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Surface irrigation management for guayule rubber production in the US desert Southwest

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ABSTRACT

Agricultural production of the desert shrub, guayule (*Parthenium argentatum* G.), requires judicious management of irrigation water for achieving economic yields and high water productivity. This study expands existing, but limited and dated knowledge on irrigation management of guayule. A 29-month guayule surface irrigation study (Oct. 2012–Mar. 2015) in Maricopa, Arizona, US, imposed five irrigation treatments whose irrigation amounts were 40, 60, 80, 100, and 120% of irrigation applied to the 100% treatment, based on the soil water depletion (SWD) of the 100%. Irrigation treatments and soil water balance measurements began in Apr. 2013, ≈6 mos. after plant establishment. Measured SWD percentage prior to irrigation for the 100% treatment averaged 59%. The total water applied (TWA), irrigation and rain from planting to final harvest, varied from 2370 to 4720 mm. Cumulative ETc measured only over the final 23 months of the study (Apr. 2013 through Mar. 2015) varied from 1740 to 3720 mm. At final harvest, dry biomass (DB) varied from 15.7 to 27.9 Mg/ha, rubber yield (RY) from 1220 to 1680 kg/ha, and resin yield from 1290 to 2720 kg/ha. The study confirms that both DB and RY respond linearly to TWA. For maximum rubber yield using surface irrigation, it is recommended to use a SWD of 50% for irrigation scheduling and apply ≈2000 mm/year of total water. However, guayule water productivity (yield per unit TWA) can be significantly increased by reducing TWA by 25% (i.e., 1460 mm/year). This irrigation rate achieved 92% of the maximum RY in this study.

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1. Introduction

The high demand and expected shortages of natural rubber have brought renewed attention to guayule (*Parthenium argentatum* G.) as a domestic natural rubber crop for the US (Rasutis et al., 2015). Guayule, a perennial, hardwood shrub, is presently being produced commercially for natural rubber on a limited-scale in Southwestern US desert areas, primarily in the state of Arizona. Guayule is native to the Chihuahuan Desert of North America (Ray et al., 2005) and is considered drought tolerant (Foster and Coffelt, 2005). In its native setting, guayule survives on about 250–380 mm of annual rainfall (Bekaardt et al., 2010). In the early 1900s, Lloyd (1911) remarked on “the abundant and ready growth of guayule under irrigation” observed in experiments conducted in Mexico. Lloyd also was convinced of guayule’s ability to withstand extreme water stress and resume normal growth after receiving water from irrigation or rain. The National Academy of Sciences (NAS, 1977) recommended limiting the total water application (TWA), i.e., irrigation water plus rainfall, to 640 mm in desert areas so that rubber formation would not diminish with the excessive vegetative growth produced with higher applied water. These irrigation estimations were largely based on research conducted at various California sites during the Emergency Rubber Project of World War II, e.g., as reported by Roberts (1946). However, increased knowledge on how to manage irrigation for guayule was generated during the 1980s when the most recent guayule irrigation research was conducted. These included field studies each conducted for ≈ two years in the US Sonoran Desert in Mesa and Yuma, Arizona (Bucks et al., 1985a,b,c,d), the US Chihuahuan Desert in El Paso, Texas (Miyamoto et al., 1984; Miyamoto and Bucks, 1985), and in the Negev Desert of Israel (Benzioni et al., 1989). Measured crop evapotranspiration (ETc) corresponding to maximum dry biomass (DB) was 2050, 1950, 1830, and ≈1200 mm in the second full year in Mesa, Yuma, El Paso, and Israel, respectively. The high annual ETc reported for guayule in the Arizona studies is not unlike that for crops grown in the US Southwest desert such as alfalfa, which has annual ETc of about

