheduling, deficit irrigation, site-specific irrigation, microirrigation, and decision support systems. Improvements to irrigation methods, systems, and management are primary solutions for improving water productivity both in the Arizona low desert and worldwide (Howell, 2001; Pereira et al., 2002).

Cotton (*Gossypium hirsutum* L.) is a primary commodity crop in the Arizona low desert, with 71,000 ha planted in 2018 and an annual production value of approximately $200 million for both fiber and cottonseed (USDA, 2019). Surface irrigation management with cotton planted on raised beds between furrows is the primary cotton

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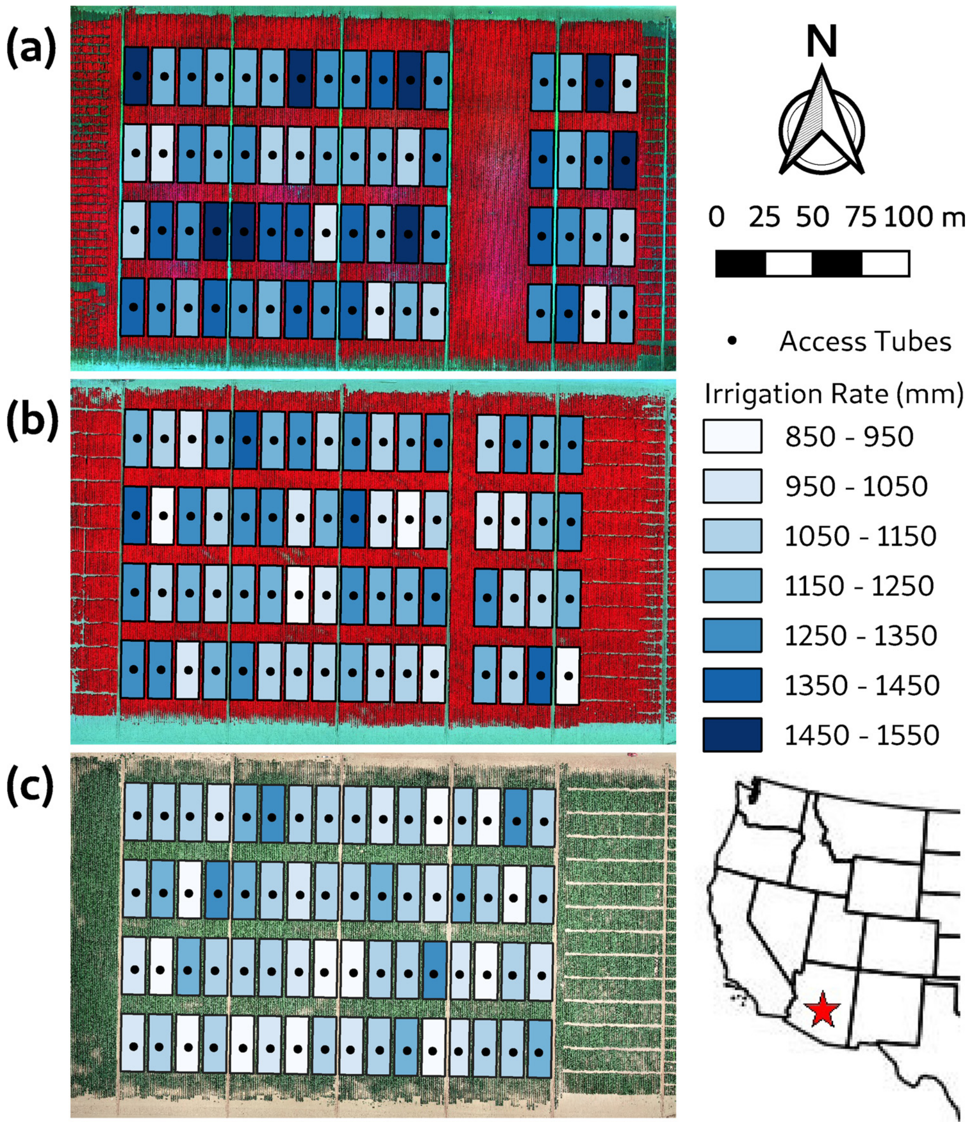


**Fig. 1.** Plot layouts for an irrigation management experiment during the (a) 2016, (b) 2017, and (c) 2018 cotton growing seasons at Maricopa, Arizona, USA. Locations of access tubes for soil water content measurements are shown near the center of each plot. Seasonal irrigation rates (mm) for each plot area are shown with false color composite images of the field on (a) 21 July 2016 and (b) 15 August 2017 and a true color image on (c) 30 July 2018.

production system in the region, mainly due to existing infrastructure for delivery of Colorado River water to growers through irrigation district canals. Early efforts to improve irrigation management for these systems sought to optimize timings for the first post-plant irrigation event (Steger et al., 1998) and the final irrigation event of the season (Unruh and Silvertooth, 1997; Tronstad et al., 2003). Both Radin et al. (1992) and Hunsaker et al. (1998) reported higher cotton yield and water productivity by applying smaller amounts of surface irrigation more frequently. Also, Hunsaker et al. (2005, 2015) developed remote sensing technologies for scientific irrigation scheduling of surface-irrigated cotton systems in Arizona. While these studies provided general recommendations for improving cotton irrigation management, they were mainly limited by the irrigation system, because amounts and placement of water cannot be precisely controlled with surface irrigation. More recently, the direction for cotton irrigation research in Arizona has shifted away from traditional surface irrigation, made possible by investments in modern overhead sprinkler irrigation systems (Bronson et al., 2017; Thorp et al., 2017). Because sprinkler systems offer much greater control of irrigation applications as compared to surface irrigation, for example with greater ability to apply smaller amounts of water more frequently and even site-specifically (Thorp, 2019), greater opportunity now exists to develop irrigation management practices and technologies that improve water productivity. Also, the unique environment of the Arizona low desert provides an added advantage for this endeavor, because limited precipitation enables scientific field investigations that are not confounded by rainfall.

Over the past several decades, high-quality field research in the Texas High Plains has led the way to use of modern irrigation equipment for clarifying impacts of irrigation management on cotton yield, water productivity, and fiber quality. At Halfway, Texas, irrigation amounts of 40%, 60%, 80%, and 100% of irrigation recommendations based on evapotranspiration (ET) were applied to field plots at 3-, 5-, 9-, and 15-day intervals using an overhead linear-move sprinkler system with site-specific irrigation technology (Bordovsky et al., 1992). Cotton fiber yield and irrigation water productivity (IWP; the ratio of irrigated yield minus dryland yield and seasonal irrigation) were both significantly higher at the 3-day irrigation interval over the three-year study. At the same site, Bordovsky et al. (2015) later field-tested combinations of three irrigation rates applied during three distinct cotton growing periods based on accumulated growing degree days, resulting in 27 irrigation management regimes. Results of the four-year study demonstrated lower IWP and sometimes lower cotton yield for

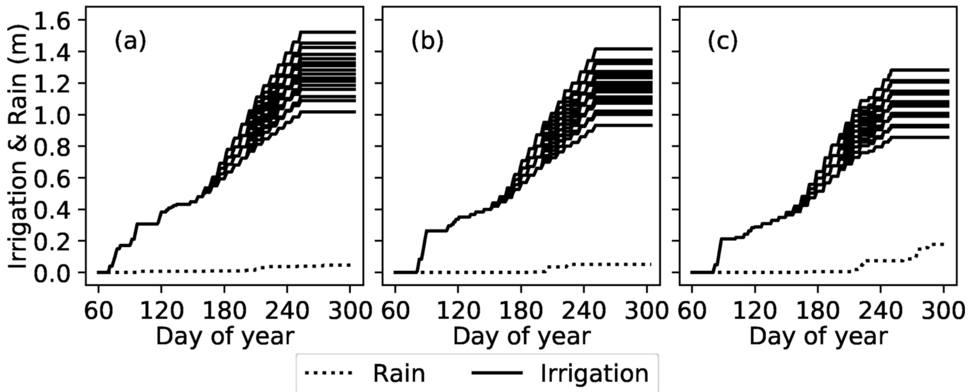


**Fig. 2.** Cumulative rainfall and applied irrigation amounts for 16 irrigation treatments from 1 March (day of year 60) through 31 October (day of year 304) in (a) 2016, (b) 2017, and (c) 2018 at Maricopa, Arizona, USA.

treatments that aimed to store water in the soil profile by overirrigating in the early season. The later cotton growth period, characterized by cotton boll filling and maturation, was the most critical time for irrigation, requiring sufficient water to maintain acceptable cotton fiber yield with high IWP. At a Lubbock, Texas site with a surface drip irrigation system, a 12-year study tested different irrigation scheduling techniques based on canopy temperature and soil water content measurements, concluding that irrigation schedules based on canopy temperature could maximize cotton fiber yield without applying excess irrigation (Wanjura et al., 2002). At Bushland, Texas, researchers measured cotton ET with large weighing lysimeters during two growing seasons, concluding that cotton yield and water productivity in the northern Texas High Plains were similar to more highly noted cotton production regions in the United States (Howell et al., 2004). Lastly, Snowden et al. (2013) measured effects of different irrigation rates on cotton yield, boll distribution, and fiber quality at Lamesa and New Deal, Texas. They found that irrigation effects on fiber micronaire depended on the growing season. These field studies from the Texas High Plains and similar studies elsewhere in the world (Conaty et al., 2015; Ghaderi-Far et al., 2012; Ibragimov et al., 2007; Lamb et al., 2015; Zhang et al., 2016) have offered great inspiration for the present study.

