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Growth, water use, and crop coefficients of direct-seeded guayule with furrow and subsurface drip irrigation in Arizona

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A B S T R A C T

Crop establishment costs of guayule (*Parthenium argentatum* A. Gray), a perennial desert shrub that produces natural rubber, can be significantly reduced using direct seeding rather than the traditional practice of transplanting greenhouse-grown seedlings. However, information regarding the irrigation application, crop evapotranspiration (ET_c), and crop coefficients (K_c) for managing direct-seeded guayule crops has not been provided. In this study, guayule was direct-seeded in Apr. 2018 in fields at two location in Arizona; Maricopa, on a sandy loam soil and Eloy, on a clay soil, and harvested 23–24 months later in 2020. At each location, five irrigation rates were applied with subsurface drip irrigation (SDI) ranging from 50 to 150 % replacement of ET_c (denoted as D50 to D150 treatments), respectively. A 6th treatment using furrow irrigation at 100 % ET_c replacement (F100) was included. Treatments were replicated three times. The ET_c was estimated for the first 74–84 days of crop establishment and thereafter, actual ET_c ($ET_{c\ act}$) was determined weekly-biweekly for the D100 and F100 treatments using a soil water balance. The objectives were to evaluate the responses in dry biomass (DB), rubber yield (RY), and resin (ReY) yield to water application rate, develop irrigation management criteria for the two soil types, and determine the ET_c and crop coefficients for the 100 % treatments.

The total irrigation applied to treatments ranged from 1830−1910 mm to 5090–5470 and averaged 3590 and 3320 mm for the 100 % SDI (D100) and furrow (F100) treatments at Maricopa and Eloy, respectively. The summed estimated ET_c plus $ET_{c\ act}$ for the D100 and F100 treatments were 3663 and 3506 mm at Maricopa, respectively and 3428 and 3320 at Eloy, respectively. Average measured mid-season K_c in the 1st year varied from 1.20 to 1.26. Average measured mid-season K_c in the 2nd year were higher for D100 (≈1.30) than for F100 (≈1.23). Adjusted to the standard climate proposed in FAO56, mid-season K_c are 1.24 for D100 and 1.17 for F100 in the 2nd year. Average DB at Eloy (28.6 Mg ha^{-1}) was not significantly higher than at Maricopa (24.0 Mg ha^{-1}). However, RY and ReY were both significantly higher at Maricopa. At each location, rubber content was significantly higher for the F100 and the two lowest SDI rates than for other treatments. The highest mean RY and ReY were achieved with D100 at Maricopa and D75 at Eloy. These two also had significantly greater water productivity (WP; DB, RY, and ReY per unit of total water applied) than those at higher SDI rates and the F100 treatments. RY and ReY and their WP were generally higher for D100 than F100 in the sandy loam but not in the clay soil. For direct-seeded guayule in clay soils, furrow irrigation should be considered due to the lower rubber content and higher costs associated with SDI.

1. Introduction

Guayule (*Parthenium argentatum,* A. Gray) is a perennial shrub, native to the desert of northcentral Mexico and southwestern Texas, which produces high quality natural rubber that is suitable for use in passenger and commercial-grade tires (Eranki et al., 2018). The plant produces

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latex that is hypoallergenic, particularly desirable in the medical device market (Rasutis et al., 2015), and resin that can be used in a variety of industrial products such as adhesives and coatings (Nakayama et al., 2001; Thames and Kaleem, 1991). The primary parts of the guayule plant of economic interest are in the parenchyma tissues of the stems and roots where the majority of the rubber particles accumulate (Kajiura et al., 2018). However, stems and roots only constitute about 6 and 9% of the total plant dry weight, respectively (Kuruvadi et al., 1997).

Noteworthy advances have been made in guayule production, including increased rubber and biomass yields using selective breeding (Ray et al., 2005), improved rubber and latex extraction processes (Cornish et al., 2013), and guayule coproduct developments, such as wood preservatives and biofuels, for the ~ 90 % of the non-rubber guayule biomass (Coffelt and Ray, 2010; Boateng et al., 2016). A more recent study explored key aspects of guayule physiology that further enhances our understanding on methods to improve yield (Placido et al., 2020).

Guayule is also drought tolerant and can survive extreme dehydration in the desert where it remains in a semi-dormant state until irrigation is resumed. Its ability to survive long periods of droughts comes from the capability of its roots to extract moisture from the lower depths of the soil profile (Bucks et al., 1985a; Hammond and Polhamus, 1965). Prior to irrigation research conducted in the Arizona deserts in the 1980s (Bucks et al., 1985a,1985b), it was believed that commercial guayule rubber production required no more than 640 mm annual total water applied (TWA) by irrigation and/or rain (National Academy of Science (NAS, 1977). Even though guayule can withstand long periods of drought, well-watered guayule grown from transplants can have cumulative crop evapotranspiration (ET_c) of over 1500 mm during its first year of growth, and over 2000 mm during its second year (Bucks et al., 1985a, 1985b; Hunsaker and Elshikha, 2017; Hunsaker et al., 2019). In these studies, TWA levels that either matched or exceeded ET_c requirements, combined with moderate nitrogen applications (65–100 kg N ha-1 per year), gave the highest biomass production. In an overhead sprinkler study, guayule dry biomass yields after two-years of growth increased linearly with TWA levels ranging from 50 to 135 % ET_c replacement, as measured for a 100 % ET_c-replacement treatment (Bucks et al., 1985b). More recently, Hunsaker and Elshikha (2017) and Hunsaker et al. (2019) found that after 2.5 years of growth, dry biomass increased linearly from 40 to 120 % TWA replacement of ET_c with level furrow irrigation, and from 25 to 125 % TWA replacement of ET_c with subsurface drip irrigation (SDI), respectively. Because percent rubber content decreases with water input, TWA that maximizes biomass may differ from that which maximizes rubber yield. Data on water input level that maximizes the water productivity (WP) for rubber yield, i.e., the ratio of the harvested rubber yield to total water applied (Pereira et al., 2012), have been inconsistent, but appear to be dependent on irrigation method and soil physical properties. In previous studies (Bucks et al., 1985c, d; Hunsaker and Elshikha, 2017; and Hunsaker et al., 2019), WP ranged from 0.035−0.078 (kg rubber per m^3 water) for loam, sand, sandy loam, and sandy clay loam soils under furrow, sprinkler and SDI irrigation with rates ranging from 40 to 100% replacement of ET. The highest WP was reported for a sandy clay loam soil using SDI at 50 % irrigation replacement of ET_c.

It has been recognized for a long time that successful commercialization of guayule is mired by the prohibitive costs of transplanting (Miyamoto and Bucks, 1985; Bucks et al., 1986; Estilai and Waines, 1987). Bucks et al. (1986) estimated direct seeding could reduce greenhouse seedling establishment and field transplanting costs by 55–65 %. Dissanayake et al. (2008) estimated that the cost of transplanted guayule in southern Australia was 1600 % that of the direct seeded guayule, mainly due to the cost of nursery production. In recent years, considerable progress has been made in developing direct seeding methods for guayule, including a successful system developed by Bridgestone Americas, Inc. Since guayule seeds are small and grow slowly, they are first conditioned (imbibed and coated), and then planted to a shallow depth using a precision planter (Dissanayake et al., 2008; Foster et al., 2002). After planting it is necessary to apply frequent, but light irrigation, to promote seed germination and emergence and to reduce soil crusting (Miyamoto and Bucks, 1985; Foster et al., 1999, 2002). For both practical and economic reasons, guayule commercial production efforts in the US Southwest are focusing on the use of direct seeding (Wang et al., 2020).

To date, information about irrigation management and yield response to irrigation is available for transplanted guayule. While some literature is available on irrigation practices needed to germinate and establish direct seeded guayule crops (Bucks et al., 1986; Foster et al., 2002), yield responses to irrigation applications and irrigation management of direct seeded guayule have not been reported to our knowledge. In theory, irrigation management factors, such as crop water-use requirements and seasonal ET_c trends, could be much different for direct-seeded compared to transplanted guayule due to differences in crop development, crop root structure and plant architecture. Direct-seeded guayule may be particularly different than transplanted guayule during the first year of growth, since transplants are about three-months old when planted and have the advantage of an initial fibrous root system. It is presumed that unlike transplants, direct-seeded guayule will eventually develop a tap root and so as time progresses, plants may be able to use soil moisture at deeper depths than for transplants, and perhaps respond differently to low level irrigation. However, it was reported that root penetration of seedlings from both planting methods were nearly parallel, which tend to equalize as the plants grow to maturity resulting in negligible differences (Muller, 1946). Recent studies that formally quantify differences in guayule root systems are still lacking.

Hunsaker et al. (2019) reported a near-doubling in maximum biomass and rubber yields at Maricopa, Arizona USA for transplanted guayule using SDI after 2.5 years compared to those in a simultaneously conducted experiment at the same location using furrow irrigation (Hunsaker and Elshikha, 2017). The benefits of higher yield and greater WP attributed to SDI with guayule transplants need to be evaluated for direct-seeded guayule, though surface irrigation will likely remain the most common irrigation method in the Arizona semi-arid desert region. The relevant guayule irrigation studies in the literature have been conducted on light well-drained soils (i.e., sandy loam, sandy clay loam, loam, and sand), and information on guayule responses to irrigation in heavier-textured soils (higher clay content) is lacking. Land in Arizona and other areas in the Southwest where large-scale guayule production is possible has a wide range of soil texture, including clay soils in central Arizona.

There is need to develop effective irrigation water management strategies and tools for direct-seeded guayule in the US Southwest that result in high yields and high water-productivity. Accurate and efficient irrigation scheduling require suitable estimates of actual ET. Assuming actual ET measurements will typically not be made in commercial fields, the FAO56 crop coefficient (K_c) approach offers a practical and effective ET estimation method (Allen et al., 1998). In this approach, daily crop ET is computed as grass reference evapotranspiration (ET_o) times seasonally adjusted single K_c values or by dual K_c values, which combine a basal crop coefficient (K_{cb}) and a soil evaporation coefficient (K_e). However, literature lacks specific direct-seeded guayule crop coefficients. Therefore, we initiated a two-year irrigation study of direct-seeded guayule in 2018 at two sites in Arizona with sandy loam and clay soils. Elshikha et al. (2019) previously reported results from the study after 11 months of guayule growth. The objectives of this paper were to evaluate the growth and yield responses (biomass, rubber, and resin) to variable water application rates using SDI and furrow irrigation, develop optimum irrigation management criteria for the two soil types, and to derive crop coefficients and FAO56 K_c curves for well-watered guayule.

2. Materials and methods

2.1. Experimental design, planting, and crop establishment

A direct-seeded guayule irrigation study was initiated in Apr. 2018 at two-field locations: one on a 1.0-ha field at The University of Arizona, Maricopa Agricultural Center farm, in Maricopa, Arizona (33.07 °N lat; 111.97 °W long; 361 m a.s.l.) and the other, on a 1.3-ha field at the Bridgestone Americas, Inc., Guayule Research Farm in Eloy, Arizona, USA (32.67 °N lat; 111.63 °W long; 482 m a.s.l.). Each field study consisted of 18, 75-m long plots that were 6.1 m wide (six rows) at Maricopa and 8.1 m wide (eight rows) at Eloy. A split-plot experimental design was employed with location as the main plot and the split-plots (irrigation treatments) arranged in a randomized complete block design, where each field was divided into three blocks and six irrigation treatments were randomly assigned within each block (Fig. 1). At both locations, five treatments were assigned to receive five levels of irrigation by SDI and one treatment was assigned to furrow irrigation at one level of irrigation. Irrigation methods and treatments are more fully described below in section 2.4.

On Apr. 17 and 20, 2018, conditioned, USDA guayule germplasm line AZ-2 (PI 599675; Ray et al., 1999) seeds were planted at the Eloy and Maricopa fields, respectively, using a four-row planter (Mini-seeder, a precision vacuum planter by Monosem, Inc., Edwardsville, KS, USA[1]), pulled behind a power train tractor along dry, raised bed rows (0.20−0.30 m wide [on top of the bed] and 0.15−0.20 m high). AZ-2 is an interspecific hybrid with good seedling vigor and high biomass production (Ray et al., 1999). It is currently the cultivar being used for expanding production by the industry. The rows were 75 m long and were spaced 1.02 m apart. Following planting, a solid set sprinkler system was installed at each field to water the soil daily (~20−24 mm day-1) for 12 and 16 days at Maricopa and Eloy, respectively, to germinate the seeds, as recommended by Dissanayake et al. (2008). The total water applied with sprinklers was 284 and 317 mm, at Maricopa and Eloy, respectively. Based on the guidance of Bridgestone Americas, Inc., and the reference mentioned above, we were required to keep the seed and seed bed moist during the first week following planting for better germination in the dry climate of Arizona. However, the unusual cool weather after planting extended the germination period from one week to two weeks, which also increased this irrigation requirement.

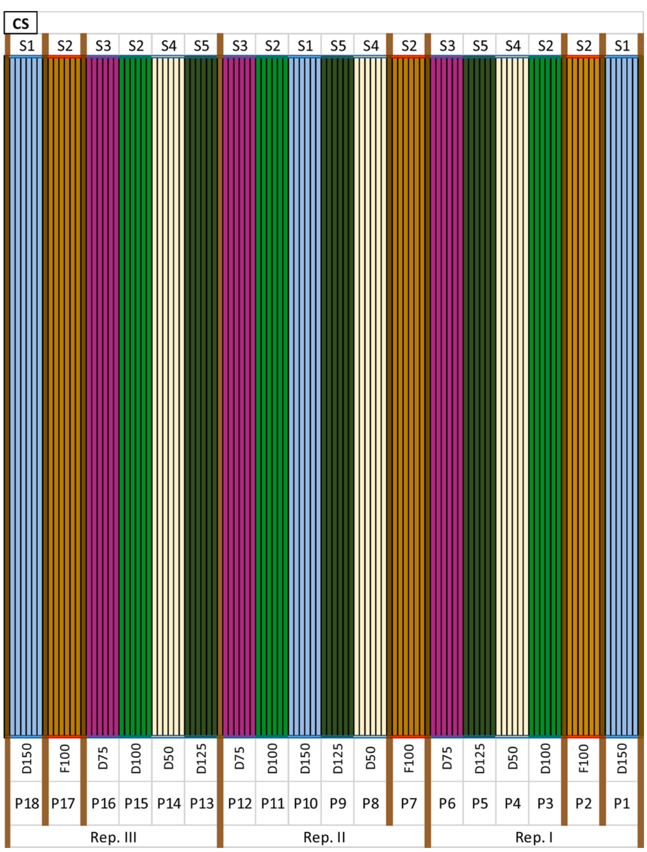

Fig. 1. Layout of the irrigation experiment. The fields at Maricopa and Eloy were divided into three blocks (Reps. I-III). Irrigation treatments (D50-D150, F100) were distributed randomly inside each block, which resulted in 18 plots (P1-P18). The control station (CS) of the subsurface drip system was located at the NE corner of the field.