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2000 mm (Erie et al., 1982). Both dry biomass and rubber yield (RY) were found to increase in a linear manner with ETc and TWA. These past studies also indicate that percent rubber in the plant tended to increase at the lower irrigation levels. However, increased rubber concentration at low irrigation input was not enough to overcome the low biomass effects on final rubber yields. For the 1980's Arizona studies, maximum DB and RY required on the order of 2000–2200 mm of TWA annually, whereas in Texas, ≈1600 mm annually. Water productivity (WP) can be calculated as the ratio of the harvested biomass or yield to total water applied (Pereira et al., 2012), and is a useful measure to compare the performance of different irrigation levels in the production of guayule. However, the effects of irrigation on the WP for dry biomass and rubber yield were inconsistent in the 1980's studies. In Mesa, the highest WP for dry biomass based on TWA (≈0.57 kg/m^3) occurred for the two wettest treatments, but WP for rubber yield was highest (0.032 kg/m^3) for both the driest and second wettest treatments. In Yuma, WP for DB was highest (0.65 kg/m^3) at both the lowest and medium irrigation treatment levels, but the WP for RY (0.044 kg/m^3) was about the same for all irrigation levels. Conversely, highest WP for both DB (0.54 kg/m^3) and RY (0.045 kg/m^3) clearly occurred at the lowest irrigation level in El Paso, while in Israel both occurred at the wettest irrigation level.

A weakness of these 1980s irrigation data sets is that the particular guayule lines used in the studies are not the same as those under current-day production. Ray et al. (1999) presented the attributes of several guayule lines that have been more recently bred for domestication. A comparison of newer lines (AZ-2 and AZ-3) to those used by Bucks et al. (1985a,d) and Miyamoto et al. (1984) showed the newer lines provided more vigorous early season growth and increased biomass and rubber yields (Ray et al., 1999). Because of the growth and yield characteristics for newer lines, a standard plant population now used for guayule production is 27,000 plants/ha (Coffelt et al., 2009; Coffelt and Ray, 2010), or ≈1/2 of the Mesa, Yuma, and El Paso plant populations. Moreover, the studies conducted in the 1980s were on a small-scale plot size, where typically six to 12 whole plants per plot were harvested to determine final yield.

Rasutis et al. (2015) stressed the importance of achieving well-managed and sustainable guayule production systems. A critical focus area involves improved methods of irrigation management for guayule to attain higher water use productivity. This is particularly important for accomplishing large-scale guayule commercialization envisioned to occur in the arid US Southwest (Cardwell, 2015; Tulio, 2015), where ETc rates and irrigation requirements are among the highest in the nation. To expand current guayule irrigation management in the US Southwest desert, we initiated a 29-month guayule irrigation field study in central Arizona in 2012. The study was conducted in larger-scale production plots utilizing a guayule cultivar that is currently being commercially produced in the Southwest, albeit on a limited scale. The objectives included determining guayule biomass and rubber yield responses to irrigation water application amounts and evaluating irrigation scheduling strategies aimed at maximizing biomass, rubber yield, and water productivity under surface irrigation, the most commonly used method in the area.

2. Materials and methods

2.1. Experimental details

A guayule irrigation study was conducted from October 2012 through March 2015 within a 1.4-ha field site at The University of Arizona, Maricopa Agricultural Center (MAC) (33°04′N, 111°58′W, elevation 361 m above mean sea level), in central Arizona, US. The irrigation method was level furrow (Martin and Gilley, 1993), a common surface irrigation method used in the area. Prior to the study, the field was laser-leveled to a uniform but slight 0.02% grade in the direction of irrigation water flow. The field-site soil is mapped as a Casa Grande series (Fine-loamy, mixed, superactive, hyperthermic Typic Natrargids) (Post et al., 1988). These soils are deep, well-drained, and comprise predominately sandy loam and sandy clay loam textures. Daily meteorological data, including rainfall, were provided by the Arizona Meteorological Network (AZMET; Brown, 1989) weather station at MAC, located ≈200 m from the field site. The AZMET station also provided daily grass reference evapotranspiration (ETo) calculated by the ASCE Standardized Penman-Monteith equation (Allen et al., 2005) as well as, daily growing-degree-day (GDD) heat units based on upper and lower temperature limits of 30 °C and 12.8 °C, respectively (Brown, 1991). The MAC site is located in the Northeastern Sonoran Desert and is characterized by high evaporation rates and low precipitation. Historical average ETo and rainfall (1990–2014) recorded by AZMET at MAC is 1880 mm and 169 mm per year, respectively. Typical maximum temperatures in June, July, and August are 40 °C and above. The winter months of December and January can be cold, where minimum temperatures often fall below 0 °C. Measured climatic parameters during the 29 months between October 2012 (planting) and March 2015 (final harvest) are summarized in Table 1. The monthly climate data for two primary growing years of 2013 and 2014 were not markedly different, except during the months of January and February when air temperatures were particularly low during those months in 2013 (Table 1). Total rainfall for the entire 2013 and 2014 years was 194 and 207 mm, respectively, typical amounts of rainfall in central Arizona. During the hot summer months of June-August, the mean air temperature and vapor pressure deficit (air dryness) were about 3% and 7% higher in 2013 than in 2014, while the daily ETo for the summer months was about 0.27 mm/d higher in 2013 than in 2014. However, annual ETo for 2013 was 1878 mm, just slightly higher than annual ETo for 2014, 1855 mm.