The overall goal was to quantify effects of irrigation rates and timing on cotton yield, water productivity, and fiber quality at a research station in the Arizona low desert. The study was motivated by recent installation of a six-span lateral-move sprinkler irrigation system at the station (Thorp et al., 2017), which was fully retrofitted with commercial site-specific irrigation equipment after the 2015 cotton season. The new system has enabled irrigation management research that was not previously possible at the site. Specific objectives were to (1) conduct a field experiment using site-specific sprinkler irrigation technology to apply different irrigation rates at different times during the cotton growing season and (2) identify irrigation management practices that improve water productivity while maintaining acceptable cotton yield and fiber quality.

## 2. Materials and methods

### 2.1. Field experiment

A cotton field experiment was conducted at the University of Arizona's Maricopa Agricultural Center (MAC) near Maricopa, Arizona (33.079° N, 111.977° W, 360 m above sea level) during the 2016, 2017, and 2018 cotton growing seasons (Fig. 1). The experiment tested responses of cotton yield, water use, and fiber quality to variable irrigation rate and timing for one commercial cotton variety (Deltapine 1549 B2XF, Monsanto Company, St. Louis, Missouri). The variety was chosen based on its performance in Arizona variety trials prior to the present study. The plots were relatively large (12.2 m (12 cotton rows) × 30.0 m) and required 3.8 ha of the 5.8-ha total field area. A randomized block design was used with four replicated blocks and 16 irrigation treatments per block for a total of 64 plots. The blocks were typically arranged within a single span of the overhead irrigation system; however, the position of the easternmost block was adjusted each year to accommodate other research activities at the site (Fig. 1). The 16 irrigation management treatments involved all the possible combinations of four irrigation rates applied during two distinct periods of the growing season. The four irrigation rates were 60%, 80%, 100%, and 120% of the recommendation provided by an irrigation scheduling tool based on the CSM-CROPGRO-Cotton agroecosystem model (Thorp et al., 2017). The two irrigation periods were from first square to peak bloom (approximately the first of June through mid-July) and from peak bloom to 90% open boll (approximately mid-July through the first week of September). The heat units since planting for the first and second irrigation periods ranged from 480 to 1155 °C-days and from 1155 to 2040 °C-days, respectively, as reported by an Arizona Meteorological Network (AZMET; http://ag.arizona.edu/azmet/) weather station approximately 1.2 km from the field site. The 16 irrigation management treatments led to cotton being grown with a variety of soil water status conditions (Fig. 2).

The environment for cotton production in the Arizona low desert is arid and hot, with daily minimum and maximum air temperatures regularly exceeding 25 and 40 °C, respectively, from July through August corresponding to day of year (DOY) 182–243 (Fig. 3). This normally coincides with the time of cotton reproductive development. Heat stress impacts cotton yield during this time, primarily by increasing flower abnormalities and abscission of bolls aged 3–5 days (Brown, 2008). As such, AZMET provides daily information on Level 1 and Level 2 heat stress conditions based on air temperature and humidity measurements. The number of days during July and August with Level 1 and Level 2 heat stress conditions was 31 and 16 in 2016, 34 and 11 in 2017, and 23 and 21 in 2018, respectively (Fig. 3). Thus, there were fewer heat stress days in 2018 but a higher number of Level 2 heat stress days. The cotton growing season also straddles the Arizona monsoon season in July and August, where relative humidity and dew point temperatures rise sharply (Fig. 3) and precipitation amounts increase (Fig. 2). As measured by the AZMET weather station, growing season precipitation from April through September (DOY 91–273) amounted to 42, 51, and 89 mm in 2016, 2017, and 2018, respectively (Table 1), while precipitation during the monsoon season in July and August amounted to 27 mm (65%), 50 mm (99%), and 70 mm (78%). In comparison, short crop reference ET (ETo) from April through September amounted to 1364, 1404, and 1372 mm in 2016, 2017, and 2018, respectively. Thus, cotton production requires irrigation to meet evaporative demand, and dryland production is not a realistic possibility. The soil texture at the field site was primarily sandy loam and sandy clay loam with drained upper limits between 0.16 and

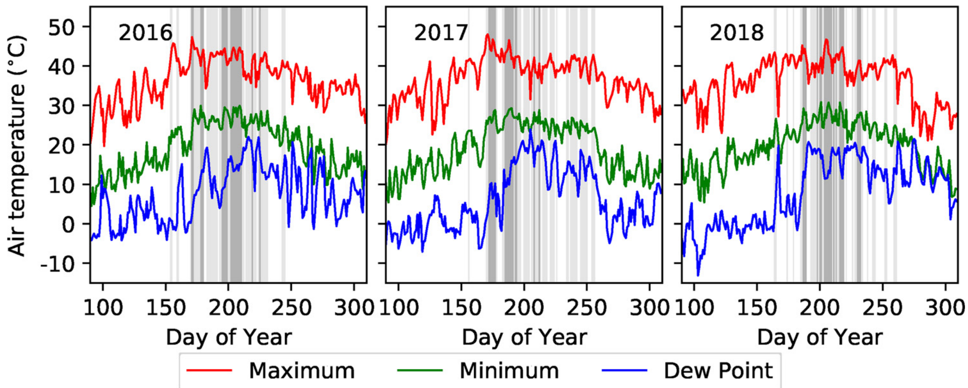


**Fig. 3.** Daily maximum, minimum, and average dew point air temperatures during the 2016, 2017, and 2018 cotton growing seasons from 1 April (day of year 91) through 30 September (day of year 273) at Maricopa, Arizona, USA. Light and dark shaded regions indicate days with Level 1 and Level 2 heat stress, respectively.

0.22 $cm^3\ cm^{-3}$ and lower limits between 0.08 and 0.11 $cm^3\ cm^{-3}$.

Cover crops were grown in the winter months between cotton seasons to reduce soil nutrient variability and improve soil quality. The field was prepared for cover crop planting by deep ripping, disking, and either planing or laser leveling. Annual ryegrass (*Festuca perennis* Lam.) was planted on 3 January 2016 (DOY 3) and terminated with glyphosate (RoundUp PowerMAX, Monsanto, St. Louis, Missouri, USA) on 22 February 2016 (DOY 53), following manufacturer's recommendations for application decisions. Barley (*Hordeum vulgare* L.) was planted on 19 December 2016 (DOY 354) and terminated with glyphosate on 3 March 2017 (DOY 63), and barley was again planted on 20 December 2017 (DOY 354) and terminated on 2 March 2018 (DOY 62). The cover crops were fully irrigated until termination, but no fertilizer was applied.

Upland cotton (*G. hirsutum* L., cv. "Deltapine 1549 B2XF") was planted with a north-south row orientation and row spacing of 1.02 m on 25 April 2016 (DOY 116), 18 April 2017 (DOY 108), and 18 April 2018 (DOY 108). Final plant density after emergence was 8.9, 9.4, and 10.9 plants $m^{-2}$ in 2016, 2017, and 2018, respectively. Prior to the 2016 and 2017 season, the field was ripped, disked, and planed in March before pre-plant irrigation. Cotton was later planted on flat ground following field cultivation and incorporation of pre-emergent herbicide containing pendimethalin (Prowl H2O, BASF, Florham Park, New Jersey, USA), following manufacturer's recommendations for application decisions. In 2018, no spring tillage was performed, and cotton was planted directly into the terminated barley cover crop. Pre-emergent herbicide was applied to the soil surface and watered in with a light 10.2-mm irrigation. Following irrigation termination in early September, cotton was defoliated using products containing thidiazuron and diuron (Ginstar EC, Bayer CropScience, Monheim am Rhein, Germany) following manufacturer's recommendations for application decisions. Defoliant was applied on 7 October (DOY 281) and 24 October (DOY 298) in 2016, 3 October (DOY 276) and 20 October (DOY 293) in 2017, and 28 September (DOY 271) and 19 October (DOY 292) in 2018.