2.2. Climatic parameters

The two farms are 72 km apart, and both are in the northeastern US Sonoran semi-arid desert, where typical maximum daily air temperatures are above 40 °C in summer. The winter months of Dec. and Jan. can be cold, where minimum daily air temperatures can fall below 0 °C. The mean annual air temperature (1987–2007) was 20.8 °C, ranging from -9.2–49.4 °C (Wall et al., 2011). Meteorological data during the study period were obtained from the Arizona Meteorological Network (AZMET; https://cals.arizona.edu/AZMET/index.html). For the Maricopa site, data from an AZMET station at Maricopa located 20 m from the field were used. For the Eloy site, data from the closest AZMET station in Coolidge, Arizona were used. However, precipitation was measured at the Eloy site by a rain gauge. Average monthly weather parameters recorded from Apr. 2018 through Mar. 2020 at Maricopa and Eloy are shown in Tables 1a and 1b, respectively. In general, monthly maximum air temperatures, wind speeds measured at 2 m height, and solar radiation were similar for the two locations during the first and second years (Tables 1a and 1b). Climatic differences were more apparent for monthly minimum air temperatures, which tended to be a few degrees warmer at Maricopa, and relative humidity, which was generally lower at Maricopa. The calculated Penman-Monteith grass--reference ET_o (Allen et al., 1998) was somewhat higher at Maricopa than Eloy from Apr. through Sep. in 2018 and 2019, and total ET_o for the two-years of growth was about 140 mm higher at Maricopa than Eloy. Precipitation was about 50 mm higher at Maricopa than Eloy during the first year but higher at Eloy than at Maricopa during 2019−2020. Total cumulative precipitation for the guayule growing period was similar for Maricopa (436 mm) and Eloy (430 mm).

2.3. Soil characteristics

The Maricopa field-site soil is mapped as a Casa Grande series (Fine-loamy, mixed, superactive, hyperthermic Typic Natrargids) (Post et al., 1988). The textures of this series are sandy loam, sandy clay loam and clay loam, and generally have high to moderate water intake and moderate water holding capacity. The Eloy field-site is mapped as a Gadsden series (Fine-loamy, montmorillontic (calcareous), hyperthermic Vertic Torrifluvents) (U.S. Department of Agriculture and Soil Conservation Service (USDA-SCS, 1991). These soils are predominantly clay or silty clay loam, having > 35 % clay content. They have relatively

[1] Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. USDA is an equal opportunity provider and employer.

Table 1a
Monthly average weather parameters* for Maricopa (AZMET station in Maricopa, AZ).

Year	Month	T_{max} (°C)	T_{min} (°C)	RH_{min} (%)	RH_{max} (%)	Rad. (MJ m^{-2})	u_2 (m s^{-1})	Prec. (mm)	ET_o (mm)
2018	Apr.	33.5	14.9	9.1	42.1	25.9	1.3	0.0	75.3
	May.	35.3	16.6	8.5	40.3	28.4	1.5	0.0	245.7
	Jun.	40.3	21.0	9.3	42.9	29.1	1.3	3.6	257.1
	Jul.	41.3	26.4	18.6	60.0	26.0	1.4	1.5	262.1
	Aug.	39.4	25.5	21.9	70.6	24.3	1.2	68.6	222.7
	Sep.	39.0	22.2	15.9	66.5	22.3	1.0	15.7	183.4
	Oct.	27.6	14.8	36.1	88.9	16.2	1.2	89.4	109.0
	Nov.	23.3	5.1	20.2	77.6	13.7	0.6	2.3	71.9
	Dec.	18.6	2.2	29.3	88.5	10.5	0.6	13.7	51.7
	Total							194.8	1481.9
2019	Jan.	18.7	2.7	32.5	90.4	12.4	0.5	12.7	59.1
	Feb.	17.1	3.6	31.3	91.4	14.4	1.3	62.7	66.9
	Mar.	24.5	7.4	19.2	77.6	20.4	1.2	6.9	131.0
	Apr.	30.5	12.8	12.6	57.5	25.7	1.5	7.9	194.8
	May.	30.6	14.2	13.6	55.5	27.7	1.6	1.5	217.3
	Jun.	39.5	20.6	8.4	40.6	29.8	1.4	0.0	264.7
	Jul.	41.6	24.9	13.4	55.4	27.4	1.4	14.2	269.0
	Aug.	41.4	25.2	16.3	66.4	25.4	1.0	11.7	231.8
	Sep.	36.7	21.8	21.6	74.3	21.7	1.1	15.8	176.7
	Oct.	31.3	11.0	11.2	59.9	19.1	1.0	0.0	138.2
	Nov.	25.1	7.9	25.3	78.1	12.9	0.9	51.1	78.3
	Dec.	17.4	4.1	42.5	92.1	9.8	0.7	38.9	48.1
	Total							223.4	1875.7
2020	Jan.	19.9	2.1	29.4	94.3	12.6	0.5	5.1	60.6
	Feb.	22.6	3.5	21.2	85.5	16.0	0.9	13.5	88.8
	Mar.	23.4	6.6	22.1	85.6	19.7	1.7	0.0	20.4
	Total							18.6	169.9

* Maximum and minimum air temperatures (T_{max} and T_{min}), maximum and minimum relative humidity (RH_{max} and RH_{min}), solar radiation (Rad.), and windspeed at 2.0 m height (u_2) are daily averaged by month; grass-reference evapotranspiration (ET_o) and precipitation (Prec.) are daily totals per month.

Table 1b
Monthly average weather parameters* for Eloy (AZMET station in Coolidge AZ).

Year	Month	T_{max} (°C)	T_{min} (°C)	RH_{min} (%)	RH_{max} (%)	Rad. (MJ m^{-2})	u_2 (m s^{-1})	Prec. (mm)	ET_o (mm)
2018	Apr.	32.1	10.5	8.8	61.2	27.5	1.5	0.0	97.6
	May.	35.3	12.6	8.8	63.6	29.9	1.5	0.0	245.2
	Jun.	39.8	17.0	10.7	67.7	29.9	1.0	1.3	245.6
	Jul.	39.4	23.5	22.6	77.1	26.5	1.0	10.7	228.4
	Aug.	38.1	22.9	25.7	83.4	24.5	0.8	18.3	196.3
	Sep.	37.8	19.2	20.7	84.9	22.1	0.7	43.9	158.8
	Oct.	27.3	13.3	37.1	93.2	16.0	1.2	50.0	101.5
	Nov.	23.9	3.5	18.3	81.6	14.0	0.8	3.6	75.9
	Dec.	19.5	1.0	27.6	94.6	10.7	1.0	18.8	56.4
	Total							145.7	1405.7
2019	Jan.	19.4	1.3	30.2	96.4	12.3	0.5	16.0	61.7
	Feb.	17.6	2.5	30.8	95.8	13.9	1.1	70.9	65.8
	Mar.	25.2	5.8	17.7	84.7	20.5	1.2	10.9	133.4
	Apr.	31.0	10.4	11.2	73.3	25.7	1.4	4.3	189.3
	May.	31.0	11.4	12.0	70.3	27.5	1.5	1.0	213.0
	Jun.	39.0	16.7	7.5	61.2	30.4	1.2	0.0	250.5
	Jul.	40.0	21.9	16.0	74.2	27.2	1.0	15.0	240.0
	Aug.	40.4	22.5	18.6	79.9	25.1	0.8	3.3	211.0
	Sep.	36.4	19.9	22.5	84.5	20.4	1.0	8.9	165.0
	Oct.	31.6	8.7	9.8	72.6	19.3	1.0	0.0	136.5
	Nov.	25.6	6.4	24.2	84.5	13.0	1.0	62.7	83.1
	Dec.	19.0	3.0	36.2	94.3	10.1	0.8	41.44	54.9
	Total							234.0	1804.3
2020	Jan.	20.7	0.7	25.8	96.9	12.7	0.5	3.8	66.8
	Feb.	21.8	1.5	19.4	88.0	16.2	1.1	15.5	88.8
	Mar.	25.9	5.9	19.2	85.8	19.8	1.7	31.2	20.9
	Total							50.5.	176.6

* Maximum and minimum air temperatures (T_{max} and T_{min}), maximum and minimum relative humidity (RH_{max} and RH_{min}), solar radiation (Rad), and windspeed at 2.0 m height (u_2) are daily averaged by month; grass-reference evapotranspiration (ET_o) and precipitation (Prec.) are daily totals per month.

high-water holding capacity but low water intake, which can impede water penetration to deeper soil layers in the profile.

Soil textures at the two sites were determined from soil samples collected in June 2018 during the installation of neutron access tubes (described in section 2.4). The samples were obtained at 36 locations in each field at soil-depths from 0−0.15 m, 0.15−0.30 m, and from 0.30 to 1.80 m in 0.30 to 0.60 m increments. The soil textures were analyzed using the Bouyoucos hydrometer method (Gee and Bauder, 1986). Table 2 provides the average measured soil texture by depth for both locations. At Maricopa, sandy loam was the soil texture for all depths,

Table 2
Sand, clay, and silt fractions, soil texture, permanent wilting point (PWP) and field capacity (FC) water contents, and soil water holding capacity (WHC) for the field sites at Maricopa (MAC) and Eloy, Arizona. Data were averaged by depth over all treatment plots at each location.

MAC							
Depth (m)	Sand (%)	Clay (%)	Silt (%)	Soil Texture	PWP (%)	FC (%)	WHC (mm m^{-1})
0–0.15	70.4	9.8	19.8	Sandy loam	12.3	24.5	122.0
0.15–0.30	69.8	10.7	19.6	Sandy loam	12.8	25.0	122.1
0.30–0.60	66.0	16.3	17.6	Sandy loam	15.4	28.1	127.1
0.60–0.90	60.0	17.6	22.0	Sandy loam	15.8	29.6	137.9
0.90–1.20	62.9	16.7	20.4	Sandy loam	15.4	28.7	112.9
1.20–1.50	66.6	16.3	17.0	Sandy loam	15.5	28.0	124.6
1.50–1.80	75.4	13.0	11.6	Sandy loam	13.8	25.8	120.0
Eloy							
Depth (m)	Sand (%)	Clay (%)	Silt (%)	Soil Texture	PWP (%)	FC (%)	WHC (mm m^{-1})
0–0.15	20.7	46.0	33.3	Clay	27.5	41.7	141.7
0.15–0.30	19.0	47.3	33.7	Clay	28.0	42.1	140.8
0.30–0.60	16.0	44.7	39.3	Clay	26.9	41.6	146.7
0.60–1.20	18.0	30.0	52.0	Silty Clay loam	18.9	36.5	175.8
1.20–1.80	23.3	30.7	46.0	Clay loam	19.5	36.1	166.7

but clay content increased in the subsoil below 0.30 m. In Eloy, soil texture was clay in the top 0–60-m profile, and silty clay loam and clay loam deeper in the profile. Field capacity (FC), permanent wilting point (PWP), and soil water holding capacity (WHC) were estimated for the soil depths (Table 2) using the Soil Water Characteristics routine of SPAW (Soil-Plant-Air-Water), a USDA hydrologic simulation model (Saxton and Willey, 2005), by entering the measured soil texture values. Soil organic matter contents were adjusted in the USDA routine to reflect typical organic matter contents at the soil depths as reported by Post et al. (1988) for the Maricopa soil type and by USDA-SCS (1991) for the Eloy soil type. The estimated WHC of the soil profiles indicated an average soil water holding capacity of 122 mm m^{-1} at Maricopa and 158 mm m^{-1} at Eloy.

2.4. Irrigation system, fertilization, and soil water content measurements

Subsurface drip irrigation systems were designed and installed during winter 2018 at both field sites to irrigate 15 of the 18 plots. At Maricopa, three plot replicates for each of the five SDI treatments were connected and irrigated via a 51 mm diameter PVC pipe (main supply line) that was buried 0.75 m underneath the soil surface. Unlike at Maricopa, each of the 15 SDI plots in Eloy had a separate station and main line. Consequently, five irrigation stations were used to control the water delivered to the five SDI treatments at Maricopa, whereas 15 control stations were used at Eloy. Each station began with solenoid valve followed by a flow meter, a pressure regulator, and an air vent and a pressure gauge. The drip tape, with 16.1 mm diameter and 15 mil (0.381 mm) wall thickness, was buried 0.20 m below the soil surface in the center of the bed. The emitter spacing of the drip tape was 0.31 m and the flow rate per emitter 1.25 l hr^{-1}. The emission uniformity of the buried drip systems was not field-measured. However, visual inspection of emitter wetting patterns during system testing prior to the experiment showed good overlapping of wetted areas along the row. The plots were also inspected periodically for any sign of clogging or leaks, which were fixed promptly as needed.

The surface irrigation method was level furrow (Martin and Gilley, 1993), a common surface irrigation method used in the area. Prior to the experiment, the fields were laser-leveled to a uniform but slight 0.02 % grade in the direction of irrigation water flow. The furrow plots were irrigated separately with water from overflow rise valves located at the head end of each plot. Plots were blocked on the far end of the field with berms so that all water applied remained in the plot area. The irrigation flow rate and volume for each furrow irrigation event in the study was measured with a calibrated in-line propeller-type water meter. The SRFR simulation model, a software package for the analysis of surface irrigation systems (Bautista et al., 2009), was used to estimate the furrow treatment irrigation distribution uniformity (DU), using field measured irrigation flow rate and furrow advance and recession times input to the model. The analyses indicated that DU was about 92 % for the furrow irrigation.

After the sprinklers were removed in early May 2018, the guayule seedlings were established during early May to late June by watering all SDI plots at each site with approximately equal amounts of total water (370 mm at Maricopa and 270 mm at Eloy). During the same period, furrow plots received an average total water of 450 and 370 mm at Maricopa and Eloy, respectively. Although the guayule in plots were established by late June 2018, it was decided to delay imposing irrigation treatments for one more month at each site. Thus, at Maricopa, 235 mm of water was applied to all SDI plots and 210 mm to the furrow plots from July 2 through July 25, one day before differential irrigation treatments commenced. At Eloy, 370 mm was applied to all SDI plots and 280 mm to the furrow plots from July 2 through Aug. 4, three days before starting irrigation treatments at Eloy. The irrigation scheduling methodology used for the establishment and differential treatment irrigations are described in section 2.5.

Fertilizer was applied to the SDI and furrow plots on Sep. 27, 2018 at Maricopa and on July 27, 2018 at Eloy in the form of urea-ammonium-nitrate (32 % N), which was injected into the water to all treatment plots (SDI and furrow) at a rate of 65 kg N ha^{-1}. The same rate was again applied in Mar 15, 2019 at both locations. This rate, 65 kg N ha^{-1} per year, was suggested by Bucks et al. (1985a) for adequate growth for guayule plants and was used in more recent guayule studies by Hunsaker and Elshikha (2017) and Hunsaker et al. (2019). The injection was done using a single head hydraulic diaphragm chemigation injection pump (Baldor Motor VL3504, Santa Fe Springs, CA, USA). The pump was connected, through injection ports, to the mainline of the SDI system and to an aluminum-pipe delivering the water to the furrow plots.