On October 18–19, 2012, 95-day old greenhouse-grown guayule seedlings of 'Yulex-B' (Sanchez et al., 2014) were transplanted using a 2-row, rotary vegetable planter, pulled behind a farm tractor. The planter was calibrated to place one ≈100-mm tall seedling every 0.36 m along 80 raised bed rows. The rows were 100 m long and were spaced 1.02 m apart giving an initial transplant population of 27,000 plants/ha. Following transplanting, the guayule plants were established by applying alternate-furrow irrigations, five times between October 18 and November 20, 2012. Establishment irrigations were managed by the MAC Irrigation Supervisor who estimated a total of 585 mm was applied.

2.2. Irrigation treatments, soil water content measurements, and crop evapotranspiration

The experimental design was a randomized complete block consisting of five irrigation treatments, replicated in three blocks. Each of the 15 plots in the study were five rows wide (north–south) and 100 m long (east to west). Prior to imposing irrigation treatments, all plots received 122 mm of water on February 28, 2013 applied by MAC personnel. For the remainder of the study, irrigation water was individually delivered to the five-row plots through a 216-mm diameter, plastic pipe, installed across the west end of the field on a raised berm. Slide gates were installed along the plastic pipe at 1.02-m spacing to allow separate flow streams to the furrows within each plot. Border dikes formed between adjacent five-row plots at the irrigation water inlet end and at the bottom end of the field protected against irrigation water run-on and runoff to furrows in adjacent treatment plots. Starting on April 15, 2013, the irrigation flow rate and volume for each irrigation event in the

Table 1
Monthly climate data summary during the October 2012 to March 2015 guayule surface irrigation study at the Maricopa Agricultural Center, Maricopa Arizona.

Year	Month	Monthly daily means							Monthly total
		T_{max} (°C)	T_{min} (°C)	VPD (kPa)	Rad. (MJ/m^2)	2-m wind (m/s)	GDD (°C–d)	ETo (mm/d)	Rain (mm)
2012	October	32.7	13.4	2.1	18.4	1.5	9.8	4.3	0.0
	November	26.7	6.3	1.3	13.8	1.0	5.5	2.4	2.0
	December	19.0	3.1	0.7	11.3	1.4	1.9	1.8	17.5
2013	January	17.4	0.5	0.7	12.0	1.4	1.6	2.0	30.5
	February	19.2	2.7	0.8	16.4	1.7	2.0	2.8	4.3
	March	27.4	8.3	1.6	20.3	1.6	6.3	4.4	14.5
	April	30.6	11.5	2.2	26.3	2.3	8.3	6.6	2.0
	May	35.1	17.2	3.1	28.9	2.5	12.0	8.3	0.0
	June	41.8	22.2	4.5	29.7	2.3	15.0	9.3	0.0
	July	40.0	26.3	3.4	24.0	2.3	16.3	7.8	7.4
	August	39.5	24.2	3.2	21.7	1.9	15.6	6.8	7.6
	September	36.5	19.7	2.4	20.8	1.5	13.2	5.4	33.3
	October	29.9	9.3	1.7	18.3	1.4	7.5	3.9	0.0
	November	24.4	7.2	1.0	12.6	1.4	4.6	2.6	74.9
	December	18.5	2.2	0.6	11.5	1.3	1.7	1.8	19.8
2014	January	21.9	1.9	0.9	12.8	1.2	2.9	2.2	0.0
	February	24.5	5.2	1.2	15.0	1.3	4.4	3.0	0.0
	March	26.6	8.5	1.5	20.4	1.8	5.8	4.5	29.0
	April	29.9	11.9	2.2	24.9	2.2	8.2	6.3	0.0
	May	34.6	16.3	3.0	27.9	2.3	11.3	7.8	0.0
	June	40.6	21.3	4.2	30.3	2.0	14.6	8.7	0.0
	July	40.3	25.6	3.4	26.2	2.0	16.1	7.9	53.9
	August	37.9	23.3	2.8	23.4	1.9	15.1	6.6	16.5
	September	36.1	22.1	2.2	20.4	1.8	14.3	5.6	69.4
	October	32.0	14.5	1.6	17.1	1.2	10.1	3.7	9.1
	November	25.2	5.7	1.2	14.5	1.5	4.9	2.9	0.0
	December	18.5	4.1	0.5	10.1	1.1	1.9	1.5	29.5
2015	January	19.6	3.8	0.6	11.0	1.4	2.3	2.0	23.4
	February	24.4	7.0	0.9	15.5	1.6	4.5	3.1	0.0
	March	28.6	9.6	1.7	20.6	1.8	7.0	4.7	8.4