### 2.2. Irrigation management

As reported by Thorp et al. (2017), an overhead lateral-move sprinkler irrigation system (Zimmatic, Lindsay Corporation, Omaha, Nebraska) was newly installed at the field site in 2014. Following the 2015 cotton growing season, advanced technology was added to the irrigation machine, which permitted site-specific irrigation applications based on georeferenced irrigation maps uploaded to the machine's control panel (GrowSmart Precision Variable Rate Irrigation, Lindsay Corporation, Omaha, Nebraska). Irrigation rates were computed uniquely for each drop hose using information from (1) the user-provided application rate map, (2) two global positioning system (GPS) receivers on opposite ends of the lateral, and (3) a database of system characteristics, which included offset distances of each drop hose along the lateral. The system used wireless communication among 88 nodes to relay information along the lateral, and each wireless node provided individual control for four drop hoses by adjusting the duty cycles of four electronic solenoid valves. The machine was equipped with 0.158 $L\ s^{-1}$ nozzles in 2016 and 2017 (#12, Senninger, Clermont, Florida) and 0.201 $L\ s^{-1}$ nozzles in 2018 (#13.5, Senninger, Clermont, Florida). Nozzles were spaced 1.02 m apart, located at the center of each cotton interrow area, and positioned to emit water less than 1.0 m above the soil surface. For uniform soil wetting prior to cotton emergence, spray pads giving a spray diameter of approximately 5.0 m were used. After cotton emergence, the pads were changed to a "bubbler" style, which emitted large droplets with a 0.3-m spray diameter at the center of each interrow area. In addition to reducing water loss to evaporation, the bubbler pads increased the spatial accuracy of irrigation applications relative to the intended application areas delineated in the georeferenced irrigation maps. Spatial application error with the site-specific irrigation machine was estimated to be less than 2.0 m.

The cotton growing season was partitioned into five distinct time periods with unique objectives for irrigation management and soil water status: (1) pre-season irrigation management to raise the soil water content and fill the soil profile prior to planting cotton, (2) post-planting irrigation to emerge the cotton crop and reduce soil crusting to prevent cotyledon breakage during emergence, (3) weekly in-season irrigation to apply four irrigation rates to plots from first square (480 °C-days after planting) to peak bloom (1155 °C-days after planting), (4) weekly in-season irrigation to apply four irrigation rates to plots from peak bloom to 90% open boll (2040 °C-days after planting), and (5) no irrigation during the field dry down period to prepare cotton for defoliant applications and harvest (Table 1).

Uniform irrigation management was used during the pre-season and emergence irrigation periods. In 2016, 307 mm was applied in March prior to planting, but pre-plant irrigation amounts were reduced to 264 mm in 2017 and to 222 mm in 2018 (Table 1). Following cotton planting, light irrigation with amounts ranging from 8 to 20 mm was applied every few days to emerge the cotton crop and reduce soil surface crusting to prevent breakage of the emerging cotyledon. After emergence, irrigation was applied approximately weekly at rates less than 20 mm for approximately four weeks until first square. Traditionally, little to no irrigation is applied to Arizona cotton at this time to encourage root growth to deeper soil layers that hold water from pre-plant irrigation and perhaps to acclimate the young plants to the hot and dry environment (Meeks et al., 2017). Total irrigation applied during the cotton emergence period was 173, 136, and 127 mm in 2016, 2017, and 2018, respectively (Table 1). Prior to initiating water management treatments at first square, the field-average soil water content from the surface to 140 cm was 25.1%, 25.4%, and 23.9% in 2016, 2017, and 2018, respectively. This means the effects of pre-

**Table 1**
Precipitation, applied irrigation, and short crop reference evapotranspiration (ETo) for 16 irrigation treatments during the 2016, 2017, and 2018 growing seasons at Maricopa, Arizona, USA. Variation in irrigation management occurred in two periods from first square to peak bloom (1Sqr-PkBlm) and from peak bloom to 90% open boll (PkBlm-90OB).

| Period | DOY range | Rain (mm) | Irrig 60–60 (mm) | Irrig 60–80 (mm) | Irrig 60–100 (mm) | Irrig 60–120 (mm) | Irrig 80–60 (mm) | Irrig 80–80 (mm) | Irrig 80–100 (mm) | Irrig 80–120 (mm) | Irrig 100–60 (mm) | Irrig 100–80 (mm) | Irrig 100–100 (mm) | Irrig 100–120 (mm) | Irrig 120–60 (mm) | Irrig 120–80 (mm) | Irrig 120–100 (mm) | Irrig 120–120 (mm) | ETo (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *2016* | | | | | | | | | | | | | | | | | | | |
| Preplant | 61-115 | 7 | 307 | 307 | 307 | 307 | 307 | 307 | 307 | 307 | 307 | 307 | 307 | 307 | 307 | 307 | 307 | 307 | 294 |
| Emergence | 116–159 | 1 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 345 |
| 1Sqr-PkBlm | 160–201 | 2 | 246 | 246 | 246 | 246 | 317 | 317 | 317 | 317 | 388 | 388 | 388 | 388 | 460 | 460 | 460 | 460 | 365 |
| PkBlm-90OB | 202–258 | 29 | 292 | 389 | 487 | 584 | 292 | 389 | 487 | 584 | 292 | 389 | 487 | 584 | 292 | 389 | 487 | 584 | 427 |
| Dry Down | 259–305 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 213 |
| Apr1-Sep30 | 92–274 | 42 | 831 | 928 | 1025 | 1123 | 902 | 999 | 1097 | 1194 | 973 | 1071 | 1168 | 1265 | 1045 | 1142 | 1239 | 1337 | 1364 |
| Mar1-Oct31 | 61–305 | 46 | 1018 | 1115 | 1212 | 1310 | 1089 | 1186 | 1283 | 1381 | 1160 | 1258 | 1355 | 1452 | 1232 | 1329 | 1426 | 1524 | 1643 |
| *2017* | | | | | | | | | | | | | | | | | | | |
| Preplant | 60–107 | 1 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 251 |
| Emergence | 108–151 | 1 | 136 | 136 | 136 | 136 | 136 | 136 | 136 | 136 | 136 | 136 | 136 | 136 | 136 | 136 | 136 | 136 | 341 |
| 1Sqr-PkBlm | 152–195 | 0 | 260 | 260 | 260 | 260 | 330 | 330 | 330 | 330 | 401 | 401 | 401 | 401 | 472 | 472 | 472 | 472 | 420 |
| PkBlm-90OB | 196–251 | 50 | 272 | 363 | 453 | 544 | 272 | 363 | 453 | 544 | 272 | 363 | 453 | 544 | 272 | 363 | 453 | 544 | 403 |
| Dry Down | 252–304 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 279 |
| Apr1-Sep30 | 91–273 | 51 | 668 | 758 | 849 | 940 | 738 | 829 | 920 | 1010 | 809 | 900 | 990 | 1081 | 880 | 970 | 1061 | 1152 | 1404 |
| Mar1-Oct31 | 60–304 | 52 | 932 | 1022 | 1113 | 1204 | 1002 | 1093 | 1184 | 1274 | 1073 | 1164 | 1254 | 1345 | 1144 | 1234 | 1325 | 1416 | 1695 |
| *2018* | | | | | | | | | | | | | | | | | | | |
| Preplant | 60–107 | 0 | 222 | 222 | 222 | 222 | 222 | 222 | 222 | 222 | 222 | 222 | 222 | 222 | 222 | 222 | 222 | 222 | 253 |
| Emergence | 108–149 | 0 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 316 |
| 1Sqr-PkBlm | 150–195 | 4 | 259 | 259 | 259 | 259 | 326 | 326 | 326 | 326 | 392 | 392 | 392 | 392 | 458 | 458 | 458 | 458 | 393 |
| PkBlm-90OB | 196–250 | 69 | 247 | 323 | 398 | 474 | 247 | 323 | 398 | 474 | 247 | 323 | 398 | 474 | 247 | 323 | 398 | 474 | 413 |
| Dry Down | 251–304 | 105 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 243 |
| Apr1-Sep30 | 91–273 | 89 | 644 | 720 | 795 | 871 | 710 | 786 | 862 | 937 | 776 | 852 | 928 | 1003 | 843 | 918 | 994 | 1070 | 1372 |
| Mar1-Oct31 | 60–304 | 179 | 856 | 932 | 1007 | 1083 | 922 | 998 | 1074 | 1149 | 989 | 1064 | 1140 | 1216 | 1055 | 1131 | 1206 | 1282 | 1617 |

season and emergence irrigation on seasonal interaction among measured variables was likely minor.

Regular irrigation scheduling and management commenced around first square (i.e., the first week of June). Due to practical considerations for field entry, labor availability, and water delivery to the field site, the irrigation scheduling methodology followed a weekly cycle. Monday and Tuesday were established as "dry days" for field entry to collect measurements and perform any required tractor-based operations. Irrigation scheduling algorithms were run on Monday, which resulted in a weekly irrigation recommendation for the 100%–100% irrigation treatment and a prescription map to alter the irrigation rates for other plots via the site-specific sprinkler irrigation machine. A water delivery request was then submitted to the research station's water manager, who required a 24-h advanced notice for water delivery. Each week, water was requested for Wednesday, Thursday, and Friday as needed, pending availability of labor to (1) manage delivery of water to the field site via concrete-lined canals and (2) operate the sprinkler irrigation machine. Analysis of soils data suggested that the field site had sufficient available water holding capacity to satisfy crop water requirements for a week or more at peak seasonal water demand (Thorp, 2019), which made the weekly irrigation management methodology more plausible.