In June 2018 at each field site, 2.25-m long, 51-mm diameter galvanized steel access tubes were installed vertically in the soil at two-field locations along the length of each plot. A neutron moisture meter (NMM) was used to measure volumetric soil water contents (θ_v, m^3 m^{-3}) from 0.15 to 1.95 m below the surface in 0.30 m increments. The field calibration of the NMM involved installing a number of randomly placed access tubes in the field and, when the soil was wet, NMM readings were made at 7 depths (0.15, 0.45, 0.75, 1.05, 1.35, 1.65, 1.95 m). Then, destructive samples were collected within a 10 cm radius to measure volumetric water at each reading depth (oven method). This process was repeated when the soil was dry, thus, enabling a calibration equation. The NMM measurements were began on July 2 and July 9 2018 at Maricopa and Eloy, respectively, and were made at all 36 plot locations, every 7–9 days from July through Nov. 2018, every two weeks from Dec. 2018 through late Mar. 2019, and then every 7–9 days Apr. 2019 through Nov. 2019 and again every two weeks from Dec. 2019 through Mar. 2020. During installation of access tubes for the NMM, soil samples were collected, as described in section 2.3.

2.5. Irrigation scheduling, crop evapotranspiration, and crop coefficients

Differential treatment irrigation amounts were initiated on July 26, 2018 at the Maricopa location and Aug. 7, 2018 at Eloy, about three months after planting. For SDI treatments, one irrigation treatment, designated as D100, served as the control treatment, whose irrigation scheduling was designed to provide ample soil water within the effective crop root zone depth (Z_r) to meet 100 % crop evapotranspiration (ET_c). Irrigation amounts applied to D100 were managed to replace ET_c losses while maintaining treatment average soil water depletion (SWD) within the root zone at no more than 35 % of the total available water (TAW), a level similar to that used for SDI by Hunsaker et al., 2019). The other four SDI treatments were designated as D50, D75, D125, D150, and received 50 %, 75 %, 125 % and 150 % of the irrigation amount applied to the D100 at each irrigation, respectively. Irrigation for the F100 treatment was applied when the treatment average SWD reached 55 %, a target depletion recommended for surface-irrigated guayule by Hunsaker and Elshikha (2017).

Irrigation scheduling of the D100 and F100 treatments for each site were based on separate daily soil water balance (SWB) models of the guayule Z_r, which calculated root zone depletion (D_r) at the end of each day, according to Eq. 1:

$$D_{r,i} = D_{r,i\text{-}1} - P_i - I_i - CR_i + RO_i + ET_{c,i} + DP_i \tag{1}$$

where $D_{r,i}$ and $D_{r,i\text{-}1}$ are the root zone depletion (mm) at the end of day i and day i-1, respectively, and P_i, I_i, CR_i, ROi, $ET_{c,i}$, and DP_i are amounts of precipitation, net irrigation depth, capillary rise, runoff from the soil surface, crop ET, and deep percolation, respectively, on day i, all in units of mm. CR_i and RO_i are considered zero due to the low groundwater table and the use of blocked furrows, respectively. The inputs for I_i were average measured irrigation depths given to the three treatment replicates. Inputs of P_i were provided by the AZMET weather stations for the two sites. When P_i was less 1.0 mm, it was assumed negligible and not applied in Eq. 1. The $Z_{r,i}$ was increased from 0.60 m in early May 2018 to a maximum depth of 2.0 m in mid-Nov. 2018, following the Z_r development pattern for first-year guayule reported by Hunsaker and Elshikha (2017). Later, the soil water content measurements (described in section 2.3) were used to evaluate the change in effective rooting depth by comparing soil water depletion at lower soil depths during the growing season. The data indicated significant soil water depletion occurred at 1.65 m by Sep.-Oct. 2018 and at 1.95 m by Nov. 2018, indicating good agreement with the estimated root depth model used in the SWB models.

Daily values of total available water (TAW_i) of the daily rooting depth ($Z_{r,i}$) were calculated as:

$$TAW_i = 10\, Z_{r,i}\, (FC - WP) \tag{2}$$

where TAW_i is in mm, $Z_{r,i}$ in m, and FC and WP were field-average values (% basis) for the two sites, shown in Table 2. The limits for $D_{r,i}$ in Eq. 1 were zero (at FC) and TAW (at WP). Since $D_{r,i}$ cannot be less than zero on a given day i following irrigation and/or precipitation, an amount for DP_i was computed, when necessary, to balance Eq. 1, if $D_{r,i}$ was less than zero on day i. Daily percent soil water depletion (SWD_i) was calculated as:

$$SWD_i = 100 \times [1- (TAW_i - D_{r,i})/TAW_i] \tag{3}$$

where SWD_i is in percent and TAW_i and $D_{r,i}$ are as previously defined.

Calculations of Eq. 1 for days prior to θ_v measurements (prior to early July 2018) relied on estimated ET_c, whereas actual ET_c ($ET_{c\ act}$) was determined thereafter using θ_v measurements (described later in this section). Initiation of the SWB models in Eq. 1 was on the day of planting where the initial $D_{r,i}$ was assumed to be the TAW at an initial $Z_{r,i}$ of 0.60 m.

Prior to measurements of θ_v, the daily ET_c used in Eq. 1 for D100 and for F100 treatments were separately estimated using the FAO56 dual crop coefficient procedures (Allen et al., 1998) that separates K_c into soil evaporation and plant transpiration (basal) coefficients:

$$ET_{c,i} = (K_{cb,i} + K_{e,i}) \times ET_{o,i} \tag{4}$$

where $ET_{c,i}$ is on day i (mm), $K_{cb,i}$ and $K_{e,i}$ are the basal crop coefficient and soil evaporation coefficient on day i, respectively (unitless), and $ET_{o,i}$ is the grass reference crop evapotranspiration calculated using the FAO56 standardized Penman-Monteith equation on day i (mm). The $ET_{o,i}$ was provided by the AZMET weather stations for the two sites. The $K_{cb,i}$ input used from planting through first θ_v measurements for the SDI treatment was linearly increased from an initial value of 0.20 to 0.68 in late June, which were based on K_{cb} data derived for early-season, well-watered, transplanted guayule, grown by SDI (Hunsaker et al., 2019). Similarly, $K_{cb,i}$ input for that period for F100 treatments was increased from 0.20 to 0.72, based on data derived for well-watered, transplanted guayule conditions with level furrow irrigation (Hunsaker and Elshikha, 2017).

Daily values of K_e ($K_{e,i}$) were estimated following irrigation or precipitation by computing Eq. 5 (FAO56, Eq. 71, Allen et al., 1998), which requires a daily SWB of the surface soil layer (here assumed as 0.1-m in thickness). For the surface layer SWB, values of total evaporable water (TEW) were calculated using the FC and PWP data for the 0−0.15-m depth (Table 2) for each site and were 20 and 30 mm at Maricopa and Eloy, respectively. The readily evaporable water (REW) was assumed as 9 mm for the sandy loam soil and 10 mm for the clay soil (Allen et al., 1998).

$$K_{e,i} = \min\, [K_{r,i}\, (K_{cmax,i} - K_{cb,i}),\ f_{ew,i} \times K_{cmax,i}] \tag{5}$$

The $K_{r,i}$ in Eq. 5 are the daily evaporation reduction coefficients dependent on the daily cumulative depth of evaporation ($D_{e,i}$) from the surface layer on day i following complete wetting of the surface. The $K_{cmax,i}$ are the daily maximum values of $K_{c,i}$ that can occur following I_i or P_i. Calculation of $K_{cmax,i}$ requires values for daily minimum relative humidity and average wind speed, (provided by AZMET), and daily crop height, which were estimated by daily interpolation of D100 and F100 measured crop height data made every few weeks starting in early June 2018 (section 2.6). The $f_{ew,i}$ values are the daily fractions of soil, both wetted and exposed. The $f_{ew,i}$ are determined from estimates of daily covered soil fraction ($f_{c,i}$) and fraction of soil wetted ($f_{w,i}$) by I_i or Pi. The daily $f_{c,i}$ were estimated by daily interpolation of D100 and F100 measured cover data made every few weeks starting in early June 2018. When irrigation occurred, a constant $f_{w,i}$ value of 0.20 was used for D100 based on manually observed surface soil wetting during SDI irrigations. However, the $f_{w,i}$ were increased to 1.0 for D100 on any day when P_i was greater than 5 mm, even though irrigation may have occurred on the same day. For F100, a constant $f_{w,i}$ value of 1.0 was used based on observed surface soil wetting of furrow irrigations.

Starting in early July 2018, measured θ_v were used to quantify the actual ET_c ($ET_{c\ act}$) for the D100 and F100 treatments. Actual ET_c was calculated as the residual of the root zone SWB (Eq. 6) for periods bounded by two adjacent dates of θ_v measurements:

$$ET_{c\ act} = (D_{r,2} - D_{r,1}) + I + P - DP \tag{6}$$

where $ET_{c\ act}$ is the total actual ET (mm) that occurred in the period from the first (1) to second (2) measurement date, $D_{r,1}$ and $D_{r,2}$ are the average treatment measured root zone soil water depletion (mm) on the first and second date, respectively. The I, P, and DP, respectively, are total depth of average treatment measured irrigation (mm), total measured precipitation, and total deep percolation below the root zone (mm) that occurred during the period. The total $ET_{c\ act}$ for each period were used to model actual ET ($ET_{c\ act,i}$) on a daily basis, where the sum of $ET_{c\ act,i}$ was required to be equal to the total $ET_{c\ act}$ in the period but whose individual values varied according to daily ET_o and daily soil evaporation. The $ET_{c\ act,i}$ values in each period were found by iteration of the FAO56 dual K_c calculations until daily values of $(K_{cb} + K_{e,i})\, ET_{o,i}$

summed to total $ET_{c\ act}$ in the period (Eq. 7):

$$ETc\ act = \sum_{i=1}^{j} \left(Kcb + Ke,i\right) ETo,i = \sum_{i=1}^{j} ETc\ act,i \quad (7)$$

where $ET_{c\ act}$ is the total (mm) for all days from 1 to j in a given period (determined in Eq. 6), K_{cb} is a uniform (single value) basal crop coefficient for each day i to j in a given period, $K_{e,i}$ is the soil evaporation coefficient on day i, and $ET_{o,i}$ is the PM ET_o (mm) on day i, and $ET_{c\ act,i}$ is daily actual crop ET (mm) on day i. The $K_{e,i}$ were determined with the FAO56 dual K_c procedures using the same K_e parameters described earlier. For each period, an average K_c was calculated as the sum of K_{cb} + $K_{e,i}$ divided by the days in the period.

The locally-derived guayule K_c and K_{cb} data for the D100 and F110 treatments at each location were used to develop FAO56 segmented crop coefficient curves described in Allen et al. (1998). The methodology requires partitioning the growing season into four growth stages: initial (where K_{cb} is at a minimum), development (increasing K_{cb}), mid-season (maximum K_{cb}), and late season (declining K_{cb} from mid-season values to an end of season minimum value). The curves for each treatment and location were developed separately for the first and second years based on growth stage durations that best approximated the trends in the average K_c and estimated K_{cb} data. After establishing the four growth stage lengths for each treatment in the first year, the values for the horizontal segments of the initial and mid-season growth stages were determined by averaging the locally-derived K_c data for periods that were within those stages, respectively. Similarly, average values for the local K_{cb} in those stages were calculated. The end of season K_c and K_{cb} values (denoted as $K_{c\ end}$ and $K_{cb\ end}$, respectively) for the first year were taken as the minimum values that occurred following irrigation determination in mid-Nov. 2018. The second year growth stage durations for treatments (and K_c and K_{cb} values) were determined in a similar manner as in the first year. However, in each treatment case, a short, second-year initial stage was included in the early winter of 2019, prior to resuming irrigations at Maricopa in early Feb. and prior to significant precipitation at Eloy starting in early Feb. The crop coefficient values for the short horizontal initial periods, were taken as the end of season values for each treatment in the first year.

Transferability of the guayule crop coefficients derived at these two arid sites is enhanced by adjusting the local values to the standard climate conditions proposed in FAO56, where minimum relative humidity (RH_{min}) = 45 % and wind speed at 2 m above the ground surface (u_2) =2 m s^{-1}. For all treatments and locations, the average mid-season K_c and K_{cb} values were adjusted to the standard climate before developing the FAO56 curves. Standard climate adjustment for end of season values were made if $K_{c\ end}$ and $K_{cb\ end}$ were 0.45 or greater (Allen et al., 1998). The climate adjustments were made using the transfer equations provided in Pereira et al. (2020).

2.6. Plant growth measurements

Plant density was measured at both field sites in early Jan. 2019 by counting the number of plants in 1.0-m^2 sections at three locations along the inner four rows of each 75-m long plot. Manual measurements of guayule canopy height and canopy widths were made for nine plants per plot starting on June 12, 2018 at Maricopa and Sep. 10, 2018 at Eloy. Thereafter, height and width measurements were made about every 30 days through Mar. 2020. Canopy cover was calculated using Eq. 8:

$$\text{Canopy cover } (\%) = (W_{ew} \text{ x } W_{ns})/(1/P_d) \text{ x } 100 \quad (8)$$

where W_{ew} is plant width in the east-west direction (m), W_{ns} is plant width in the north-south direction (m), P_d is the average plant density of the plot (plants m^{-2}). The canopy cover in percent were divided by 100 to convert to the f_c used in the K_e calculations.

Whole plant samples were harvested on Mar. 05 and Apr. 16, 2020 at Maricopa and Eloy, approximately 23 and 24 months after planting, respectively. Previously, whole plant samples were harvested after 11 months of growth as reported by Elshikha et al. (2019). For the 23–24-month samples, three 3-m^2 sections from each plot were hand-harvested at both sites. All plant harvests were limited to the inner three rows of each plot to minimize any edge effects on plant growth. Plants were cut at the ground level and immediately weighed for fresh weight and then air-dried outdoors on shaded wire shelves for 7 days and re-weighed for dry weight (Coffelt and Ray, 2010; Kuruvadi et al., 1997). Next, the air-dried whole plants were shredded and ground into a powder before subsamples were taken. Separate samples from the powder were weighed, then placed in the oven at 110 °C for 24 h, and then re-weighed to determine moisture content (Placido et al., 2020). The air-dried subsamples were then analyzed at Bridgestone Americas Inc., Eloy, for resin and rubber concentrations, determined using a Soxhlet-based near-infrared spectroscopy (NIR) method that has high correlation to other rubber analysis methods (Suchat et al., 2013; Placido et al., 2020). After the dry biomass (DB), rubber yield (RY), and resin yield (ReY) were calculated in units of kg $ha^{-1}$for each treatment, the water productivity (WP) for each yield component was calculated. The WP equation is Eq. 9:

$$WP = \text{yield / total water applied} \quad (9)$$

where WP is in kg m^{-3}, yield (DB, RY and ReY) are in kg ha^{-1}, and total water applied is the sum of irrigation and precipitation received by the plants during the two years of growth in m^3.

2.7. Statistical analyses

Location and irrigation treatment effects for the two-year harvests were analyzed statistically using a split plot model within the Proc Mixed procedure (SAS v.9.4 Institute Inc., 2016, Cary, NC) for the following parameters: rubber (R) and resin (Re) contents, dry biomass (DB), rubber yield (RY), resin yield (ReY), and WP of DB, RY, and ReY. Location was the main plot (2 levels); irrigation treatment was the split-plot (6 levels); and both were considered as fixed effects, as was their interaction. Random effects were block and block x location. Proc Mixed estimated the random components and the residual by the residual maximum likelihood (REML). To avoid pseudo-replication, data for the three harvest samples within each plot replicate were averaged for the Proc Mixed analyses. When location, treatment, or interaction F tests were significant ($p < 0.05$), then least square means were separated using the *P*diff option in SAS (with $p < 0.05$). Statistical analysis of irrigation treatment effects on measured crop height and crop cover were made separately for each location since measurements were not concurrent at the two locations.