Note: Tmax = maximum temperature; Tmin = minimum temperature; VDP = vapor pressure deficit; Rad. = radiation (solar); 2-m wind = wind speed at 2.0-m height; GDD = growing degree days; ETo = grass reference evapotranspiration. Data were obtained from the AZMET weather station (Brown, 1989) located at the Maricopa Agricultural Center.

study were measured with a calibrated in-line propeller-type water meter, placed 4.0 m before the entry point of the plastic gated-pipe system.

Field-calibrated, neutron moisture meters were used to measure volumetric soil water contents (θ_v) from 0.10 to 2.5 m below the surface in 0.20 m increments. Installation of the neutron access tubes was made using a tractor-mounted soil sampler. Installation was delayed until early April 2013 to give the guayule transplants time to establish without disturbances from the tractor and worker traffic necessary in tube installation. Five, 2.6-m long, metal access tubes were installed vertically in the soil along the length of each plot at distances of 10, 30, 50, 70, and 90 m from the irrigation inlet (75 tubes total). The access tubes were located in the middle row, viz., row 3, in each 5-row plot. Measurements of θ_v were begun on April 5, 2013 and continued through March 13, 2015. From April through early November when guayule growth was active, θ_v measurements were made every 7–11 days at all 75 tube locations, except during October 2013 when θ_v was measured only once in plots due to a 17-day US government shutdown that occurred in that month. During slower-growth months from mid-November through March, θ_v was measured about every two to three weeks at all tube locations. During installation of the access tubes, soil samples from 0 to 1.8 m were collected in 0.3 m increments at all locations. The soil samples were immediately analyzed in the laboratory to determine the upper ('field capacity') and lower ('permanent wilting point') volumetric soil water contents. Field capacity (FC) and permanent wilting point (PWP) soil water contents were determined at the −0.33 kPa and −1500 kPa soil matric potentials, respectively, using pressure membrane extractors. The soil samples were also analyzed for soil particle size fraction (soil texture) using the Bouyoucos hydrometer method (Gee and Bauder, 1986).

Differential irrigation amounts to treatments were initiated on May 8, 2013, six months after planting. One irrigation treatment, designated as $I_{100\%}$, served as a control treatment, whose irrigation scheduling was intended to provide ample soil water within the crop root zone depth (Z_r) so that full crop evapotranspiration would not be reduced due to soil water stress. Irrigation scheduling for the $I_{100\%}$ treatment was based on the depletion of total available water (TAW), defined as the total amount of water the soil can store between FC and PWP over the crop root zone depth (Martin and Gilley, 1993). Irrigations were applied when the average measured available soil water (ASW) over Z_r for the $I_{100\%}$ treatment was 35–40% of TAW, i.e., when the soil water depletion percentage (SWD_p) reached 60–65%:

$$SWD_p = (1 - (ASW/TAW)) \times 100\% \qquad (1)$$

where ASW and TAW are in mm and SWD_p is percent. Allen et al. (1998) in their FAO-56 publication, tabulated an allowable soil water depletion percentage for many principle agricultural crops. The allowable SWD_p (denoted as the p fraction in FAO-56) is the maximum soil water depletion of the TAW within Z_r that can occur before the effects of soil water stress cause a reduction in full ETc. Although guayule was not included in FAO-56, Allen et al. (1998) recommended a maximum SWD_p of 65% for crops that maintain full ETc under dry soil conditions (i.e., drought tolerant crops). The Bucks et al. (1985a) results suggested an allowable SWD_p for guayule could be as high as 70–75%. However, to minimize reductions in full ETc for the $I_{100\%}$ treatment, we used a lower allowable SWD_p of 60–65%. For irrigation scheduling of the $I_{100\%}$ treatment, the Z_r was estimated at a 1.2-m depth for the first 7 months after planting (through late May 2013), the same root depth used by Bucks et al. (1985a) for scheduling during the first six month after planting their guayule experiment. From June 2013 onward, we used a Z_r of 2.0 m, slightly different than the 1.8-m depth used by Bucks et al. (1985a) after six months. The amount of soil water storage (SWS) at field capacity over Z_r was calculated by Eq. (2) using the lab analyses of soil water contents for FC determined at each sampling depth (D_i) and sampling location of the treatment replicates:

$$SWS_{FC} = \sum_{i=1}^{j} \theta_{FC,i}\ D_i \times 10 \tag{2}$$

where SWS_{FC} is soil water storage at field capacity over the crop root zone depth in mm, $\theta_{FC,i}$ are the field capacity soil water contents (%) determined at each incremental D_i. The D_i are 0.3-m soil sample depths (e.g., 0–0.3 m, 0.3–6 m, etc.), except a D_i of 0.5 m was used with the $\theta_{FC,i}$ determined at 1.5–1.8 m to account for the SWS over the 2.0 m Z_r. Similarly, the SWS at PWP (SWS_{PWP}) over Z_r was calculated using Eq. (2) by replacing $\theta_{FC,i}$ with the lab analyzed $\theta_{PWP,i}$ for each depth, D_i. Thus, TAW over Z_r for each treatment location was computed as the difference between SWS_{FC} and SWS_{PWP}.

The measured soil water storage (SWS_m) for the root zone was calculated by Eq. (3) for each of the 15 locations in the treatment using the 0.2-m incremental measurements of the soil water contents summed over the crop root depth zone:

$$SWS_m = \sum_{i=1}^{j} 0.2\ (\theta_{vi}) \tag{3}$$

where SWS_m is the measured soil water storage over Z_r in mm, $\theta_{v,i}$ are the volumetric soil water contents at each incremental 0.2-m measurement depth, from 0.1 m to 1.1 m for a Z_r of 1.2 m, and from 0.1 to 1.9 m for Z_r of 2.0 m. The available soil water over Z_r (Martin and Gilley, 1983) was calculated as:

$$ASW = SWS_m - SWS_{PWP} \tag{4}$$

and the soil water depletion (SWD) was calculated as:

$$SWD = SWS_{FC} - SWS_m \tag{5}$$

where all units were in mm.

The measured data used in determining irrigation scheduling for the $I_{100\%}$ treatment (Eqs. (1)–(5)) were applied in daily soil water balances computed for each location to project SWD and percent depletion for days following θ_v measurements. The soil water balances were used to anticipate when average SWD_p for the $I_{100\%}$ treatment would be at 60–65%. Projection was necessary since the θ_v data collection was weekly or longer and a day or two of planning was needed before an irrigation event took place. The irrigation application amounts applied for the $I_{100\%}$ were intentionally planned to replace 70–80% of the estimated SWD at each irrigation to minimize deep percolation (DP) losses that could occur if irrigation amounts replaced 100% of the SWD. All four of the other irrigation treatments were governed by the $I_{100\%}$ irrigation dates and application amounts. The four treatments were designated as $I_{40\%}$, $I_{60\%}$, $I_{80\%}$, $I_{120\%}$, and received 40%, 60%, 80%, and 120% of the irrigation amount applied to the $I_{100\%}$ at each irrigation, respectively.

Soil texture was not appreciably different among the 75 field locations. Field average sand, silt, and clay fractions over a 1.8-m soil depth were 64, 15, and 21%, respectively (Table 2), fractions typical of the sandy clay loam soils at MAC. The volumetric soil water contents determined for FC and PWP averaged over 1.8 m varied somewhat by irrigation treatment, 23.7–26.0% for FC and 12.4–13.5% for PWP (Table 2). The influence of FC and PWP among irrigation treatments accounted for some of the variation among treatments in TAW. While total available water for all locations averaged 236 mm, average TAW for individual irrigation treatments was lowest for $I_{80\%}$ (219 mm) and highest for $I_{60\%}$ (251 mm).