Following the method of Thorp et al. (2017), irrigation schedules were determined using the Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM), specifically the CSM-CROPGRO-Cotton model (Jones et al., 2003). A thorough description of the model was provided by Thorp et al. (2014a). Also, Thorp et al. (2014b) and Thorp et al. (2017) described efforts to calibrate the model using data from other cotton field experiments at the research station prior to 2016. Furthermore, DeJonge and Thorp (2017) described recent efforts to update the ET algorithms in the DSSAT-CSM model. Thorp et al. (2017) described the methodology for combining past weather measurements and future weather predictions to conduct CSM-CROPGRO-Cotton simulations for in-season irrigation management decisions. While Thorp et al. (2017) based irrigation decisions only on simulated root zone soil water depletion, additional model outputs were analyzed in the present study, including future predictions for ET and water stress factors for growth and photosynthesis. The irrigation recommendation was the smallest irrigation amount that supplied model-predicted ET, eliminated model predictions of water stress, and maintained root-zone soil water depletion below 45%, based on average simulated responses among predictions from future weather scenarios that were estimated from historical weather data at the site. This amount was assigned to plots receiving 100% of the irrigation recommendation in both the first and second irrigation periods. Because some plots received 120% of this amount (i.e., 20% more), the number of passes of the irrigation machine was increased to supply the extra water to these plots.

Prior to each growing season, field plots were mapped in a geographic information system (QGIS, www.qgis.org) based on data from field surveys with real-time kinematic (RTK) global positioning equipment with cm-level horizontal accuracy (Fig. 1). Following the randomized block experimental design, a shapefile was created to delineate plot areas for site-specific irrigation applications, and the shapefile was loaded to the commercial software provided by the manufacturer of the site-specific irrigation equipment (FieldMAP, Lindsay Corporation, Omaha, Nebraska). The irrigation rate percentages for each plot could be adjusted in the software. However, because rates could only be specified from 0% to 100%, the irrigation treatments of 60%, 80%, 100%, and 120% of the model-based irrigation recommendation were mapped to rates of 50.0%, 66.7% 83.3% and 100.0% in the software. By adjusting the total number of irrigation passes to supply the required irrigation amount for the 120% treatment, these rates ensured that plots received the intended irrigation amounts. After finalizing the irrigation rates, the software wrote an irrigation prescription file to a USB flash drive, which was transported to the field for uploading the prescription map to the irrigation machine.

Plot-specific irrigation for the first irrigation period (first square to peak bloom) commenced on 8 June (DOY 160), 1 June (DOY 152), and 30 May (DOY 150) in 2016, 2017, and 2018, respectively (Table 1). Rate adjustments for the second irrigation period (peak bloom to 90% open boll) occurred on 20 July (DOY 202), 15 July (DOY 196), and 15 July (DOY 196) in 2016, 2017, and 2018, respectively. Adjusting the irrigation rates was easily accomplished by simply changing the rate percentages for all plots in the irrigation prescription map. The final irrigation of each season occurred on 9 September 2016 (DOY 253), 8 September 2017 (DOY 251), and 7 September 2018 (DOY 250), giving a total of 16 irrigation management regimes in each cotton season (Fig. 2).

To allow for spatial application errors with the site-specific irrigation equipment and to minimize impacts of overland flow between adjacent plot areas, buffer regions were established in the area between plots (Fig. 1). A 10-m buffer distance was established between plots along the row, and a 2-m (i.e., 2-row) buffer distance was established between plots perpendicular to the row. Due to compaction from tractor tires, greater potential for overland flow existed parallel to the rows, thus a larger buffer distance was used. Impacts of overland flow were also minimized by operating the irrigation machine at full speed and making multiple passes over consecutive days to supply the weekly irrigation rates. Using these tactics, overland flow was typically not observed in excess of 10 m from the point of application. Reduced visual observations of overland flow in the 2018 growing season suggested that no-till management improved infiltration rates and provided increased surface residue for obstructing overland flow. Substantial efforts were made to identify and implement ways to reduce impacts of overland flow on the irrigation treatments.

Based on pre-plant soil sampling for soil nitrate concentration, liquid urea ammonium nitrate (UAN 32-0-0) was uniformly applied in three or four split applications, amounting to seasonal nitrogen (N) application rates of 111 kg N $ha^{-1}$ in 2016, 148 kg N $ha^{-1}$ in 2017, and 179 kg N $ha^{-1}$ in 2018. These N amounts were based on a 1960 kg fiber $ha^{-1}$ yield goal and a pre-plant soil nitrate test from the soil surface to a depth of 0.9 m (Bronson et al., 2017). In 2016 and 2017, a fertigation trailer, which included a fertilizer tank, metering pump, and gasoline-powered generator, was hitched to the lateral-move irrigation machine, and fertilizer was injected into the overhead pipe at a rate of 0.032 L $s^{-1}$. After the metering pump malfunctioned in early 2018, a metering box with a flotation switch was used to meter fertilizer into the canal immediately prior to the intake pipe of the irrigation machine. During each fertigation event, the irrigation machine was operated at 25% of full speed, which applied N fertilizer with 16 mm of water in 2016 and 2017 and 20 mm of water in 2018. To ensure uniform fertilizer applications, no site-specific irrigation management was conducted during fertigation events. Fertilizer application dates were 3 June (DOY 155), 16 June (DOY 168), and 8 July (DOY 190) in 2016; 17 May (DOY 137), 8 June (DOY 159), 21 June (DOY 172), and 5 July (DOY 186) in 2017; and 16 May (DOY 136), 20 June (DOY 171), 5 July (DOY 186) and 19 July (DOY 200) in 2018.

### 2.3. Field measurements

Soil water content was measured weekly via a field-calibrated neutron moisture meter (model 503, Campbell Pacific Nuclear, Martinez, California). After crop emergence, steel access tubes were installed at the center of each plot (Fig. 1) using a tractor-mounted soil sampler (model 25-TS, Giddings Machine Co., Windsor, Colorado). From mid-May to early October, the neutron moisture meter was deployed on a weekly basis (approximately 20 times per growing season) to measure soil water content from 0.1 to 1.9 m in 0.2-m incremental depths at each access tube. Soil water content data were used to estimate ET and deep seepage between successive measurement events. The specific details of the ET and deep seepage calculations were previously described by Thorp et al. (2018), based on the soil water balance approach of Hunsaker et al. (2005).

Three zones were delineated in each plot for cotton yield measurements; each zone was 1.02 m (i.e., two rows) by 10 m. Cotton in each zone was machine-harvested with a two-row picker (Case IH 1822, Case IH, Grand Island, Nebraska) on 1 November 2016 (DOY 306), 8 November 2017 (DOY 312), and 30 October 2018 (DOY 303). Cotton yield samples from each harvest zone were bagged and weighed separately. After weighing, a yield subsample of approximately 150 g was collected from each bag for moisture analysis. Subsamples were stored in sealed plastic bags until transfer to drying ovens, with wet and dry sample weights used to calculate moisture content. The remainder of the cotton yield samples was transferred to the MAC ginning facility to separate fiber, cottonseed, and trash. Moisture content and fiber turnout percentages were used to correct the original bulk cotton yield sample weights to dry fiber yield (FBY, kg $ha^{-1}$) and cottonseed yield (SDY, kg $ha^{-1}$). Dry seed cotton yield (SCY, kg $ha^{-1}$) was computed as the sum of the dry fiber and dry cottonseed weights, and fiber fraction (FRC, %) was computed as the ratio of dry fiber yield and seed cotton yield. Yield measurements from the three harvest zones in each plot were averaged to obtain the plot-level yield amounts used for subsequent analysis. After ginning, a cotton fiber subsample of approximately 10 g was obtained for each plot and sent to Cotton Incorporated (Cary, NC, USA) for analysis of fiber quality via High Volume Instrument (HVI) methods. Six measurements of fiber quality were obtained, including micronaire (MIC, unitless), upper half mean length (UHM, mm), uniformity index (UFI, mm $mm^{-1}$), fiber strength (STR, HVI g $tex^{-1}$), elongation at failure (ELO, %), and short fiber content (SFC, %).

Seasonal crop water productivity (CWP, kg $m^{-3}$) was calculated as the ratio of dry fiber yield and seasonal ET, based on neutron moisture meter readings from mid-May to early October. Irrigation water productivity (IWP, kg $m^{-3}$) was calculated as the ratio of dry fiber yield and seasonal irrigation water applied from March through October (Table 1). Thus, IWP incorporated effects from pre-season and emergence irrigation, while CWP did not.

### 2.4. Statistical analysis

Data collection efforts resulted in 12 measured variables for statistical analysis: FBY, SDY, SCY, ETC, CWP, IWP, MIC, UHM, UFI, STR, ELO, and SFC. The main water-related treatment effects were quantified as the total water applied (rainfall + irrigation) normalized by the total short crop reference ET (ETo) during the irrigation period (IPETo, mm $mm^{-1}$):

$$\text{IPETo} = \frac{\sum_{j=1}^{n} (R_j + I_j)}{\sum_{j=1}^{n} E_j} \quad (1)$$

where $n$ is the total number of days in the irrigation period and $R_j$, $I_j$, and $E_j$ are respectively the precipitation, net irrigation, and ETo that occurred on day $j$ within the period. Precipitation was added to irrigation rates such that measured variables could be evaluated considering the total water input to the system during each irrigation period. This amount was normalized by ETo to account for variation in atmospheric demand among the two irrigation periods and three growing seasons, which likely resulted in differential amounts of water required. The relationship between IPETo and irrigation treatment percentages is shown in Fig. 4, with high correlation between the two variables.