3. Results and discussion

3.1. Irrigation, precipitation, and soil water depletion

The cumulative irrigation application amounts for the first two years of growth are shown for treatments in Fig. 2 (a and b for Maricopa and Eloy, respectively). Prior to differential treatment irrigation in late July and early Aug., a total of ≈890 and ≈950 mm was applied to all plots in the field at Maricopa and Eloy, respectively. Irrigation was terminated on Nov. 15, 2018, resumed in Feb. 2019 and then terminated again on Nov. 15, 2019 at both locations. A final irrigation was applied to all plots in mid-Feb. 2020 at both locations before the plots were harvested in early Mar. 2020, at Maricopa, and mid-April 2020, at Eloy. Typical SDI irrigation treatment events ranged from 6−18 mm applications for the D50-D150 treatments, respectively, at 3–6 irrigations per week depending on time of year. Furrow (F100) irrigation events ranged from 40 to 130 mm applications, where frequency ranged from 1 to 3 irrigations per month. Table 3 shows irrigation amounts summed for

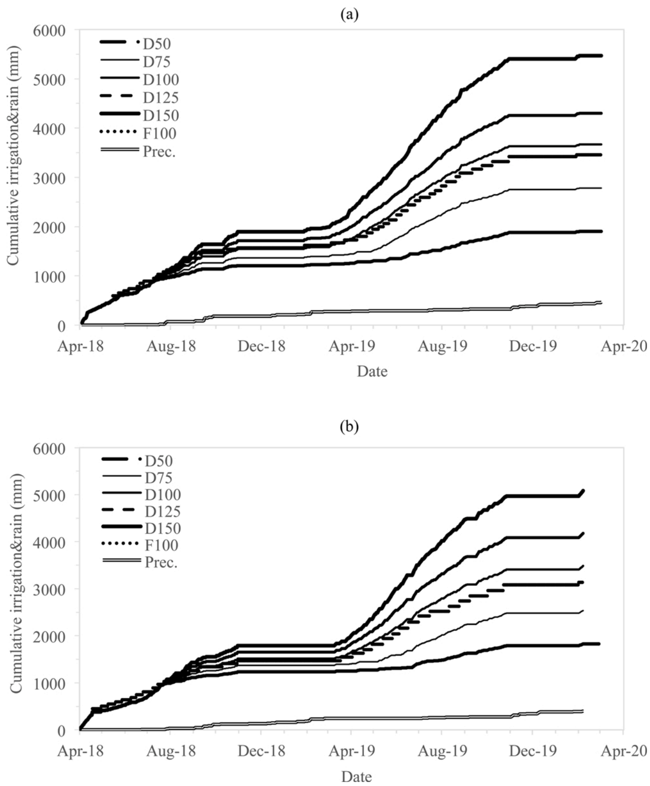

Fig. 2. Cumulative irrigation applied to the subsurface drip [SDI] (D50-D150) and furrow (F100) treatments and cumulative precipitation (Prec.) with time at Maricopa (a) and Eloy (b). The numbers following the letters D (for SDI) and F (furrow) are irrigation rates (i.e., percent replacement of crop evapotranspiration [ET_c]).

Table 3
Irrigation amounts and number of events for the D100 (SDI) and F100 (furrow) treatments for direct seeded guayule at Maricopa and Eloy. Data were summed for each season (Spring [Mar. 21-June 20], Summer [June 21-Sep. 20], Fall [Sep. 21-Dec. 20] and Winter [Dec. 21-Mar. 20]). Total water applied by irrigation and precipitation are summed at the bottom of each treatment column for the two locations.

Maricopa	Amount (mm)	Events	Amount (mm)	Events
Spring-18	626	36	696	19
Summer-18	693	47	646	12
Fall-18	254	14	215	4
Winter-18	62	6	98	2
Spring-19	751	63	630	9
Summer-19	895	67	854	10
Fall-19	363	37	328	4
Winter-19	38	4	39	1
Irrigation	3682	276	3506	61
Irrigation + prec.	4118		3942	
	SDI		Furrow	
Eloy	Amount (mm)	Events	Amount (mm)	Events
Spring-18	560	30	643	21
Summer-18	700	46	617	10
Fall-18	204	20	210	3
Winter-18	0	0	0	0
Spring-19	688	57	570	6
Summer-19	890	65	798	7
Fall-19	319	25	345	3
Winter-19	48	4	51	1
Irrigation	3409	247	3233	51
Irrigation + prec.	3839		3663	

seasonal months and number of irrigations in the months for the D100 and F100 treatments at each site. Highest D100 and F100 frequencies occurred the spring and summer in 2019 at both locations. Irrigation frequency was higher for both D100 and F100 in the sandy loam soil at Maricopa than that in the clay soil at Eloy. Total irrigation applied during the ≈two years after planting for D100 and F100 was 3682 mm and 3506 mm, respectively, at Maricopa, and 3409 mm and 3233 mm, respectively, for Eloy (Table 3). The largest treatment differences in the total irrigation applied were between the D150 (5470 and 5100 mm) and D50 (1900 and 1800 mm) at Maricopa and Eloy, respectively (Fig. 2).

The germination and stand establishment irrigation amounts for Maricopa and Eloy in spring 2018 were 626 and 560 mm for SDI plots and 696 and 643 mm for furrow plots, respectively (Table 3). These amounts represent about 17 % and 20 % of the total water applied to the D100 and F100 treatments, respectively, and even higher percentages for the lower irrigation treatments. The amounts for the D100 and F100 were also ≈ 34 % and 50 % and 20 % and 38 % higher for the sandy loam and clay soils, respectively, than that reported by Bucks et al. (1985a) in the two-month establishment of spring-transplanted guayule on a Laveen loam soil in Arizona, using primarily sprinkler irrigation in establishment. However, such differences can be expected since transplanted guayule did not require two weeks of daily applications to germinate the seed, as needed for direct seeded guayule. In the present studies, guayule establishment with furrow required somewhat higher irrigation input than SDI due to the constraints in applying lighter, furrow irrigation applications with high distribution uniformity. Bucks et al. (1986) reported sprinkler irrigation studies on a sand in Yuma, Arizona, to determine irrigation requirements needed to germinate and establish direct seeded guayule. They reported that direct seeded guayule (in spring) required as much as 560 mm of irrigation, which was similar to the present study SDI treatment amounts. Potential guayule growers will need to weigh the higher costs of transplanting versus direct seeding in light of potentially higher early season water use requirements following direct seeding. In addition, the irrigation method employed during establishment needs to be carefully considered.

The irrigation totals for the F100 treatment at Maricopa and Eloy (Table 3) were similar to what was applied to a well-watered furrow treatment (3357 mm) in a 21-month, guayule irrigation experiment in a loam soil in Arizona by Bucks et al. (1985a). Hunsaker and Elshikha (2017) applied 3573 mm within a two-year period for their 100 % ET_c replacement treatment using furrow irrigation, also at Maricopa. Using SDI at Maricopa, Hunsaker et al. (2019) applied 3692 mm during two years for their 100 % ET_c replacement treatment, which was similar to the D100 treatment irrigation totals in the present (Table 3). Yet, the similarity in water application rates in the three studies in Maricopa did not result in similar rubber yields for 100 % ET_c replacement treatments. Despite the possibility of different factors, which may have caused the difference in yield, comparing irrigation amounts applied under different growth conditions and years can provide a range of expected amounts that can be used to validate calculated amounts in future guayule irrigation systems.

Total precipitation amounts received (Apr. 2018-Mar. 2020) was 436 mm during the 23 months of growth at Maricopa and was 430 mm for the 24 months of growth at Eloy. Precipitation amounts during the 2018 "monsoon" season (June-Oct.) following planting were unusually high for the Maricopa (179 mm) and Eloy (128 mm) locations (Tables 1a and 1b, respectively). However, precipitation was above average in Feb. and Nov.-Dec. 2019, while summer monsoon rainfall was light in 2019.

Soil water depletion (%) showed a separation between the high (D100, D125 and D150) and the low (D75 and D50) treatments, starting in Aug. 2018 for Maricopa (Fig. 3) and in Sep. for Eloy (Fig. 4). The lower-water SDI treatments had higher SWD values. During the summer of 2018, higher SWD occurred for the flood irrigated (F100) treatment than D100 at both locations, particularly during July, when it exceeded 60 % on 2–3 soil water measurement dates. However, treatment

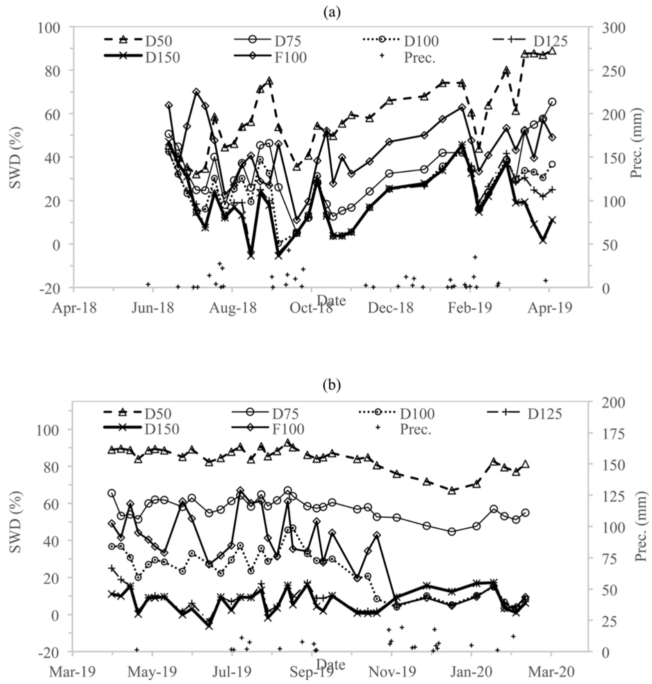

Fig. 3. Measured soil water depletion (SWD) with time for SDI (D50-D150) and furrow (F100) treatments for Maricopa: (a) year 1 and (b) year 2. Treatment terms in legend same as described in Fig. 2.

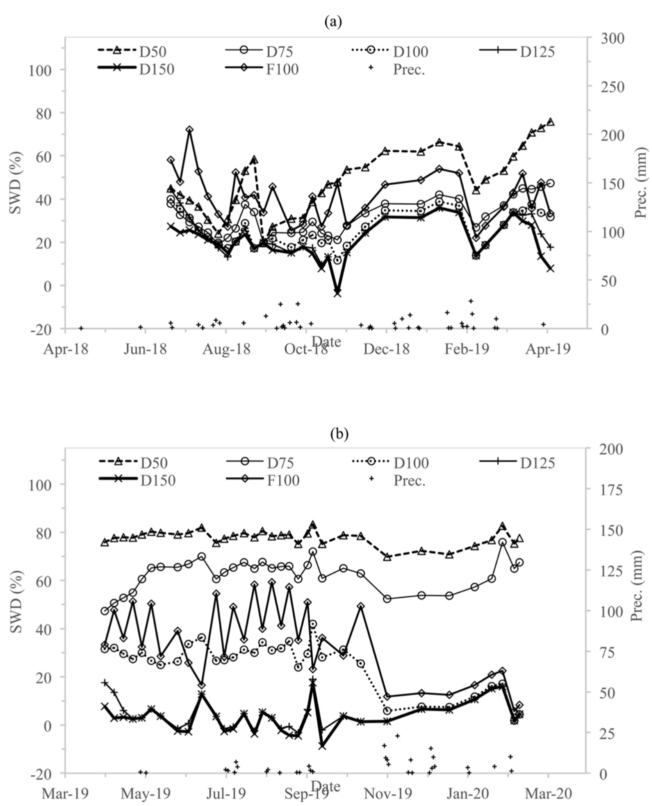

Fig. 4. SWD with time for SDI (D) and furrow (F) treatments for Eloy: (a) year 1 and (b) year 2. Terms in legend same as described in Fig. 2.

separation in SWD was generally moderated by Oct. 2018, following significant summer monsoon precipitation at Maricopa and Eloy (Figs. 3a and 4a, respectively). The 2018 summer precipitation events also reduced the measured SWD for the higher SDI treatments to values near or below FC starting in early Aug. through Nov. at Maricopa and Sept. to Nov. at Eloy. During the second year, SWD for SDI treatments decreased in a consistent trend from the highest level in the D50 to the lowest level for the D125 and D150 treatments, which had similar SWD (Figs. 3b and 4 b, Maricopa and Eloy, respectively). Measured SWD for the D125 and D150 treatments during 2019 was often near or even less than zero at both locations. The magnitude of the SWD difference among treatments decreased substantially during the winter months for both locations, which coincided with the termination of irrigation (mid Nov.) and plants going into growth dormancy about the end of Nov. in 2018 and 2019. Excluding winter dormancy periods from Dec. to Feb. in 2018 and 2019, the SWD for the D100 treatment was maintained within the target of <35 %, except on two occasions at Maricopa in Sep. 2019 (~45 %), which was due to system maintenance. However, often during May to Sep. 2019, the F100 at Maricopa slightly exceeded the 55 % SWD target by 5–10%. In Eloy, measured SWD for both the D100 and F100 were within the target SWD except on three occasions for F100 between late Aug. and early Sep. in 2019.

The near zero SWD at times for the D100 to D150 treatments at Maricopa and Eloy in both years suggests that some of the water applied at these higher rates was likely lost to deep percolation below the root zone and, therefore, was unavailable for crop evapotranspiration. Similar near-zero SWD was also noted by Hunsaker et al. (2019) for their highest SDI treatment irrigated at 125 % ET_c. The higher SWD for F100 compared to D100 resulted from the less frequent (but higher volumes) of irrigation applied by flood, which also resulted in more variable seasonal SWD than the more uniform SWD for D100.

3.2. *Crop evapotranspiration and crop coefficients*

The cumulative soil water balance components calculated for the D100 and F100 irrigations treatments for the first 74 and 84 days after planting for Maricopa and Eloy, respectively, are shown in Table 4. These initial periods were when ET_c was estimated using K_{cb} data derived in the transplanted guayule field studies cited in section 2.5. Measured ET_c ($ET_{c\ act}$) by the SWB (Eq. 6) began on July 3 and July 10, 2018 at Maricopa and Eloy, respectively. The cumulative SWB components for the $ET_{c\ act}$ periods are also shown for locations in Table 4. During the initial period, which included the germination and establishment irrigations, large amounts of DP were estimated in the daily SWB for both treatments. Highest cumulative DP during the initial period was for the F100 treatments, 319 mm and 225 mm at Maricopa and Eloy, respectively. The cumulative estimated ET_c were also higher during this period for the F100 than D100 treatments at both locations (70 and 100 mm at Maricopa and Eloy, respectively) due to more soil evaporation calculated in the daily SWB. During the $ET_{c\ act}$ period, cumulative irrigation plus effective precipitation were 290 mm and 340 mm higher for the D100 and F100 than for the Eloy treatments, respectively (Table 4). The changes in soil water depletion, as measured at the beginning and end of the $ET_{c\ act}$ period, were similar for the SDI (−38 and −36) and also for the F100 (−71 and −72 mm) at the two locations. Cumulative deep percolation losses were higher for the D100 than F100 at both locations. Primary times that DP was calculated for the D100 treatments were during late summer to fall in 2018 and again during fall 2019, which corresponded to the times when SWD for the D100 treatments were near zero (Figs. 3 and 4). Either F100 treatment had little DP calculated during the $ET_{c\ act}$ period.