Prior to initiating irrigation treatments, 30 mm of water was applied to all plots on April 15, 2013. During this irrigation, nitrogen fertilizer in the form of urea-ammonium-nitrate (UAN) was injected into the water to all plots at a rate of 32 kg N/ha. A second UAN fertilizer application of 32 kg N/ha was applied during irrigation of all plots on July 13, 2013. A third and final UAN application was applied to all plots during irrigations on March 18, 2014, at a rate of 64 kg N/ha. Weed control in plot furrows was accomplished using a vegetable cultivator in February, April and July 2013. Starting in September 2013, weeds were controlled manually.

Crop evapotranspiration (ETc) for all treatments was determined beginning in April 2013 following the installation of neutron probes, ≈six months after planting. The ETc was calculated using the soil water balance method (Jensen et al., 1990) for each successive interval between two soil water content measurement dates starting from April 5, 2013 and ending on March 13, 2015. Eq. (6) shows the soil water balance components for determining ETc:

$$ETc = R + IW - DP + \Delta S \tag{6}$$

where ETc is in mm, R is measured rainfall (mm), IW is measured irrigation water (mm), DP is deep percolation (mm), and ΔS is the change in soil water storage between measurement dates determined using Eq. (3) (mm), assuming a crop root zone depth of 2.0 m for all treatments. For soil water balance measurement intervals that included irrigation and/or rainfall, DP was evaluated by calculating the change in SWS below the 2.0-m root zone, i.e., for the soil depth from 2.0 to 2.6 m. During these intervals, an increase in SWS of 1.0 mm or more below the root zone was considered to be DP and the amount was included in the Eq. (6). Since plots were blocked by dikes on all sides, runoff of irrigation water or rainfall was considered to be negligible. Cumulative ETc was determined as the summation of the interval measurements. Measurements to

Table 2
Soil texture and soil water retention properties for five guayule irrigation treatments at the Maricopa Agricultural Center, Maricopa Arizona.

Soil property	Irrigation treatment[a]					
	$I_{120\%}$	$I_{100\%}$	$I_{80\%}$	$I_{60\%}$	$I_{40\%}$	Field average[b]
Sand (%)	64 ± 8	62 ± 10	66 ± 9	64 ± 8	62 ± 7	64 ± 9
Silt (%)	15 ± 5	16 ± 5	15 ± 6	14 ± 6	15 ± 6	15 ± 5
Clay (%)	21 ± 6	24 ± 6	19 ± 6	22 ± 5	23 ± 5	21 ± 6
Field capacity (%)	24.2 ± 4	26.0 ± 6	23.7 ± 4	25.2 ± 5	24.9 ± 6	24.8 ± 4
Permanent Wilting point (%)	12.6 ± 5	13.5 ± 4	12.6 ± 3	12.4 ± 6	12.8 ± 2	12.8 ± 3
Total available water (mm)	228 ± 28	247 ± 34	219 ± 28	251 ± 32	237 ± 29	236 ± 32

[a] Irrigation treatment data for soil texture fractions, field capacity, and permanent wilting point are averaged over all six 0.3-m depths and over all 15 soil sampling locations per treatment over a 0–1.8-m depth. Total available water data were calculated for all locations by SWS_{FC} minus SWS_{PWP} over a crop root zone depth of 2.0 m (using Eq. (2)) and are presented as averages for each treatment. ± are plus one and minus one standard deviation of the average.

[b] Field average data are calculated over all 75 sampling locations in the field.

separate the soil evaporation and transpiration contributions of ETc were not made.