Linear mixed models were computed using the “lme4” package within the R Project for Statistical Computing (http://r-project.org). For all models, the Year × Replicate interaction was fit as a single random effect, as it accounted for substantially more variability than Replicate alone. Hierarchical modeling methods were used to identify fixed effects that explained further variation in each variable. Likelihood ratio

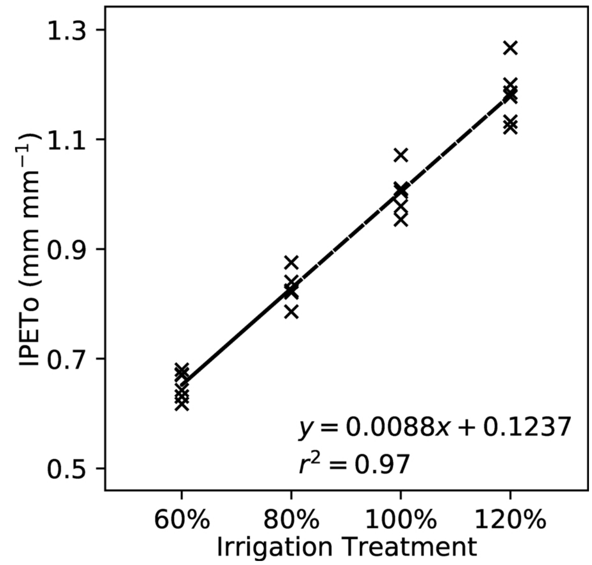


**Fig. 4.** Irrigation plus rainfall normalized by short crop reference evapotranspiration (IPETo) versus the rate percentages for irrigation treatments during two irrigation periods in three cotton growing seasons at Maricopa, Arizona, USA.

tests were conducted for one model that included the fixed effect and a second model with the fixed effect removed, which established whether the fixed effect in question significantly contributed to explained variability. Fixed effects were tested in the following order: (1) Year, (2) IPETo for the first irrigation period from squaring to peak bloom (IPETo1), (3) IPETo for the second irrigation period from peak bloom to 90% open boll (IPETo2), (4) the Year × IPETo1 interaction, (5) the Year × IPETo2 interaction, (6) the IPETo1 × IPETo2 interaction, and (7) the Year × IPETo1 × IPETo2 interaction. If the $p$-value for a likelihood ratio test was less the 0.05, the fixed effect was incorporated into the model for subsequent hierarchical tests and modeling analysis. Otherwise, the fixed effect was eliminated from further consideration. After selecting fixed effects via hierarchical modeling, the accuracy of the final model was evaluated using leave-one-out cross validation. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality.

The final linear mixed models were applied to simulate the effects of fine adjustments to IPETo1 and IPETo2 on outcomes of each variable. Model input values for IPETo1 and IPETo2 were each varied from 0.56 to 1.28 with an increment of 0.01, based on the range of IPETo values encountered during the field trials. This analysis extended the field data via a statistical model to permit a finer understanding of the effects of irrigation rates than could be possible with the field data alone.

## 3. Results

### 3.1. Model construction

Hierarchical linear mixed modeling highlighted the fixed effects that explained significant variation in the measured variables (Table 2). For all variables except ETC, the Year effect explained significant variation ($p < 0.05$), meaning variation was due to growing season conditions independent from water management. As for ETC, the cultivar did not change and irrigation management was carefully controlled, which resulted in no crop water use variability due to growing season. For all cotton yield measurements, ETC, CWP, and four of six fiber quality metrics, the IPETo1 fixed effect explained significant variability in the measurements. Notably, variation in FRC, IWP, MIC, and ELO could not be explained by IPETo1, but variation in these metrics could be explained by IPETo2. Thus, FRC, IWP, MIC, and ELO were more

**Table 2**
Chi squared ($\chi^2$) statistics and probability ($p$) values from likelihood ratio tests and hierarchical linear mixed modeling. Results demonstrate the effects of year, total water applied normalized by short crop reference ET (ETo) for the first irrigation period (IPETo1) and the second irrigation period (IPETo2), and their interactions on cotton fiber yield (FBY, kg ha$^{-1}$), cottonseed yield (SDY, kg ha$^{-1}$), seed cotton yield (SCY, kg ha$^{-1}$), fiber fraction (FRC, %), cumulative seasonal ET (ETC, mm), crop water productivity (CWP, kg m$^{-3}$), irrigation water productivity (IWP, kg m$^{-3}$), micronaire (MIC, unitless), upper half mean fiber length (UHM, mm), uniformity index (UFI, mm mm$^{-1}$), fiber strength (STR, HVI g tex$^{-1}$), elongation at failure (ELO, %), and short fiber content (SFC, %). Significant effects with $p < 0.05$ are highlighted in bold.

| Metric | Mean | Standard deviation | Year | | IPETo1 | | IPETo2 | |
|---|---|---|---|---|---|---|---|---|
| | | | $\chi^2$ | $p$ | $\chi^2$ | $p$ | $\chi^2$ | $p$ |
| FBY | 1583.7 | 338.6 | 24.547 | **0.000** | 16.139 | **0.000** | 22.011 | **0.000** |
| SDY | 2030.2 | 405.8 | 25.131 | **0.000** | 16.254 | **0.000** | 29.682 | **0.000** |
| SCY | 3613.9 | 738.8 | 24.718 | **0.000** | 16.351 | **0.000** | 26.348 | **0.000** |
| FRC | 43.762 | 1.405 | 31.083 | **0.000** | 1.764 | 0.184 | 15.788 | **0.000** |
| ETC | 934.82 | 118.3 | 3.0807 | 0.214 | 84.521 | **0.000** | 599.77 | **0.000** |
| CWP | 0.1708 | 0.038 | 26.134 | **0.000** | 8.837 | **0.003** | 16.953 | **0.000** |
| IWP | 0.1353 | 0.024 | 16.578 | **0.000** | 2.477 | 0.116 | 9.859 | **0.002** |
| MIC | 4.5632 | 0.432 | 25.575 | **0.000** | 0.539 | 0.463 | 48.318 | **0.000** |
| UHM | 27.908 | 1.664 | 45.726 | **0.000** | 20.576 | **0.000** | 48.440 | **0.000** |
| UFI | 79.816 | 2.019 | 42.306 | **0.000** | 11.178 | **0.001** | 1.207 | 0.272 |
| STR | 29.907 | 2.726 | 47.846 | **0.000** | 4.238 | **0.040** | 40.380 | **0.000** |
| ELO | 5.9422 | 0.416 | 53.888 | **0.000** | 0.012 | 0.913 | 12.775 | **0.000** |
| SFC | 11.013 | 2.072 | 44.728 | **0.000** | 16.952 | **0.000** | 12.632 | **0.000** |

| Metric | Year × IPETo1 | | Year × IPETo2 | | IPETo1 × IPETo2 | | Year × IPETo1 × IPETo2 | |
|---|---|---|---|---|---|---|---|---|
| | $\chi^2$ | $p$ | $\chi^2$ | $p$ | $\chi^2$ | $p$ | $\chi^2$ | $p$ |
| FBY | 61.133 | **0.000** | 29.006 | **0.000** | 0.006 | 0.941 | 4.737 | 0.192 |
| SDY | 64.458 | **0.000** | 33.684 | **0.000** | 0.299 | 0.585 | 9.078 | **0.028** |
| SCY | 63.708 | **0.000** | 31.960 | **0.000** | 0.111 | 0.739 | 6.979 | 0.073 |
| FRC | 14.965 | **0.002** | 9.384 | **0.009** | 8.565 | **0.003** | 3.443 | 0.179 |
| ETC | 50.232 | **0.000** | 13.895 | **0.001** | 3.950 | **0.047** | 4.523 | 0.104 |
| CWP | 63.435 | **0.000** | 28.125 | **0.000** | 0.339 | 0.560 | 3.178 | 0.365 |
| IWP | 60.623 | **0.000** | 25.842 | **0.000** | 0.216 | 0.642 | 3.186 | 0.364 |
| MIC | 13.213 | **0.004** | 1.707 | 0.426 | 5.485 | **0.019** | 0.370 | 0.831 |
| UHM | 5.105 | 0.078 | 5.892 | 0.053 | 2.247 | 0.134 | 13.48 | **0.004** |
| UFI | 0.332 | 0.847 | 7.834 | **0.050** | 1.065 | 0.302 | 1.378 | 0.711 |
| STR | 3.452 | 0.178 | 17.068 | **0.000** | 0.331 | 0.565 | 3.603 | 0.308 |
| ELO | 1.787 | 0.618 | 13.907 | **0.001** | 0.066 | 0.797 | 1.481 | 0.687 |
| SFC | 7.040 | **0.030** | 16.702 | **0.000** | 0.086 | 0.770 | 0.267 | 0.966 |

determined by late-season water management as compared to early-season water management. With the exception of UFI, the IPETo2 fixed effect explained significant variability in all measurements. Thus, water management during the boll filling period had a substantial role in most of the cotton production outcomes. These results suggest that opportunities for improving IWP without sacrificing yield or fiber quality exist primarily in the early growing season.