Summation of the estimated ET_c and $ET_{c\ act}$ indicates that after ≈23 months the total ET_c for the D100 and F100 treatments were 3663 and 3506 mm at Maricopa and were 3428 and 3320 mm at Eloy, respectively (Table 4). Differences between the SDI and furrow total ET_c were small (3–4 %) at the locations. However, total estimated soil evaporation for F100 (424 mm) was 75 mm higher than that for the D100 at Maricopa, while the total for F100 at Eloy (417 mm) was 53 mm higher than for the D100. The data also indicate that total ET_c was slightly higher at Maricopa than Eloy (6–7 %) for the same irrigation method. However, all

Table 4
Cumulative estimated (ET_c) and measured ($ET_{c\ act}$) guayule evapotranspiration and soil water balance components for the D100 and F100 treatments at Maricopa and Eloy, where I is cumulative measured irrigation, P is cumulative measured effective precipitation, ΔS is the measured change in the soil water depletion of the root zone from start to end of period, and DP is estimated cumulative deep percolation below the root zone.

Location	Period	Treatment	ET_c or $ET_{c\ act}$ (mm)	I (mm)	P (mm)	ΔS (mm)	DP (mm)
Maricopa	Apr. 20-Jul. 2, 2018[a]	D100	349	671	3.6	−32	293
	Jul. 3, 2019-Mar. 2, 2020[b]		3314	3011	425	−38	84
	ET_c plus $ET_{c\ act}$		3663	3682	429	−71	377
	Apr. 20-Jul. 2, 2018[a]	F100	420	726	3.6	10	319
	Jul. 3, 2019-Mar. 2, 2020[b]		3086	2780	425	−80	39
	ET_c plus $ET_{c\ act}$		3506	3506	429	−70	358
Eloy	Apr. 17-Jul. 9, 2018[a]	D100	427	643	7.1	−52	172
	Jul. 10, 2019-Feb. 29, 2020[b]		3001	2766	379	−36	109
	ET_c plus $ET_{c\ act}$		3428	3409	386	−87	281
	Apr. 17-Jul. 9, 2018[a]	F100	526	745	7.1	−1.2	225
	Jul. 10, 2019-Feb. 29, 2020[b]		2794	2488	379	−72	1.6
	ET_c plus $ET_{c\ act}$		3320	3233	386	−73	227

[a] Period when ET_c was estimated using basal crop coefficients derived in previous transplanted guayule studies.
[b] Period when $ET_{c\ act}$ was measured by soil water balance (Eq. 6).

values were lower than the ET_c reported for a 21-month transplanted guayule experiment (3824 mm) that was furrow irrigated at 65 % depletion in Arizona (Bucks et al., 1985a). After 24 months at Maricopa, transplanted cumulative ET_c for the 100 % SDI treatment of Hunsaker et al. (2019) was 3325 mm and for the 100 % furrow treatment of Hunsaker and Elshikha (2017) it was 3274 mm, suggesting that after two years the cumulative ET_c may be similar for transplanted and direct-seeded guayule.

Average daily $ET_{c\ act}$ of the D100 treatment at Maricopa over the individual measurement periods ranged from less than 1.0 mm d^{-1} in Jan. 2020 to 12.8 mm d^{-1} in late June 2019. Maximum average daily $ET_{c\ act}$ in summer 2019 were 11.5, 11.5, and 10.8 mm d^{-1} for the F100 at Maricopa and the D100 and F100 treatments at Eloy, respectively. The maximum $ET_{c\ act}$ rates were similar to those in the second year for transplanted guayule grown with SDI and furrow irrigation for well-watered treatments (Hunsaker et al., 2019; Hunsaker and Elshikha, 2017). In both years of the present study, there was a rapid reduction in $ET_{c\ act}$ from Nov. to Jan., winter dormancy, for all treatments. The winter dormancy and the reduction in ET_c is likely caused by the rapid lowering in temperature starting in late Nov. (Withers and Cooper, 2019; López-Bernala et al., 2020).

The rising sections of the estimated K_{cb} beginning in early June 2018 appear to agree with the following K_{cb} that were calculated for the D100 treatments at Maricopa (Fig. 5a) and Eloy (Fig. 6a) after starting the SWB measurements in early July. Just prior to the start of SWB for $ET_{c\ act}$, the estimated K_{cb} value for the D100 treatments was 0.68 on July 1 and 2 at Eloy and Maricopa, respectively. The K_{cb} calculated for the two subsequent measurement periods was 0.60 and 0.70 for the D100 at Maricopa and 0.72 and 0.80 for the D100 at Eloy. For Eloy, the estimated daily K_{cb} for D100 was then joined upward from 0.68 on July 1 to meet the 0.72 K_{cb} of the first measurement period (starting on July 10) using interpolation (Fig. 6a). The higher K_{cb} value assumed for the F100 treatments (0.72) on July 1 and 2 were considerably higher than the first K_{cb} values calculated after SWB began, which were 0.59 and 0.65 at Maricopa (Fig. 5b) and Eloy (Fig. 6b), respectively. For Eloy, the estimated daily K_{cb} for F100 was then joined downward from 0.72 on July 1 to meet the 0.65 K_{cb} of the first measurement period.

Figs. 5 and 6 also show the estimated daily K_{cb}, K_c, average K_c as determined by the SWB, as well as the standard climate adjusted FAO56

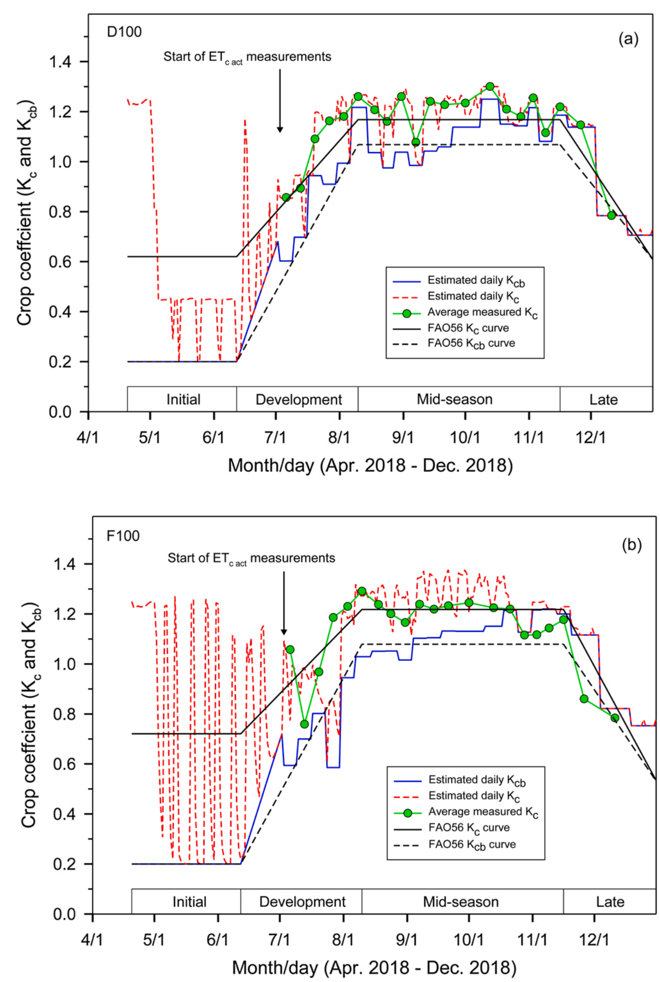

Fig. 5. Estimated daily basal (K_{cb}), single (K_c) crop coefficients, average measured (K_c), and standardized FAO56 curves for 2018 (1st year) guayule at Maricopa for the (a) D100 and (b) F100 treatments.

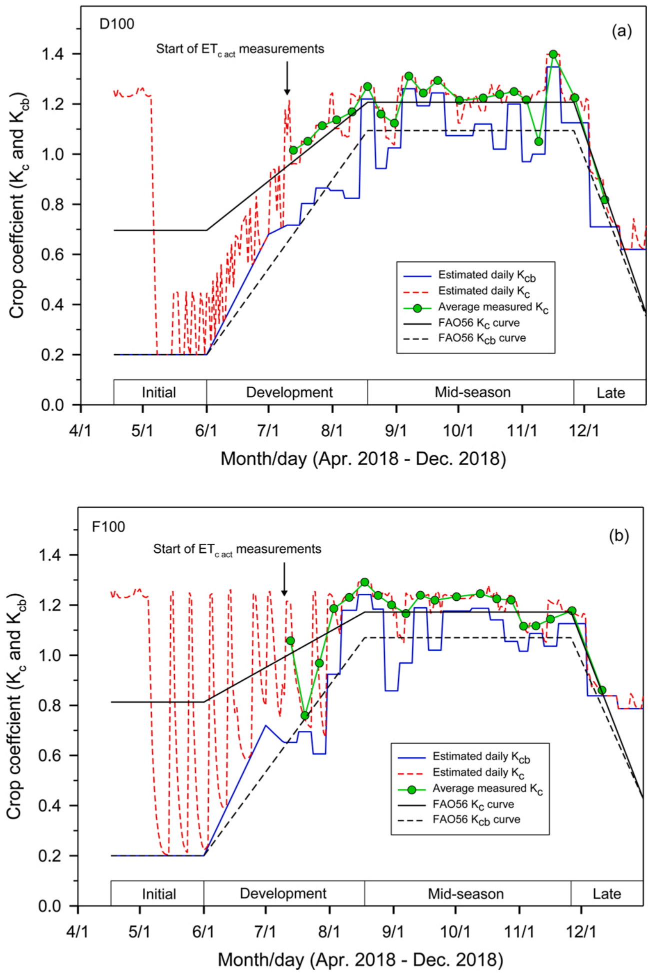

Fig. 6. Estimated daily basal (K_{cb}), single (K_c) crop coefficients, average measured (K_c), and standardized FAO56 curves for 2018 (1st year) guayule at Eloy for the (a) D100 and (b) F100 treatments.

segmented curves for the first year. The difference between daily K_c and K_{cb} represents the magnitudes of K_e for the two irrigation methods. The figures indicate significant soil evaporation occurred for all treatments during the sprinkler germination and that more soil evaporation (higher K_c) occurred for the F100 than D100 during the initial stage. The presumed K_{cb} of 0.20 for the initial stage resulted in an average K_c of 0.62 and 0.72 for D100 and F100 at Maricopa, respectively. Initial K_c at Eloy were computed as 0.70 and 0.81 for the D100 and F100, respectively, somewhat higher than that for the sandy loam in Maricopa. Peak mid-season K_c and K_{cb} values occurred from mid-Aug. through mid-Nov. 2018 for the treatments at Maricopa (Fig. 5) and from mid-Aug. to late-Nov. at Eloy (Fig. 6). At Maricopa, the average measured K_c values during the mid-season were 1.21 and 1.26, while average estimated daily K_{cb} were 1.11 and 1.12 for the D100 and F100, respectively. At Eloy, the average measured K_c during mid-season were 1.24 and 1.20, while the average estimated daily K_{cb} were 1.13 and 1.10 for the D100 and F100, respectively. That peak K_c and K_{cb} continued into Nov. in the first year coincides with the high incidence of precipitation events during Sep. and Oct. at both locations (Tables 1a and 1b). Percent measured canopy cover for the treatments (presented in the next section) was close to 100 % by early Nov. and mid-Jan. at Maricopa and Eloy, respectively. The average K_c for the treatments began declining to values less than 1.0 in mid-Dec. 2018 at both locations. However, it wasn't until late Jan. 2019 when K_c values declined to minimum values, indicating that $K_{c\ end}$ was reached shortly after the end of 2018. The $K_{c\ end}$ values were higher at Maricopa (0.63 and 0.55) than at Eloy (0.36 and 0.43) for the D100 and F100 treatments, respectively. Because soil evaporation was minimal in Jan. 2019, the $K_{cb\ end}$ values were the same or slightly less than the $K_{c\ end}$. Standard climate adjustments were made for the mid-season crop coefficients for the first-year FAO56 curves at both location (Figs. 5 and 6 for Maricopa and Eloy, respectively). However, climate adjustments were only made for $K_{c\ end}$ and $K_{cb\ end}$ for the Maricopa treatments. For the first-year guayule, standardized mid-season K_c for the D100 treatments were 1.17 and 1.21, whereas the mid-season K_{cb} values were 1.07 and 1.09 at Maricopa and Eloy, respectively. Standardized mid-season K_c for the F100 treatments were 1.22 and 1.17, while the mid-season K_{cb} were 1.08 and 1.07 at Maricopa and Eloy, respectively. Thus, there was little difference in the FAO56 standardized mid-season crop coefficients for the locations or the irrigation method in the first-year for direct-seeded guayule. However, standardized values for $K_{c\ end}$ and $K_{cb\ end}$ varied, where values for D100 at Maricopa were 0.61 and 0.61 versus 0.36 and 0.35 at Eloy, respectively. The $K_{c\ end}$ and $K_{cb\ end}$ for F100 were 0.53 and 0.53 at Maricopa, respectively, and 0.43 for both at Eloy. The location difference in $K_{c\ end}$ might be due to slightly higher minimum temperatures at Maricopa than Eloy in Jan. 2019 (Tables 1a and 1b).

In the second year, following a short initial period, there was a rapid increase in crop coefficients starting in Feb. 2019 for both the D100 and F100 treatments in Maricopa (Fig. 7a and b, respectively). Peak mid-season K_c and K_{cb} started in early June 2019 for the D100 and about 11 days later for the F100. At Eloy in the second year (Fig. 8), increase in crop coefficients following the initial stage was slower relative to

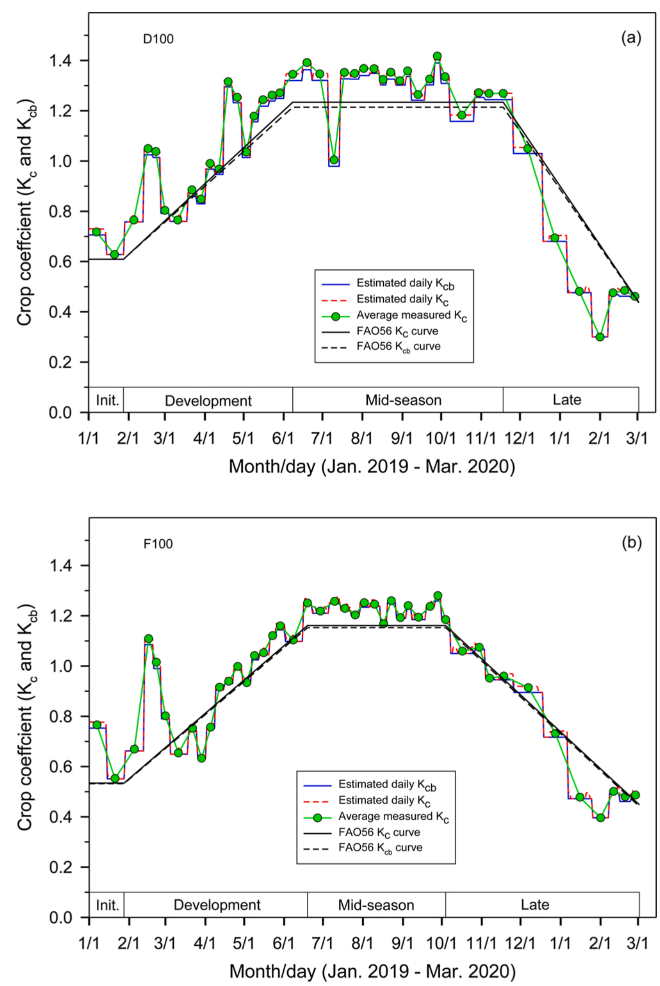

Fig. 7. Estimated daily basal (K_{cb}), single (K_c) crop coefficients, average measured (K_c), and standardized FAO56 curves for 2019-20 (2nd year) guayule at Maricopa for the (a) D100 and (b) F100 treatments.