2.3. Plant growth and destructive sampling

Guayule canopy height and canopy cover measurements commenced in April 2013. Measurements were made for three plants in each plot ≈every 25 days from April to November 2013, for six plants in each plot ≈ every 36 days from February to September 2014, and for five plants on March 9, 2015. Destructive whole plant samples were harvested by hand for each plot three times between July and November 2013, and four times between February and September 2014. A final destructive hand harvest of whole plants was made on March 9, 2015, about two weeks prior to a final bulk harvest made in late March. During destructive harvests, the plants were extracted from the soil to a depth of ≈0.1 m below the soil surface. All plant measurements and plant harvests were limited to the three inner rows (rows 2, 3, and 4) of each 5-row plot to minimize the influence on plant growth due to irrigation from adjacent treatment plot furrows. The sample locations along the 100-m long rows were at a distance of ≈10, 50, and 90 m (in 2013), ≈10, 25, 40, 55, 70, and 90 m (in 2014), and ≈10, 30, 50, 70, and 90 m (in 2015) from the irrigation water inlet. Fresh biomass weights obtained from whole plant harvests were immediately measured and then dried in open greenhouses for 2–4 weeks, depending on the weather. Each biomass sample was periodically weighed until there was no significant change in dry weight. After drying, the plants in each plot were chopped and ground with a chipper/shredder. The samples were analyzed for resin and rubber by the University of Arizona, Tucson. Resin and rubber concentrations were determined through a sequential extraction, in which, acetone was first used to extract resin. When the acetone extraction was completed, cyclohexane, a strong organic solvent, was used to extract the rubber. The extraction protocol closely followed the methods recommended by Cornish et al. (2013).

2.4. Final harvest

Final bulk harvest of the irrigation study took place on March 25 and 26, 2015 when entire 100-m lengths of two plant rows (rows 2 and 3) were bulk-harvested for each of the 15 plots. The equipment used was a modified potato-digger harvester that pulled two rows of plants including main roots up to the surface. All removed plants from the two rows of each plant were loaded onto a trailer and immediately weighed on a large truck-scale on the MAC farm. The concentration of moisture in the fresh weights of the bulk final harvests and the resin and rubber contents were determined from the destructive samples within each plot taken during hand-harvests on March 9, 2015. The dry biomass (DB) in kg/ha was multiplied by the rubber and resin concentrations to obtain final rubber and resin yields (Ray et al., 2005), respectively. The water productivity (WP) of the total water applied during the 29 month field study was calculated as the ratio between yield and TWA (kg/m^3) using the dry biomass and yield data obtained from final harvest.

Prior to bulk harvests, each plant within the entire 2-row lengths was counted to obtain actual harvested plant populations. This was necessary since a significant number of the initial transplanted guayule seedlings had not survived. The plant loss was due to several factors, of which, the exposure of young plants to unusually cold temperatures that occurred during the first winter, six to ten weeks after transplanting, was likely the leading cause. Other factors causing non-survival of plants included improperly rooted seedlings during transplanting, destruction of some plants during cultivator operations, and recurring plant removal during destructive harvests.

2.5. Statistical analysis

Irrigation treatment effects for ETc, plant growth parameters, DB, rubber and resin contents, final yields, and water productivity were analyzed statistically using a randomized complete block model within the Proc Mixed procedures of SAS (SAS Institute Inc., 2009). The Proc Mixed estimation method used the residual maximum likelihood (REML) option. Block and block x irrigation treatment were considered random effects, while irrigation treatment was the fixed effect with four degrees of freedom. The error term had eight degrees of freedom. The COVTEST option in Proc Mixed was used to test the block and interaction effects. Inferences about treatment trends were made using linear and quadratic estimates within Proc Mixed within the 'Estimate' statement. Treatment means were separated using the Pdiff (least significance difference, LSD, at $p = 0.05$) option.