The Year × IPETo1 and Year × IPETo2 interaction effects were significant for all measured variables, except a few of the fiber quality metrics. The SFC was the only fiber quality metric with significant results for both of these interaction effects ($p < 0.05$). Overall, the responses of most measured variables to water management factors depended on the year, in spite of efforts to normalize applied water by cumulative ETo in the irrigation period (Eq. (1)). Significant interaction effects for IPETo1 × IPETo2 and for Year × IPETo1 × IPETo2 were less common among the variables. Notably for FRC and MIC, the IPETo1 × IPETo2 effect was significant even though the IPETo1 main effect was not significant. This means IPETo1 affected these variables, but only through its interaction with IPETo2.

### 3.2. Model evaluation

Finalized linear mixed models included only the significant fixed effects (Table 2) for a given variable as well as a random effect for the Year × Replicate interaction. Leave-one-out cross validation among 192 measurements (64 plots times 3 years) provided evaluations of model performance for each variable (Fig. 5). Linear mixed models estimated cotton yield and water productivity measurements, including FBY (Fig. 5a), SDY (Fig. 5b), SCY (not shown), CWP (not shown), and IWP (Fig. 5d), with root mean squared errors of cross validation (RMSECV) between 10.9% and 12.5%. Seasonal ET was estimated very well with RMSECV of 1.8% (Fig. 5c), likely because the ET estimates were computed in part from irrigation amounts (Thorp et al., 2018) which were also incorporated into the main effects of the model (Eq. (1)). All the fiber quality metrics were estimated with RMSECV less than 8%. Except for MIC (Fig. 5e), the fiber quality data typically demonstrated clustering according to the growing season (e.g., STR shown in Fig. 5f), which suggested that variation in these variables was primarily caused by growing season factors and was less related to water management. For example, the lower values for STR (Fig. 5f) were all in 2018, which may be related to a higher frequency of Level 2 heat stress days during boll development in that year (Fig. 3c). Overall, the cross-validated linear mixed models estimated the measured variables with low error and were deemed reasonable for simulations to further understand the outcomes of the field study.

### 3.3. Cotton yield

Measured and modeled cotton yield demonstrated similar patterns of yield differences among the 16 irrigation management treatments (Fig. 6). Reducing irrigation rates to 60% of recommended values in either the first or second irrigation periods substantially reduced yield. However, if first-period irrigation rates were dropped to 80%, reasonable yield could be achieved as long as second-period irrigation rates were 100% or 120% of the recommendation. On the other hand, if second-period irrigation rates were dropped to 80%, reasonable yield

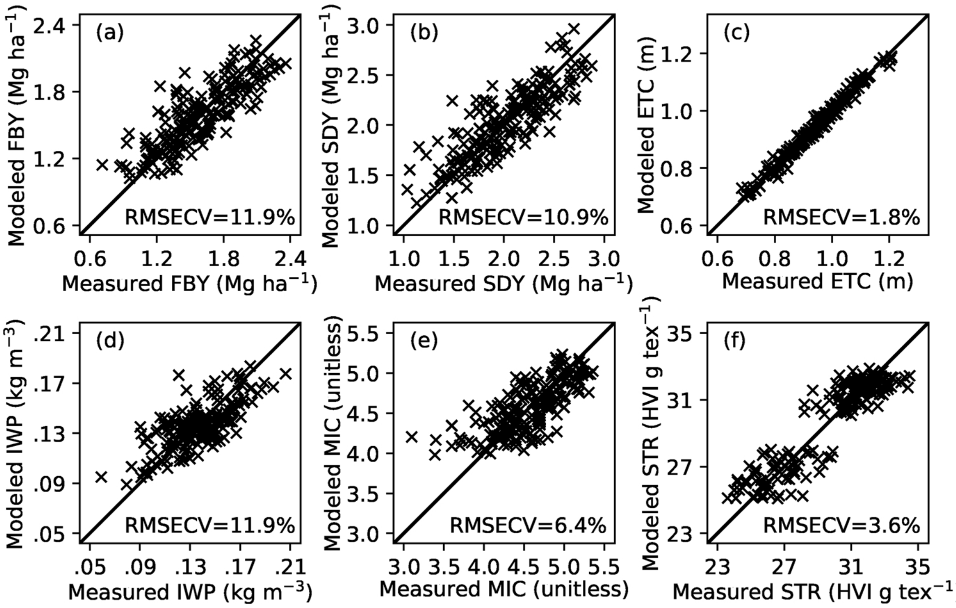


**Fig. 5.** Cross-validated linear mixed modeling results versus measured data for (a) cotton fiber yield (FBY), (b) cottonseed yield (SDY), (c) seasonal cumulative evapotranspiration (ETC), (d) irrigation water productivity (IWP), (e) fiber micronaire (MIC), and (f) fiber strength (STR) for three cotton growing seasons with variable irrigation management at Maricopa, Arizona, USA.

could be achieved only if overwatering at the 120% rate had previously occurred during the first irrigation period. The results suggest that greater opportunities for water savings without substantial yield reduction exist by fine-tuning irrigation rates in the first half of the growing season, while full irrigation needs to be maintained during the second half. Modeled fiber yield was highest for the 120%–120% irrigation treatment; however, measured data did not demonstrate a similar yield increase for this treatment. Thus, the model tended to overestimate yield for the 120%–120% treatment, and the additional water applied was likely wasteful. Overall, the irrigation scheduling algorithm, which provided the recommendation for the 100%–100% treatment, performed adequately to achieve acceptable measured yield. Potential reductions to rate recommendations without substantial yield declines were no greater than 70 mm (6% of total water applied to the 100%–100% treatment). This would require formalizing improvements that shift recommendations from rates within the 100%–100% treatment region to the 80%–100% treatment region (Fig. 6). Similar figures for cottonseed yield and seed cotton yield (not shown) displayed nearly identical patterns as fiber yield among the irrigation treatments.

### 3.4. Water productivity

Increases in both measured and modeled ET closely followed increases in irrigation rate (Fig. 7), suggesting that cotton water use was highly correlated with water applied. Estimated deep seepage did not exceed 97 mm (11% of applied water), 63 mm (9% of applied water), or 46 mm (6% of applied water) in 2016, 2017, and 2018, respectively (not shown). The decline in deep seepage over the three growing seasons was likely related to reductions in pre-plant irrigation each year (Table 2).

Measured IWP demonstrated reduced efficiency when overwatering at the 120% rate during either the first or second irrigation periods (Fig. 8), and reduced IWP for the 60%–60% treatment was also apparent. The highest mean measured IWP occurred with the 80%–80% irrigation treatment, and IWP with the 80%–100% irrigation treatment was also higher than that for the 100%–100% treatment. Similar to results for yield, IWP improvements could be obtained by formalizing methodologies to shift irrigation recommendations from the 100%–100% rate toward the 80%–100% treatment and possibly the 80%–80% treatment. Linear mixed modeling highlighted the reductions in IWP when overirrigating at the 120% rate during the second irrigation period. This likely occurred due to cotton reaching cut-out and therefore benefiting little from the additional water. In addition to fine-tuning early season irrigation rates, opportunities also exist to fine-tune decisions for irrigation termination.

Optimizing both fiber yield and IWP are often conflicting objectives that require inspection of the Pareto frontier (Fig. 9). The data confirm that efforts to schedule irrigation away from the 100%–100% treatment and toward the 80%–100% treatment could improve IWP without reducing yield. Scheduling more toward the 80%–120% treatment may increase both yield and IWP slightly, while scheduling more toward the 80%–80% may substantially increase IWP but with a moderate yield

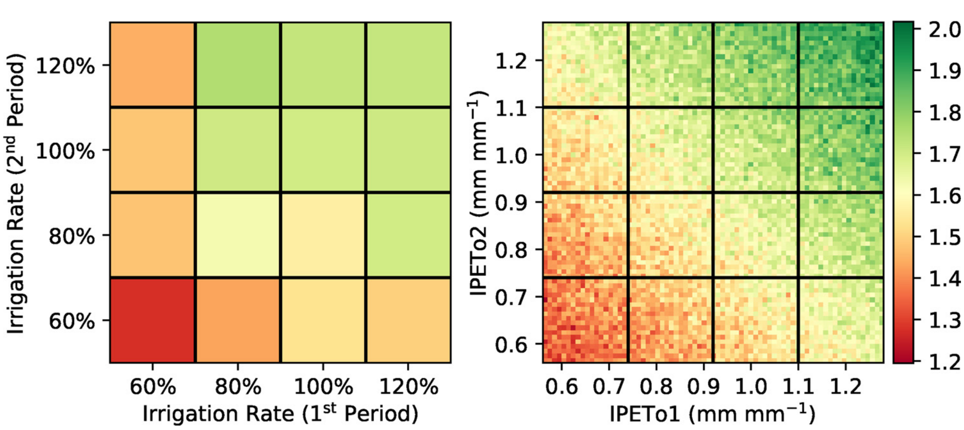


**Fig. 6.** Mean measured cotton fiber yield (left, Mg ha$^{-1}$) for each first-period and second-period irrigation treatment combination and mean modeled cotton fiber yield (right, Mg ha$^{-1}$) for irrigation plus rainfall normalized by short crop reference evapotranspiration in the first irrigation period (IPETo1) and second irrigation period (IPETo2) over three growing seasons at Maricopa, Arizona, USA.