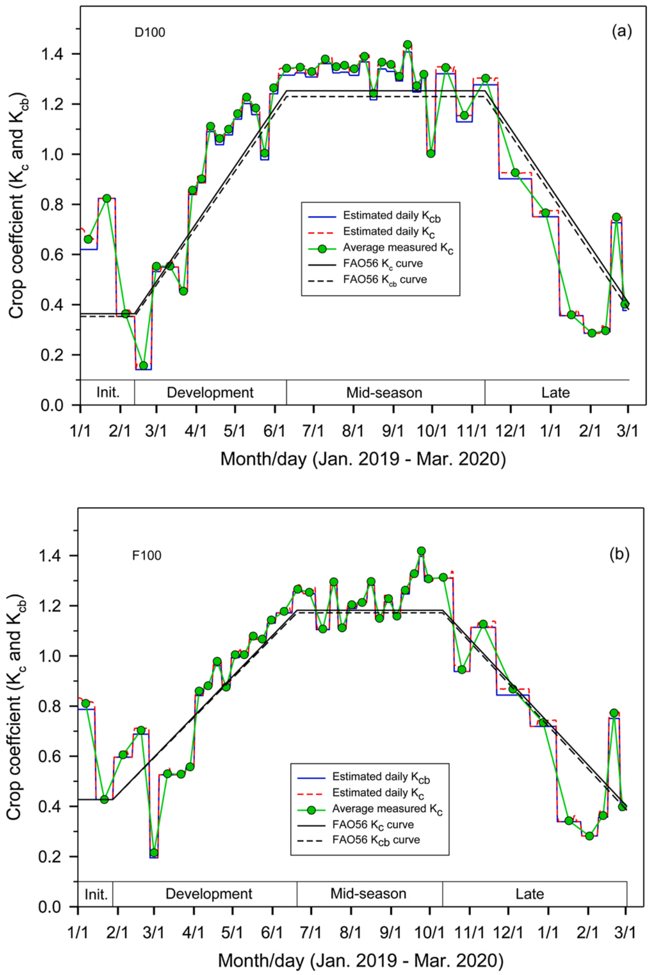

Fig. 8. Estimated daily basal (K_{cb}), single (K_c) crop coefficients, average measured (K_c), and standardized FAO56 curves for 2019-20 (2nd year) guayule at Eloy for the (a) D100 and (b) F100 treatments.

Maricopa, likely because irrigation at Eloy in 2019 resumed later than at Maricopa. However, the mid-season peak K_c and K_{cb} values at Eloy happened at about the same time as in Maricopa, early and late June for the D100 (Fig. 8a) and F100 (Fig. 8b) treatments, respectively. The primary differences in crop coefficients for the second year was that the D100 reached higher mid-season K_c and K_{cb} than F100 at both locations and that the mid-season durations were longer for D100 (≈170 days for D100 and ≈120 days for F100). The average measured mid-season K_c values for the D100 was 1.30 and 1.31 at Maricopa and Eloy, respectively. The corresponding average estimated daily K_{cb} was 1.27 and 1.29 at Maricopa and Eloy, respectively. Average K_c during the mid-season for the F100 was 1.23 and 1.24 at Maricopa and Eloy, respectively, while K_{cb} was 1.22 and 1.23, respectively. Average K_c for treatments declined to less than 1.0 by early Dec. 2020 and then remained quite low during the winter months of 2020, prior to final harvest. As in the first year, $K_{c\ end}$ and $K_{cb\ end}$ values were higher in Maricopa (0.46 for both for D100 and 0.49 and 0.48 for F100) than Eloy (0.40 and 0.38 for D100 and 0.40 and 0.38 for F100). Minimum temperatures were lower at Eloy than Maricopa during Jan.-Feb. 2020. Adjusted to standard climate, mid-season K_c for the second year of guayule for D100 were 1.23 and 1.25 at Maricopa and Eloy, respectively. Corresponding mid-season K_{cb} for D100 were 1.21 and 1.23 at Maricopa and Eloy, respectively. For the F100 treatments, adjusted mid-season K_c were 1.16 and 1.18, while the K_{cb} were 1.15 and 1.17. respectively, at Maricopa and Eloy. Standard climate adjusted $K_{cb\ end}$ values at Maricopa were 0.44 for both the D100 and F100 treatments, somewhat lower than those at the end of the first year.

The measured K_c and growth stage durations were similar for both treatments and locations during the first year of direct-seeded guayule. While the F100 had higher mid-season K_c than D100 in the sandy loam soil at Maricopa in the first year, the estimated mid-season K_{cb} were about the same for the treatments. Thus, the F100 had presumably more soil evaporation than D100 in the first year at Maricopa, particularly so when considering the period prior to the $ET_{c\ act}$ measurements. During the winters of 2019 and 2020 (end of season), there were subtle differences in K_c due to location, where lower $K_{c\ end}$ values occurred at Eloy than Maricopa. These location differences were attributed to the lower minimum temperatures that occurred in Eloy than Maricopa at the end of the season. Beginning in late-spring in the second year there were notable differences between the K_c of the D100 and F100 treatments at both locations. The mid-season stages were longer for D100 and their values were 6–7 % higher than those for the F100, also closely reflecting the 6–7 % increase in total $ET_{c\ act}$ of the D100 (Table 4), mentioned earlier. However. the mid-season K_c differences between the D100 and F100 treatments in the second year in this study were not as profound as those between the well-watered SDI and furrow treatments in the second year of transplants at Maricopa, which were about 16 % higher for the SDI (Hunsaker and Elshikha, 2017; Hunsaker et al., 2019). Hunsaker et al. (2019) suggested that the differences in the guayule $ET_{c\ act}$ between SDI and furrow irrigation is due primarily to the high frequency SDI applications. While the canopy cover was full during the second year for both methods in the transplant study, soil evaporation was about equal for the methods. The difference is that frequent SDI application allowed more available soil water use by the plants, thus higher basal ET_c, as also indicated by the higher K_{cb} values for D100 than F100 in the present direct-seeded study. The FAO56 standard mid-season K_c and K_{cb} values for guayule in the second year were similar to those expected in dense, perennial crops, e.g., sugar cane and alfalfa (Allen et al., 1998). The standard $K_{c\ end}$ values for guayule shortly before harvest are on the order of 0.40 to 0.45, which are similar for many crops that are harvested dry.

3.3. *Plant growth*

Average plant population density (APD) was significantly higher at Eloy, ~7 plants m^{-1}, than at Maricopa, ~5 plant m^{-1} (Table 5). However, standard errors for treatments indicated about the same plant population density variability regardless of location. At a given location, APD was not significantly different among irrigation treatments. APD was equivalent to 48,000 plants ha^{-1} for Maricopa and 73,000 plants ha^{-1} for Eloy. The lower plant population density at Maricopa compared to Eloy might have been due to the low water holding capacity of the lighter sandy loam soil at Maricopa. That might have resulted in less water availability during germination and plant establishment. Additionally, there were several days of significant sand blowing at Maricopa shortly after emergence resulting in abrasion and desiccation of

Table 5
Average plant population density (APD) and standard error (SE) for guayule subsurface drip [SDI] (D50-D150) and furrow (F100) treatments at Maricopa and Eloy, measured in Jan. 2019. The numbers following the letters D (for SDI) and F (for furrow) are irrigation rates (percent replacement of crop evapotranspiration [ET_c]).

Treatment	Maricopa		Eloy	
	APD plants m^{-2}	SE	APD plants m^{-2}	SE
D50	5.7	0.6	8.3	0.6
D75	5.7	0.6	6.6	0.4
D100	4.4	0.3	7.8	0.4
D125	5	0.5	7.8	0.3
D150	4.1	0.5	8	0.3
F100	4.4	0.5	6	0.1

seedlings. Total plant population density at Maricopa was relatively close to the planting rate of 54,000 plants ha^{-1} used in a guayule irrigation experiment with transplants by Bucks et al. (1985a), and much higher than transplanted guayule densities of about 27,000 plants ha^{-1} used by Hunsaker et al. (2019) and in other earlier studies using transplants by Ray et al. (2005). These studies have indicated a negative correlation between plant population density and plant size at harvest. It is important to study the combined effect of water application rate and planting density on guayule plant growth and yield. Therefore, it is recommended to include planting density as a treatment in future guayule irrigation studies.

At Maricopa, plant height consistently increased in all treatments with time, until the intense rain that occurred in Aug.-Sep. 2018 resulting in a rapid height increase in all treatments in relatively a short period between Sep.-Oct. (Fig. 9a). The height difference at Maricopa in 2018 was only significant in late Sep. (and only between D50 and the rest of the treatments). From Nov. 2018 until Mar. 2019, the increase in plant height was minimal due to dormancy. Then, by Apr. 2019, all the treatments were separated with the highest water application rate having the greatest height and the lowest rate having the smallest plant height. The treatments started to separate in Apr. 2019 (D50 from the rest of the treatments). However, from July 2019-Mar. 2020, plant heights for the high-water treatments (D100-D150) were significantly greater ($p < 0.05$) than heights for the low water treatments (D50 and D75). The plant height measurements at the Eloy field started in Sep. 2018, so only part of the rapid change in plant height was observed (Fig. 9b). In Sep. 2018, the difference in plant height was only significant between D75 (0.63 m) and D125 (0.70 m). After the excessive rainfall, some of the plots had a minor decrease in plant height, which is a phenomenon that was seen mainly at the Eloy field. For Eloy, significant differences in plant height were not seen in the second year until June-July 2019 (between D50 [0.80 m] and the rest of the irrigation treatments [1–1.03 m]), then between D50 and the F100 until plants were harvested in Mar. 2020. The major difference in plant height between high (D100-D150) and low (D50-D75) water treatments that started in the second year might be due to the establishment of a more developed root system by the end of the first year (Hunsaker and Elshikha, 2017), which might have resulted in quicker response to differences in irrigation rates in the second year. The slight decrease in plant height by the end of the first year at Eloy might be due to the change in branch orientation, where most branches began lodging instead of maintaining their normal upright position. It is possible that the rain and heavy irrigation combination in a clay soil with high water holding capacity resulted in the change in branch orientation (canopy architecture) and the slower increase in plant height at Eloy when compared to Maricopa. From Nov. 1–15, 2018, both fields were irrigated heavily, before irrigation was stopped by mid-Nov., the start of the dormancy period. Despite the reduction in plant activity and crop evapotranspiration during dormancy period (≈3 months), plant water consumption is not fully eliminated. Therefore, filling the soil profile was necessary.

Change in percent canopy cover with time for treatments differed between the two locations (Fig. 10). At Maricopa, the difference in percent canopy cover among the treatments was not significant until Sep. 2018. Afterwards, significant differences were observed between D50 and all the higher treatments in Sep. 2018-Jan. 2019. While all treatments but D50 in Maricopa had achieved a near full canopy by Nov. 2018, after Apr. 2019, all treatments were at full cover. In Eloy, the percent cover during Sep.-Nov. 2018 was higher for the F100 and D75 treatments than the rest of the treatments. By mid-Jan. 2019, all but the D50 treatment in Eloy were at 100 % cover, whereas the D50 reached full cover in Apr. 2019.

3.4. Yield and water productivity

Percent rubber content (R) and resin content (Re) at the two-year harvest for treatments are shown in Fig. 11. The vertical bars in Fig. 11 represent the treatment standard errors, which were small. Average R (over all treatments) was significantly higher in Maricopa. The F100 and D50 treatments had the highest average R (4.4 and 3.9 %)

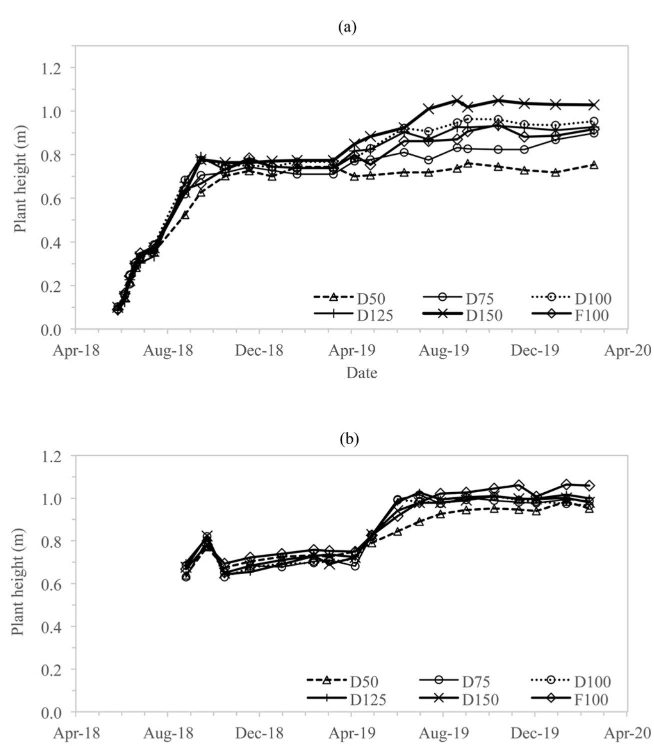

Fig. 9. Plant height for SDI (D) and furrow (F) treatments with time: (a) Maricopa and (b) Eloy. Terms in legend same as described in Fig. 2.

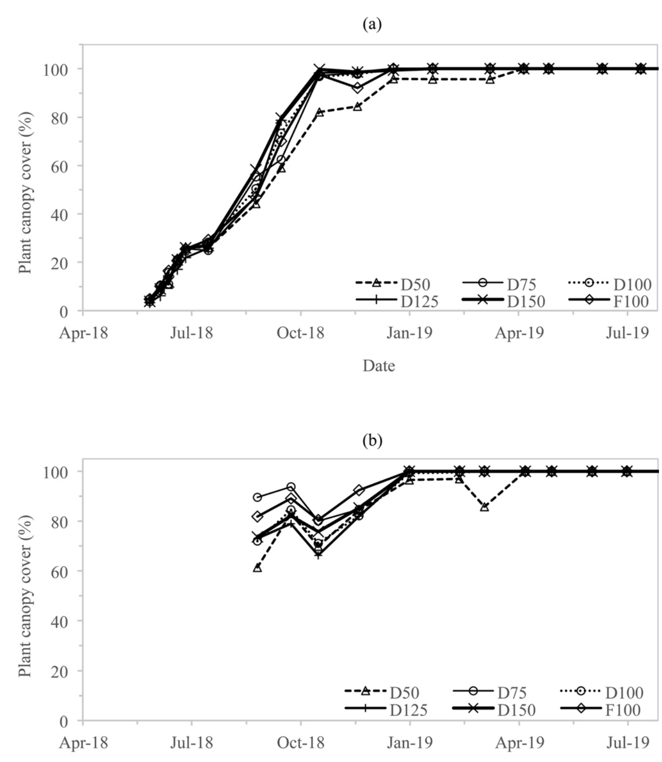

Fig. 10. Plant canopy cover for SDI (D) and furrow (F) treatments with time: (a) Maricopa and (b) Eloy. Terms in legend same as described in Fig. 2.