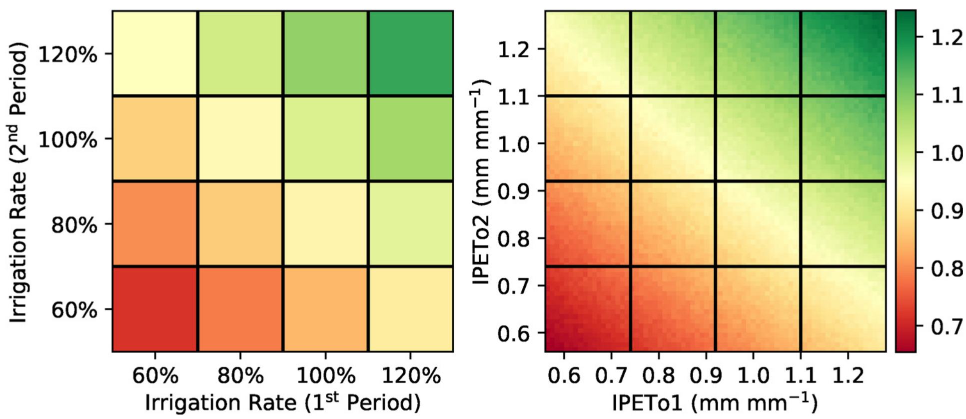


**Fig. 7.** Mean measured cumulative seasonal evapotranspiration (left, m) for each first-period and second-period irrigation treatment combination and mean modeled cumulative seasonal evapotranspiration (right, m) for irrigation plus rainfall normalized by short crop reference evapotranspiration in the first irrigation period (IPETo1) and second irrigation period (IPETo2) over three growing seasons at Maricopa, Arizona, USA.

reduction. Mean seasonal irrigation amounts among these four treatments did not differ by more than 176 mm, which means any irrigation scheduling adjustments would be constrained to within −12.6% and +1.5% of that for the 100%–100% treatment.

### 3.5. Fiber quality

Micronaire between 3.7 and 4.2 is considered optimal for yarn spinning, and growers can receive a premium price for MIC within this range. Fiber MIC for Arizona cotton is often high, due to high air temperatures during the Arizona cotton growing season (Bange et al., 2010). Measured and modeled fiber MIC was reduced (i.e., closer to the optimal range) when the 120% rate was used during the second irrigation period (Fig. 10). On the other hand, fiber MIC was highest (i.e., worst) for the 60%–60% and the 80%–60% irrigation treatments. Lower canopy temperatures due to higher evaporative cooling with higher irrigation rates during boll filling may have contributed to the improvements in fiber MIC. With a mean value just below 4.2 over three growing seasons, only the 60%–120% irrigation treatment achieved fiber MIC within the optimal range. However, due to reduced fiber yield (Fig. 6) for this treatment, it is likely an impractical management scenario. Optimal fiber micronaire may be difficult to achieve with this variety in Arizona, and increasing irrigation during boll filling to improve micronaire may therefore be wasteful. Other cotton varieties may demonstrate a different response.

Other cotton fiber quality metrics demonstrated expected trends. The 60% and 80% rates during the second irrigation period were both detrimental for cotton fiber STR (Fig. 11), while the 100% and 120% rates during the second irrigation period provided consistently higher fiber STR. Two fiber quality metrics, UHM and SFC (not shown), generally followed trends similar to ETC (Fig. 7), indicating their values were correlated with the total amount of water applied. Therefore, more applied water generally led to longer fibers and reduced content

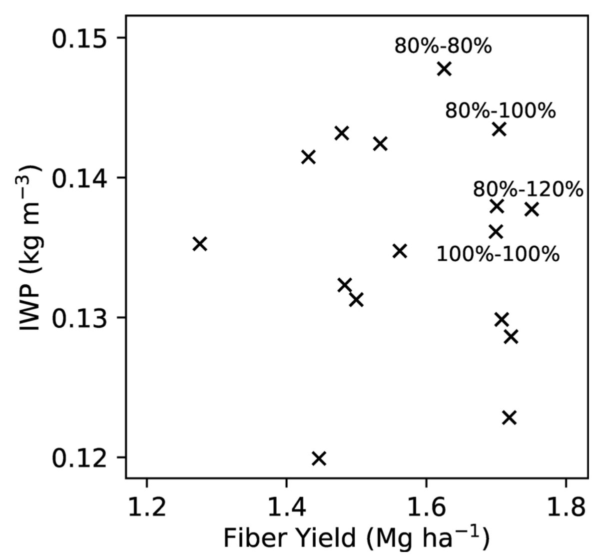


**Fig. 9.** Mean measured irrigation water productivity (IWP) versus mean measured fiber yield over three growing seasons at Maricopa, Arizona, USA.

of short fibers. Reductions for ELO were found only when the 60% rate was used in the second irrigation period (not shown). Otherwise, ELO was fairly consistent among irrigation treatments.

## 4. Discussion

The greatest opportunity for fine-tuning irrigation recommendations exists in the earlier half of the growing season, primarily during the period of vegetative development. At this time, weather variability controls variation in cotton growth and development rates, and soil

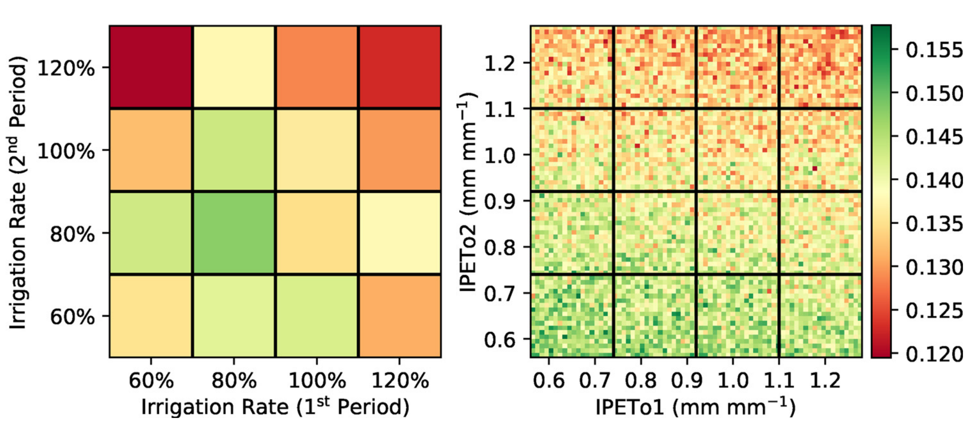


**Fig. 8.** Mean measured irrigation water productivity (left, $kg\,m^{-3}$) for each first-period and second-period irrigation treatment combination and mean modeled irrigation water productivity (right, $kg\,m^{-3}$) for irrigation plus rainfall normalized by short crop reference evapotranspiration in the first irrigation period (IPETo1) and second irrigation period (IPETo2) over three growing seasons at Maricopa, Arizona, USA.

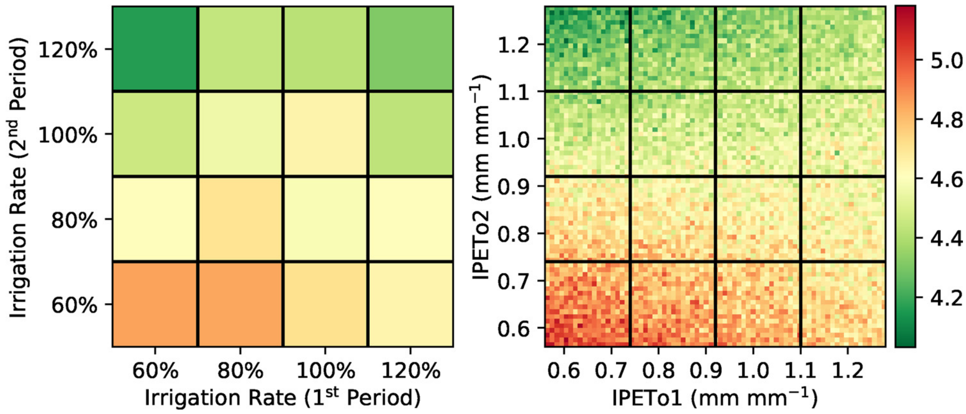


**Fig. 10.** Mean measured cotton fiber micronaire (left, unitless) for each first-period and second-period irrigation treatment combination and mean modeled fiber micronaire (right, unitless) for irrigation plus rainfall normalized by short crop reference evapotranspiration in the first irrigation period (IPETo1) and second irrigation period (IPETo2) over three growing seasons at Maricopa, Arizona, USA.

water status impacts root growth distribution. Current research suggests that young cotton plants acclimate to their environment, and early-season irrigation management affects this acclimation process (Meeks et al., 2017). Furthermore, application of growth-regulating chemicals is often used to control cotton growth responses, and careful early-season irrigation management may affect the need for such chemicals. Irrigation may also be used to regulate heat stress effects on loss of squares and young bolls, an issue that is particularly important for Arizona cotton production. Thus, a great opportunity is available for development of robust scientific irrigation scheduling tools to manage cotton growth and development, particularly during the earlier half of the growing season.