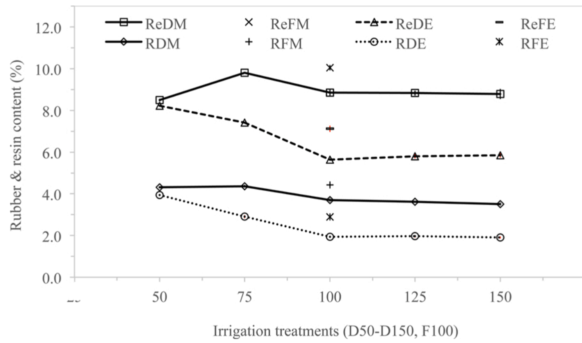

Fig. 11. Plant rubber (R) and resin (Re) content for SDI (D) and furrow (F) treatments at Maricopa (M) and Eloy (E). For example, RDM represents rubber content (R), for SDI (D) treatments at Maricopa (M). Irrigation treatment levels are indicated by the numbers seen along the x-axis (i.e., 50 to 150 % ET_c replacement).

for Maricopa and Eloy, respectively. For the F100 treatment, R was higher at Maricopa than Eloy (significant at $p < 0.05$). The R for the lower-rate SDI (D50 and D75) and F100 treatments were significantly higher than the R for the higher-rate SDI treatments at both Maricopa and Eloy. The highest R for F100 (4.4 %) at Maricopa was lower than the rubber content obtained from 29-month old transplanted guayule (6.25 %) and furrow irrigated with 100 % replacement of estimated ET_c in a recent study at this site (Hunsaker and Elshikha, 2017). The relatively lower R in this experiment compared to other studies was partly due to the use of a different laboratory analytic method (the Soxhlet-based NIR vs. Accelerated Solvent Extraction in the other studies). The NIR method calibrated with Soxhlet is a standard method used by the tire industry. Efforts are currently under way to establish standards for guayule natural rubber, which will help to make comparisons between experiments possible. Given the difference in rubber analytical methods, direct comparison with the Hunsaker and Elshikha (2017) and other experiments concerning rubber yields will not be made.

The longer irrigation intervals for the furrow treatment at Maricopa might create a stress response and lead to the increase in R, compared to SDI. Consequently, change in rubber content as a function of irrigation interval should be considered in future studies. The decrease in rubber content with the increase in water application depth (rate) for SDI treatments at Maricopa and Eloy fields has been reported elsewhere (Hunsaker and Elshikha, 2017; Hunsaker et al., 2019). These two authors and several others (Benedict and Robinson, 1946; Bucks et al., 1985b; Ramachandra Reddy and Rama Das, 1988; Foster and Coffelt, 2005) have observed that water stress results in higher rubber content. The positive correlation of guayule DB and the negative correlation of R with irrigation rate makes it difficult to predict final RY. However, changing the irrigation technique by exposing the guayule plants to alternate periods of low- and high-water application rates (as suggested by Benedict et al., 1947) may increase both R and DB and ultimately reduce water-use. One way to evaluate this would be to apply a limited amount of water in the first year, followed by a sufficient amount applied in the second year.

Resin content at the two-year harvest was also significantly higher at Maricopa (Fig. 11) and the highest Re was obtained with the F100 and D75 treatments (10.0 % and 9.8 %, respectively). In Eloy, the highest Re occurred with the D50 treatment (8.2 %). Resin content tended to decrease with irrigation rate until the rate reached 100 % replacement of estimated ET_c. Water stress associated with the D50−75 treatments and the longer irrigation intervals associated with the F100 treatment might have caused the Re to increase. Previous studies showed unclear trends for the change in resin content with irrigation rate (Miyamoto and Bucks, 1985; Hunsaker et al., 2019). The maximum Re for the furrow and SDI treatments at Maricopa (10.0 and 9.8 %, respectively) is higher than what was obtained from transplanted guayule irrigated with furrow and subsurface drip techniques (9.1 and 8.6 %) at 100 and 75 % replacement, respectively, of estimated ET_c (Hunsaker and Elshikha, 2017; Hunsaker et al., 2019). Also, it is higher than what was reported by Dissanayake et al. (2008) at 6.4–7.4 %. As for rubber yield, due to the different analytic methods, comparisons of resin yield with other studies cannot be fairly made.

The highest mean dry biomass (DB) was attained in the D100-D150 treatments at Eloy (Table 6). However, there was no location difference in DB. At both locations, the DB mean increased as water application rate increased, from D50 to D100 for Maricopa (from D50 to D125 for Eloy), but increasing the application depth above D100 for Maricopa (and above D125 for Eloy) resulted in slightly lower DB. Among SDI treatments, DB difference was significant between the higher and lower SDI rates (Table 6). Biomass at both locations was significantly higher for the D100 SDI treatments than the F100 treatment (Table 6). The D150 received double the irrigation water applied to D75, but the higher rate resulted in only a 9.3 % increase in DB yield for Eloy, while a 38 % increase resulted for the D150 at Maricopa. Similarly, increasing the irrigation rate from D75 to D100 (25 % increase in water) provided a significant DB increase at Maricopa but not at Eloy. The reason of the different responses in DB with irrigation level at Eloy than Maricopa is unknown.

The decrease in DB with the increase in water application rate above D100 for Maricopa (and above D125 for Eloy) contradicts the assumption by Fangmeier et al. (1985) and Hunsaker and Elshikha (2017) that guayule DB responds linearly to water application rate. The DB for 29-month-old guayule transplants in a recent study at Maricopa (Hunsaker and Elshikha, 2017) was 24.5 Mg ha^{-1} when irrigated with furrow irrigation at 100 % of ET_c. Coffelt and Ray (2010) reported DB of 21.6 Mg ha^{-1} after 24 months for well-watered guayule transplants grown in furrows. In our study, the DB achieved after 23–24 months for the F100 treatment was higher at Eloy (26.4 Mg ha^{-1}) and similar at Maricopa (22.5 Mg ha^{-1}) compared to these previous studies using furrow irrigation. In contrast, DB for transplants using SDI irrigated with 75 % of ET_c at Maricopa was 38.6 Mg ha^{-1} after 29 months (Hunsaker et al., 2019). This was 31 % (Maricopa) and 17 % (Eloy) higher than those of the D100 treatment in the present study. Also, data for twelve-month old plants indicated higher DB for transplanted guayule (18.9 Mg ha^{-1}, Hunsaker and Elshikha, 2017) compared to direct seeded guayule (14.6

Table 6
Means of dry biomass (DB), rubber yield (RY), and resin yield (ReY) for harvested guayule after 23 and 24 months of growth by location and by irrigation treatment at Maricopa and Eloy, respectively. Treatment names are the same as described in Table 3.

		Maricopa			Eloy		
		DB (Mg ha^{-1})	RY (kg ha^{-1})	ReY (kg ha^{-1})	DB (Mg ha^{-1})	RY (kg ha^{-1})	ReY (kg ha^{-1})
Location		24.03A *	941B	2193B	28.63 A	705A	1866 A
Treatments	D50	14.07 a	607 Aa	1195 Aa	18.80 a	741 Aab	1546 Aa
	D75	21.25 b	929 Ab	2085 Ab	28.88 bc	839 Ab	2142 Ab
	D100	29.49 c	1092 Bb	2611 Bc	33.00 c	639 Aa	1858 Aab
	D125	27.59 c	997 Bb	2436 Bcd	33.26 c	654 Aa	1928 Ab
	D150	29.34 c	1029 Bb	2579 Bcd	31.55 c	601 Aa	1847 Aab
	F100	22.46 b	993 Bb	2255 Bd	26.31 b	759 Aab	1873 Aab

* For DB, RY, and ReY means, different capital letters indicate significant location differences ($p < 0.05$). When the location difference was significant, different capital letters for a given irrigation treatment indicate the yield was significantly different for the treatment. Different small letters in rows for DB, RY, and ReY indicate significant irrigation treatment differences at the location.

Mg ha^{-1}, Elshikha et al., 2019). The increased DB from Hunsaker et al. (2019) SDI study had the benefit of an additional six months of growth before harvest. Additionally, in this SDI study, the seedlings were already three months old at the time they were transplanted. Thus, it is possible that the growing-time difference between the transplanted and the direct-seeded guayule in the present study may have caused the significant difference between the two planting methods.

Water productivity of the dry biomass (DB-WP), i.e., biomass production per unit of total water applied, was significantly lower in Maricopa than Eloy (Table 7). In Eloy, the DB-WP of the D75 treatment was significantly higher (0.98 kg m^3) than all other treatments, as well as being the highest DB-WP at either location (Table 7). Significantly higher DB-WP was observed for the D75 and D100 treatments than the other treatments, at Maricopa. The DB-WP for D75 at Eloy was about double those obtained with furrow irrigation in previous studies, including Hunsaker and Elshikha (2017). It was, however, lower than those in the well-watered SDI treatments (≈1.20 kg m^{-3}) reported by Hunsaker et al. (2019). Having higher DB-WP response in Eloy than at Maricopa suggests possible effects of the higher plant population at Eloy and better soil water conditions for guayule plant production in the clay soil.

The trend of rubber yield (RY) with irrigation (Table 6) at Maricopa was similar to DB, although the RY and DB trends with irrigation were not similar at Eloy. Also, unlike the lower DB attained at Maricopa compared to Eloy, average RY was significantly higher at Maricopa than Eloy, where the average RY for Maricopa and Eloy locations were 941 and 705 kg ha^{-1}, respectively (Table 6). All SDI treatments at Maricopa, except at the D50 and D75 levels, were significantly higher in RY than the corresponding SDI treatments at Eloy due to the higher rubber content at Maricopa. At Maricopa, the highest RY was in the D100 treatment. However, the difference in RY was only significant between D50 and all the other treatments. At Eloy, the D75 treatment had significantly higher RY than the high SDI treatments (D100-D150), though it was not significantly higher than D50 and F100 at that location (Table 6). A notable result of the present study is that applying rates above the D75 did not result in significantly higher RY at Maricopa and caused a significant decrease in RY at Eloy. At Maricopa, the RY water productivity (RY-WP) for SDI treatments did not change significantly among the D50-D100 treatments nor for the F100 treatment (Table 7). At Eloy, both D50 and D75 achieved significantly higher RY-WP than all other treatments. Also, there was no location difference in mean RY-WP.

Table 7
Means of water productivities* of dry biomass (DB-WP), rubber yield (RY-WP), and resin yield (ReY-WP) for harvested guayule after 23 and 24 months of growth by location and by irrigation treatment at Maricopa and Eloy, respectively. Treatment names are the same as described in Table 3.

		Maricopa			Eloy		
		DB-WP (kg m^{-3})	RY-WP	ReY-WP	DB-WP (kg m^{-3})	RY-WP	ReY-WP
Location		0.61 A[e]	0.024 A	0.056 A	0.79 B	0.021 A	0.053 A
Treatments	D50	0.60 Ab	0.026 c	0.051 ab	0.84 Bc	0.033 c	0.069 d
	D75	0.66 Abc	0.029 c	0.065 c	0.98 Bd	0.029 c	0.073 d
	D100	0.72 Ac	0.027 c	0.064 c	0.85 Bc	0.016 a	0.048 bc
	D125	0.58 Aab	0.021 ab	0.051 ab	0.73 Bb	0.014 a	0.042 ab
	D150	0.50 Aa	0.017 a	0.044 a	0.58 Aa	0.011 a	0.034 a
	F100	0.58 Aab	0.026 bc	0.058 bc	0.74 Bb	0.022 b	0.053 c

* Water productivity (WP) is based on total water applied (irrigation plus precipitation) from planting to harvest.

[e] *For DB-WP, RY-WP, and ReY-WP, different capital letters indicate significant location differences ($p < 0.05$). When the location difference was significant, different capital letters for a given irrigation treatment indicate the WP was significantly different for the treatment. Different small letters in rows for DB-WP, RY-WP, and ReY-WP indicate significant irrigation treatment differences at the location.

Significantly higher resin yield (ReY) was found at Maricopa compared to Eloy (Table 6). The highest resin yield at Maricopa was in the D100-D150 treatments. The D125 and D150 treatments had significantly higher ReY than the D50 and D75 treatments at Maricopa. At Eloy, the D50 treatment had the lowest ReY (1546 kg ha^{-1}), which was significantly lower than the ReY for D125 (1928 kg ha^{-1}) and D75 (2142 kg ha^{-1}, highest for Eloy) but not for other treatments. For Maricopa treatments, D100-D150 and F100, ReY was significantly higher than the corresponding treatments at Eloy (Table 6). The resin yield water productivity (ReY-WP) at Maricopa was significantly different among treatments with highest ReY-WP for the D100 and D75 (Table 7). At Eloy, D75 and D50 had significantly greater ReY-WP than that for other treatments. The ReY-WP clearly decreased from that at D75 with increasing irrigation water applied at Eloy. However, there was no difference in the location average ReY-WP.

Based on the three yield components (i.e., DB, RY, ReY), the D100 treatment on the sandy loam soil at Maricopa had yield production and/or WP advantages over the other treatments. The D100 at Maricopa achieved the highest means for DB, RY, and ReY, which for DB and ReY, were significantly greater than those for D50, D75, and F100. The mean yields for D100 were not significantly greater than those for D125 and D150, however when considering irrigation inputs, D100 had significantly higher WP than D125 and D150 in all yield cases. Thus, in the sandy loam soil, irrigation water use was less efficient for production at the higher irrigation levels, while yields declined at the lower irrigation levels. These yield trends differed considerably from those using SDI in a previous study at Maricopa with transplanted guayule (Hunsaker et al., 2019) where yields for DB and RY increased significantly from the 100 %–125 % irrigation level and the WP was also slightly increased in the 125 % treatment. However, in the Hunsaker et al. (2019) SDI study, the yield gains for D125 over D100 may be related to an additional six months of growth (29 months total) at the higher irrigation rate, compared to only 23 months of total growth in the present study. While the D75 treatment at Maricopa in the present study had significantly lower DB and ReY than D100, its RY was only 15 % less than that for D100, which was not statistically different. Furthermore, the WP for the yields in D100 were comparable to those of the D75. Thus, a case could be made that D75 management in the sandy loam using SDI could save significant amounts of water while attaining RY near that irrigated at 100 % ET_c replacement. The DB and ReY for the F100 at Maricopa was significantly less than that for the D100, which would agree with the furrow and SDI difference in yields found by Hunsaker et al. (2019). However, unlike the previous study findings, RY for F100 was not significantly lower than for D100, reflecting the higher rubber content realized for the F100 after 23 months. Based on this observation and relative capital cost, furrow irrigation would have been preferred over SDI, however, DB and ReY, were significantly higher for D100 than F100. Therefore, D100 is considered the best irrigation management strategy for Maricopa.