Thorp et al. (2017) demonstrated the use of an agroecosystem model for irrigation management in cotton, and this approach was further developed and tested in the present study. Results demonstrated that model recommendations (i.e., the 100%–100% treatment) for in-season irrigation management were reasonable for achieving high cotton yield (Fig. 6) with adequate irrigation water productivity (Fig. 8). However, results also suggested that opportunities exist to improve cotton production outcomes by fine-tuning recommendations from such irrigation scheduling models. Methods that incorporate remote or proximal sensing data from satellites, unmanned aerial systems, irrigation machines, or ground-based stations can provide in-season measurements to guide recommendations from irrigation scheduling models. While site-specific irrigation may be useful for some fields in some regions, better management of the temporal scheduling of irrigation in response to soil, weather, and crop feedback will likely contribute more to improving IWP in Arizona (Thorp, 2019).

After the cotton crop reaches full canopy and shifts toward reproductive growth, the present study showed that cotton should be fully irrigated. On average, cotton yield was lower for treatments that withheld water late (e.g., 100%–80%) rather than early (e.g., 80%–100%) (Fig. 6). Also, several fiber quality metrics were improved with full (100% rate) and even excess (120% rate) irrigation during the second irrigation period (Figs. 10 and 11). This result corroborated results from a previous study in the Texas High Plains (Bordovsky et al., 2015). The best time to be liberal with irrigation applications is during the cotton boll filling period. However, further development is needed to fine-tune the specific time period when irrigation is more critical. A limitation of the present study was the division of the cotton season into only two growth periods with the somewhat arbitrary division at "peak bloom" or 1155 °C-days after planting. As noted by Brown (2008), fruit abscission due to heat stress was most common in bolls aged three to five days. Also, in a controlled environment, Reddy et al. (1992) found that 100% of squares abscised from cotton plants grown at 40 °C daytime and 32 °C nighttime air temperatures. Thus, irrigation scheduling algorithms may require information on boll age and squaring onset as well as heat stress forecasts, such that irrigation could be timed to reduce heat stress effects on fruit loss. Furthermore, measurements of canopy temperature or leaf fluorescence during this time period may provide insights about plant stress status. Because overirrigation in the second irrigation period tended to reduce IWP (Fig. 8), the decision to terminate irrigation is also critical for maintaining high water productivity. Information on the number of nodes above white flower or the ratio of immature to open bolls should be incorporated into irrigation scheduling algorithms, and sensing technologies capable of monitoring cotton development would be useful for deducing how irrigation recommendations should adjust to plant status throughout the growing season. Overall, the results suggest that improvements to cotton yield and IWP are possible by incorporating improved plant feedback metrics into irrigation scheduling algorithms.

While the results of the present study are informative, a variety of opportunities exist for designing new field studies to more thoroughly evaluate options for reducing applied irrigation and improving IWP for Arizona cotton production. Foremost, the role of pre-plant irrigation was not directly tested in the field experiment. Because the study was

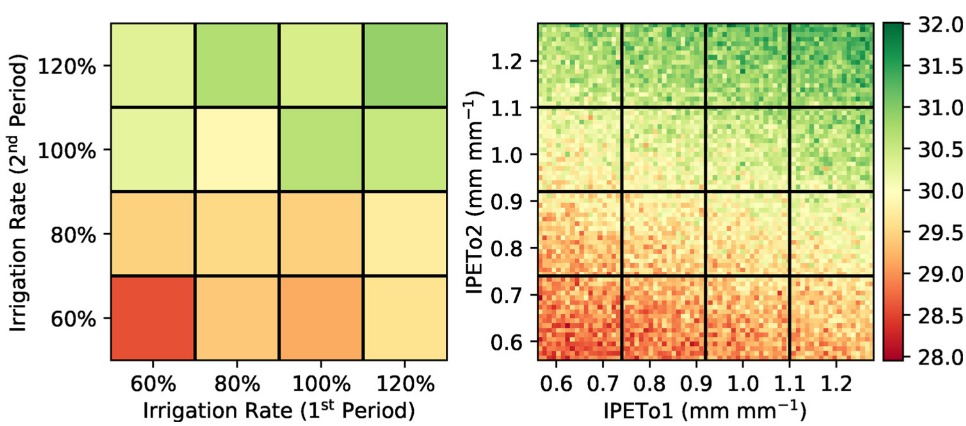


**Fig. 11.** Mean measured cotton fiber strength (left, HVI g tex$^{-1}$) for each first-period and second-period irrigation treatment combination and mean modeled fiber strength (right, HVI g tex$^{-1}$) for irrigation plus rainfall normalized by short crop reference evapotranspiration in the first irrigation period (IPETo1) and second irrigation period (IPETo2) over three growing seasons at Maricopa, Arizona, USA.

initiated with limited experience in managing Arizona cotton using overhead sprinkler irrigation, the overall strategy was to generally follow management practices for proven conventional surface-irrigation methods while gradually honing approaches for improving IWP with sprinkler irrigation. As such, this study followed the long-standing tradition to fill the entire soil profile with voluminous pre-plant irrigation up to 307 mm or 23% of seasonal applied irrigation (Table 1), as is usually done with conventional surface-irrigated cotton in Arizona. The traditional approach seeks to “wet plant” into pre-irrigated soil followed by a long period without irrigation to encourage roots to “follow the water down.” It seeks to pre-load the soil with water for young seedlings, because crop water use at this time is small relative to the amount of water typically applied with surface irrigation. It seeks to bank water in the soil to hedge against times when the relative infrequency of surface irrigation results in periods of water stress. However, because the availability of an overhead sprinkler irrigation system relieves some constraints of surface irrigation systems, the need for pre-water irrigation must be reevaluated. Possibly, the amount of pre-water irrigation could be reduced or even eliminated when a sprinkler irrigation system is available, which may substantially reduce seasonal applied irrigation and lead to improved IWP. In this case, post-plant irrigation decisions would require much more careful consideration and scientific basis.

Aside from improved irrigation management and technological developments, further agronomic improvements may also contribute to improved IWP for Arizona cotton. In the final year of the present study, no-till cotton with overhead sprinkler irrigation was tested at MAC for the first time. Visual evidence from the field trials suggested improved infiltration and better overall crop responses to irrigation treatments. Furthermore, as compared to neighboring field areas with no surface residue, no-till greatly reduced seedling damage due to blowing sand on windy days following emergence. Future studies will continue to develop conservation tillage practices for cotton production under irrigation sprinklers in Arizona. Secondly, because planting dates were fairly consistent for the three growing seasons, there is opportunity to assess planting date effects on cotton yield and IWP. Further opportunities exist to plant cotton after small grains or other winter crops in Arizona. Reports of the practice are few (Wang et al., 2013), but IWP could possibly be improved by planting a short-season cotton variety later in the season, which may avoid the timing of sensitive cotton growth stages during the high ETo and high heat stress periods in June and July. The length of the cotton season would likely be abbreviated and yield likely reduced, but water requirements would also be lower. Adding the winter small grain crop would provide additional opportunity for profitability while hedging against weather and market risk. Further research is needed to evaluate IWP for these alternative cotton production systems in Arizona. Overall, the present study demonstrates the use of modern irrigation equipment, including site-specific irrigation technology, to broaden and multiply the agronomic evaluation of irrigation management approaches in cotton. Future research can expand such tests to other varieties and crops while also incorporating tests of precision fertigation to evaluate nitrogen management impacts on IWP.

## 5. Conclusions

Because the irrigation treatments were established as a percentage of the recommendation from an in-season irrigation scheduling model, the field experiment provided important validation of irrigation recommendations by demonstrating agroecosystem outcomes when the recommendations were adjusted higher or lower during two periods of the growing season. While results demonstrated that the scheduling tool generally led to reasonable outcomes for cotton yield, water productivity, and fiber quality, the study also provided ample guidance on ways to further improve irrigation management, both within and external to the scope of the study itself. To continue improving cotton irrigation management with overhead sprinkler irrigation in Arizona, future research should clarify the requirements for pre-plant and early-season irrigation; develop better linkages between crop growth stages, crop sensing technologies, and irrigation scheduling tools; identify methodologies to reduce water and heat stress during reproductive growth; and clarify strategies for decisions on irrigation termination.

## Conflict of interest

None declared.

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