In Eloy, the D75 represented the best irrigation management in terms of yield and WP. The D50 treatment had a 12 % RY reduction from the D75 RY and had high RY-WP. If RY is considered as the primary goal, the D50 represents a more water-efficient management that may maintain the RY close to the higher D75 irrigation. However, with significantly less DB produced, there would be considerable reliance on the ability of the low water use management to reach high rubber content. In the clay soil at Eloy, RY decreased significantly with 100 % ET_c replacement (D100 and F100) compared to the D75, due to the decrease in rubber content. Since water holding capacity is higher in the clay soil compared to sandy loam, a higher yield and WP might be attained in heavier soils with furrow irrigation managed at a lower rate than 100 %.

4. Conclusions

Sprinkler germination and subsequent establishment irrigations of direct-seeded guayule are critical but require significant amounts of water. Subsurface drip irrigation offers some advantage during establishment compared to furrow because of the ability to apply much smaller applications, which results in less deep percolation than occurs using high-application furrow irrigation. However, after the crop is established, furrow irrigation can be efficiently applied during summer as soil water depletion increases to levels more amenable to high irrigation applications. The crop evapotranspiration of spring, direct seeded guayule for two years is on the order of 3300–3700 mm for full irrigation in the Arizona desert climate. However, 100 % irrigation replacement of crop ET may not increase yield production and, hence, water productivity when lesser irrigation is applied, as shown in the Eloy study. Yet, the crop ET data for the full irrigation treatments in the studies provide a basis for determining direct-seeded guayule crop coefficients that are compatible with the standardized FAO56 methodology. It was not unexpected that the single K_c for this large, densely planted shrub were high under full irrigation. Average values of K_c in mid-season (summer to fall) in the first year varied from 1.20−1.26. The average K_c in the second year mid-season were higher for SDI (1.30–1.31) but were about the same as in the first year with furrow irrigation (1.23–1.24). For estimating direct-seeded guayule crop ET at different climates using FAO56 procedures, standardized mid-season K_c and K_{cb} were provided and averaged 1.20 and 1.08 in the first year, respectively. For the second year of guayule, standardized mid-season K_c and K_{cb} increase to 1.24 and 1.22, respectively, when high-frequency irrigation was used, while mid-season K_c and K_{cb} were both about 1.17 when lower-frequency surface irrigation was used. The crop coefficients reported provide a reference point for irrigation management of direct-seeded guayule for future guayule growers in the region.

Rubber and resin contents decreased with increasing water application rate, which is consistent with previous research. The optimal biomass, rubber, and resin yields and water productivities were achieved for D100 at Maricopa and D75 at Eloy. Obtaining equivalent biomass with less than 100 % irrigation in Eloy but not Maricopa was most likely due to the higher water holding capacity for the heavier (clay) soil in Eloy, which resulted in better germination and higher plant density. High biomass in both locations was observed with the D100 treatment and the increase in biomass with water reached a plateau at the D100 treatment. This indicates that the maximum irrigation rate that should be applied for sandy loam and clay soils is 100 % of estimated ET_c. However, the DB for D75 treatment at Eloy was not significantly different compared to D100, therefore D75 could be used to manage irrigation more efficiently. Maricopa, with sandy loam soil, had higher rubber and resin yields than Eloy, with clay soil. The highest rubber and resin yields at Maricopa were in the D100 treatment. Rubber yields decreased after D75 at Eloy, while there was no change in resin yield. Applying higher rates than D100 for Maricopa and D75 for Eloy may result in deep percolation and lower WP.

Despite the higher dry biomass for Eloy, the rubber and resin yields at Maricopa were higher due to the higher rubber and resin content. Based on all the yield components, the optimal irrigation rate at Maricopa (sandy loam) was D100, which required 700 mm (25 %) more water than the optimal irrigation rate (D75) for Eloy (clay). Reducing the irrigation rate for both locations by about 25 %, i.e. from D100 to D75 for Maricopa and from D75 to D50 for Eloy, resulted in reducing rubber yield by only 12–15 % (not significant). Therefore, if rubber is the only product of interest, these lower rates should be considered. Given the higher yield and insignificant difference in water application rate, the SDI system would be preferred over furrow for direct-seeded guayule planted in sandy loam (but not in clay). However, furrow irrigation may be favored in clay soil to eliminate the relatively higher SDI system cost.

Future research is needed to determine Best Management Practices and more efficient early season irrigation practices for establishing direct-seeded guayule crops. Also, given that guayule becomes semi-dormant during the winter and can survive long periods in summer without irrigation, deficit irrigation studies are needed to help determine the least amount of water that can be applied and the critical times when delaying or totally withholding water application would affect obtaining economically viable yields. Finally, more research is needed on developing appropriate irrigation management with furrow irrigation in heavier soils.

CRediT authorship contribution statement

Diaa Eldin M. Elshikha, Peter M. Waller, Douglas J. Hunsaker, David Dierig, Guangyao Wang, Von Mark V. Cruz, conceived and planned the experiments. **Diaa Eldin M. Elshikha, Peter M. Waller, Douglas J. Hunsaker, David Dierig, Guangyao Wang, Von Mark V. Cruz, Matthew E. Katterman**, carried out the experiments. **Diaa Eldin M. Elshikha, Peter M. Waller, Douglas J. Hunsaker, David Dierig, Guangyao Wang, Von Mark V. Cruz, Kelly R. Thorp, Kevin F. Bronson, Gerard W. Wall, Matthew E. Katterman** contributed to the interpretation of the results. **Diaa Eldin M. Elshikha** took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis, and manuscript.

Declaration of Competing Interest

Authors have no relevant interest(s) to disclose.

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References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration. FAO Irrigation and Drainage Paper 56. Food and Agric. Org. of the United Nations, Rome, Italy.

Bautista, E., Clemmens, A.J., Strelkoff, T.S., Schlegel, J., 2009. Modern analysis of surface irrigation systems with WinSRFR. Agric. Water Manage. 97 (6), 1146–1154.

Benedict, H.M., Robinson, J., 1946. Studies on Germination of Guayule Seed. USDA Tech. Bull. 921, Washington, DC, p. 48.

Benedict, H.M., McCrary, W.L., Slattery, M.C., 1947. Response of guayule to alternating periods of low and high moisture stress. Bot. Gaz. 100, 535–549.

Boateng, A.A., Elkasabi, Y., Mullen, C.A., 2016. Guayule (Parthenium argentatum) pyrolysis biorefining: fuels and chemicals contributed from guayule leaves via tail gas reactive pyrolysis. Fuel 163, 240–247.

Bucks, D.B., Nakayama, F.S., French, O.F., Legard, W.W., Alexander, W.L., 1985a. Irrigated guayule-evapotranspiration and plant water stress. Agric. Water Manag. 10, 61–79.

Bucks, D.B., Nakayama, F.S., French, O.F., Rasnick, B.A., Alexander, W.L., 1985b. Irrigated guayule-plant growth and production. Agric. Water Manag. 10, 81–93.

Bucks, D.B., Nakayama, F.S., French, O.F., Legard, W.W., Alexander, W.L., 1985c. Irrigated guayule Production and water use relationships. Agric. Water Manag. 10, 95–102.

Bucks, D.A., Roth, R.L., Nakayama, F.S., Gardner, B.R., 1985d. Irrigation water, nitrogen, and bioregulation for guayule production. Trans. ASAE 28, 1196–1205.

Bucks, D.A., Roth, R.L., Powers, D.E., Chandra, G.R., 1986. Direct seeding for economical guayule field establishment. In: Fangmeier, D.D., Alcorn, S.M. (Eds.), Guayule, a Natural Rubber Source. Proc. Fourth Intl. Guayule Res. and Dev. Conf., Tucson, AZ. 16-19 Oct. 1985. Guayule Rubber Soc., Inc. Inc., pp. 71–87, 1986.

Coffelt, T.A., Ray, D.T., 2010. Cutting height effects on guayule latex, rubber, and resin yields. Ind. Crops Prod. 32, 264–268.

Cornish, K., Pearson, C.H., Rath, D.J., 2013. Accurate quantification of guayule resin and rubber requires sample drying below a critical temperature threshold. Ind. Crops Prod. 41, 158–164.

Dissanayake, P., George, D.L., Gupta, M.L., 2008. Direct seeding as an alternative to transplanting for guayule in southeast Queensland. Ind. Crops Prod. 27, 393–399.
Elshikha, D.M., Waller, P.M., Hunsaker, D.J., Dierig, D., Wang, S., Cruz, M.V., Bronson, K., Katterman, M.E., 2019. Direct seeded guayule grown in Arizona under furrow and subsurface drip irrigation. ASABE Annual International Meeting 1900040. https://doi.org/10.13031/aim.201900040.
Eranki, P.L., El-Shikha, D., Hunsaker, J., Bronson, K.F., Landis, A.E., 2018. A comparative life cycle assessment of flood and drip irrigation for guayule rubber production using experimental field data. Ind. Crops Prod. 99, 97–108.
Estilai, A., Waines, J.G., 1987. Variation in regrowth and its implication for multiple harvest of guayule. Crop Sci. 27, 100–103.
Fangmeier, D.D., Samani, Z., Garrot (Jr.), D., Ray, D.T., 1985. Water effects on guayule rubber production. Trans. ASAE 28 (6), 1947–1950.
Foster, M.A., Coffelt, T.A., 2005. Guayule agronomics: establishment, irrigated production, and weed control. Ind. Crops Prod. 22, 27–40.
Foster, M.A., Fowler, J.L., Kleine, L.G., Puppala, N., 1999. Establishing new guayule lines by direct seeding. Ind. Crops Prod. 9, 93–100.
Foster, M.A., Fowler, J.L., Kleine, L.G., Grote, M.M., Puppala, N., 2002. Performance of direct-seeded and transplanted guayule. Ind. Crops Prod. 15, 23–31.
Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In: Klute, A. (Ed.), Methods of Soil Analysis, Part I. Am. Soc. Agron., Madison, WI.
Hammond, B.L., Polhamus, L.G., 1965. Research on guayule (Parthenium argentatum): 1942-1959. USDA Tech. Bull. 1327. U.S. Government Printing Office, Washington, DC, pp. 1–157.
Hunsaker, D.J., Elshikha, D.M., 2017. Surface irrigation management for guayule rubber production in the US desert Southwest. Agric. Water Manag. 185, 43–57.
Hunsaker, D.J., Elshikha, D.M., Bronson, K.F., 2019. High guayule rubber production with subsurface drip irrigation in the US desert Southwest. Agric. Water Manag. 220, 1–12.
Kajiura, H., Suzuki, N., Mouri, H., Watanabe, N., Nakazawa, Y., 2018. Elucidation of rubber biosynthesis and accumulation in the rubber producing shrub, guayule (Parthenium argentatum Gray). Planta 247, 513–526.
Kuruvadi, S., Jasso Cantu, D., Angulo-Sanchez, J.L., 1997. Rubber content in different plant parts and tissues of Mexican guayule shrubs. Ind. Crops Prod. 7, 19–25.
López-Bernala, Á., García-Tejerab, O., Testi, L., Orgaz, F., Villalobos, F.J., 2020. Studying and modelling winter dormancy in olive trees. Agric. For. Meteorol. 280, 107776.
Martin, D.L., Gilley, J.R., 1993. Irrigation water requirements. Part 623, Nat. Eng. Handbook. USDA-SCS, Washington, D.C. Chapter 2.
Miyamoto, S., Bucks, D.A., 1985. Water quantity and quality requirements of guayule: current assessment. Agric. Water Manag. 10, 205–219.
Muller, C.H., 1946. Root development and ecological relations of guayule. USDA Technical Bulletin 923. U.S. Gov. Print Office, Washington, D.C.
Nakayama, F.S., Vinyard, S.H., Chow, P., Bajwa, D.S., Youngquist, J.A., Muehl, J.H., Krzysik, A.M., 2001. Guayule as a wood preservative. Ind. Crops Prod. 14, 105–111.
National Academy of Science (NAS), 1977. Guayule: An Alternative Source of Natural Rubber. NAS, Washington, D.C.
Pereira, L.S., Cordery, I., Iacovides, I., 2012. Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agric. Water Manag. 108, 39–51.
Pereira, L.S., Parades, P., Hunsaker, D.J., Lopez-Urrea, R., Mohammadi Shad, Z., 2020. Standard single and basal crop coefficients for field crops. Updates and advances to the FAO56 crop water requirements method. Agric. Water Manage. 243, 106466.
Placido, D.F., Dierig, D.A., Cruz, V.M.V., Ponciano, G., Dong, C., Dong, N., Huynh, T., Williams, T., Cahoon, R.E., Wall, G.W., Wood, D.F., McMahan, C., 2020. Downregulation of an allene oxide synthase gene improves photosynthetic rate and alters phytohormone homeostasis in field-grown guayule. Ind. Crops Prod. 153, 112341 https://doi.org/10.1016/j.indcrop.2020.112341.
Post, D.F., Mack, C., Camp, P.D., Sulliman, A.S., 1988. Mapping and characterization of the soils on the university of Arizona maricopa agricultural center. Proc. Hydrology and Water Resources in Arizona and the Southwest. University of Arizona, Tucson, Arizona, pp. 49–60.
Ramachandra Reddy, A., Rama Das, V.S., 1988. Enhanced rubber accumulation and rubber transferase activity in guayule under water stress. J. Plant Physiol. 133, 152–155.
Rasutis, D., Soratana, K., McMahan, C., Landis, A.E., 2015. A sustainability review of domestic rubber from the guayule plant. Ind. Crops Prod. 70, 383–394.
Ray, D.T., Dierig, D.A., Thompson, A.E., Coffelt, T.A., 1999. Registration of six guayule germplasm with high yield ability. Crop Sci. 39, 300.
Ray, D.T., Coffelt, T.A., Dierig, D.A., 2005. Breeding guayule for commercial production. Ind. Crops Prod. 22, 15–25.
SAS Institute Inc, 2016. The SAS System for Windows Version 9.4. SAS Inst., Cary, NC.
Saxton, K.E., Willey, P.H., 2005. The SPAW model for agricultural field and pond hydrologic simulation. Watershed Models. CRC Press, Boca Raton, FL, pp. 401–422. Doi 10.
Suchat, S., Pioch, D., Palub, S., Tardan, E., Nicolaas, E.N., van Looc, Davrieux, F., 2013. Fast determination of the resin and rubber content in Parthenium argentatum biomass using near infrared spectroscopy. Ind. Crops Prod. 45, 44–51.
Thames, S.F., Kaleem, K., 1991. Guayule resin in amine-epoxy strippable coatings. Bioresour. Technol. 35, 185–190.
U.S. Department of Agriculture, Soil Conservation Service (USDA-SCS), 1991. Soil Conservation Service: Part 650. U.S. Department of Agriculture, Washington, D.C.
Wall, G.W., Kimball, B.A., White, J.W., Ottman, M.J., 2011. Gas exchange and water relations of spring wheat under full-season infrared warming. Glob. Change Biol. Bioenergy 17, 2113–2133.
Wang, G., Lynch, A.L., Cruz, V.M.V., Heinitz, C.C., 2020. Temperature requirements for guayule seed germination. Ind. Crops Prod. 45 (157), 112934.
Withers, P., Cooper, C.E., 2019. Dormancy. In: Encyclopedia of Ecology, second edition, Vol. 3, pp. 309–314.