3. Results

3.1. Irrigation

Total irrigation to the $I_{100\%}$ treatment for 2013 averaged 1315 mm, which included 122 mm (Feb.) and 30 mm (early Apr.) applied equally to all treatments (Table 3). The $I_{120\%}$ treatment received 17% more irrigation than the $I_{100\%}$, and the $I_{80\%}$, $I_{60\%}$, and $I_{40\%}$ received 82, 65, and 49% of the irrigation applied to the $I_{100\%}$ in 2013, respectively. The variation between the actual and intended irrigation amounts based on the $I_{100\%}$ irrigation amount for the four treatments was mainly due to the equal irrigation amounts applied to all treatments during the February and April irrigations of 2013. In addition, all treatments received 194 mm of rain in 2013 (Table 3). In 2014, the $I_{100\%}$ treatment received an average of 1673 mm of irrigation (Table 3). The $I_{120\%}$ treatment received 20% more irrigation than the $I_{100\%}$, whereas the $I_{80\%}$, $I_{60\%}$, and $I_{40\%}$ received 79, 58, and 38% of the $I_{100\%}$ irrigation in 2014, respectively. All treatments received 207 mm of rain in 2014. Only one irrigation was applied to treatments in 2015 (Table 3). This early February irrigation was given at the break of winter dormancy, prior to final bulk harvests in late March. During the 29 month period from late October 2012 to late March 2015, the total water applied to the $I_{100\%}$ treatment was 4125 mm (Table 3). For the same period, the $I_{120\%}$ treatment received 14% more in TWA than the $I_{100\%}$, and the $I_{80\%}$, $I_{60\%}$, and $I_{40\%}$ received 85, 71, and 57% of the TWA applied to the $I_{100\%}$, respectively. The TWA was significantly different between each irrigation treatment at $p < 0.01$. Prorated on an annual basis for the 29 month period, TWA for the $I_{100\%}$ treatment was about 1770 mm/year. For the $I_{120\%}$, $I_{80\%}$, $I_{60\%}$, and $I_{40\%}$ treatments, the TWA on an annual basis was 1950, 1460, 1210, and 980 mm/year, respectively.

3.2. Soil water depletion

Periodic changes of measured percent soil water depletion (measured θ_v using Eqs. (1)–(3), are shown for the $I_{100\%}$ treatment in Fig. 1. For the 23-month period of measurements (April 2013 through March 2015), the SWD_p measured one to three days prior to irrigation for $I_{100\%}$ varied from 45 to 69%. On seven occasions average SWD_p prior to irrigation was above 65%, while the lowest SWD_p prior to irrigation (45 and 47%) occurred in mid-September 2013 and early-July 2014, respectively, when significant rain occurred a few days before the scheduled irrigations (Fig. 1). For the entire period, the average measured SWD_p for the $I_{100\%}$ was 59%, somewhat lower than the target allowable SWD_p range of 60–65%. Measured SWD_p following irrigations of the $I_{100\%}$ treat-

Table 3
Summary of rain and irrigation water applied to five treatments during the 2012–2015 guayule surface irrigation study at Maricopa, Arizona.

Year	Month	Rain (mm)	Irrigation treatments				
			$I_{120\%}$	$I_{100\%}$	$I_{80\%}$	$I_{60\%}$	$I_{40\%}$
			Irrigation water applied (mm)				
2012	October		260	260	260	260	260
	November		325	325	325	325	325
	Year total	20	585	585	585	585	585
2013	February		122	122	122	122	122
	April		30	30	30	30	30
	May		221	184	148 ± 1	111	78 ± 6
	June		242	202	162 ± 1	122 ± 1	81
	July		253	211	169	127	105 ± 12
	August		241 ± 2	203 ± 2	161	125 ± 3	81
	September		176	147	118 ± 1	89	64 ± 7
	October		254 ± 8	216	173	130	86
	Year total	194	1538 ± 10	1315 ± 2	1083 ± 3	855 ± 4	647 ± 24
2014	February		111 ± 2	92	73	55	37
	March		121	101	81	61	40
	April		143	120	96	72	48
	May		319	265	213	159	106
	June		374	311	248	187	126 ± 3
	July		307 ± 1	251	195	139	84
	August		156 ± 1	124 ± 3	97	65 ± 1	34
	September		298	248 ± 1	199	149	99
	November		182 ± 3	161 ± 19	120	90	60
	Year total	207	2010 ± 4	1673 ± 21	1322	977 ± 1	634 ± 3
2015	February		120	100	79	60	40
	Year total	32	120	100	79	60	40
Total	2012–2015	453	4253 ± 6	3672 ± 20	3069 ± 3	2478 ± 4	1906 ± 23
Total water applied (mm)			4706 ± 6	4125 ± 20	3522 ± 3	2931 ± 4	2359 ± 23

Notes: Establishment irrigation amounts were equally applied to all treatments in 2012 and on February 28, 2013.
All treatments received 30 mm of irrigation and 32 kg N/ha of fertilizer on April 15, 2013.
Differential irrigation treatments began on May 08, 2013.
All treatments were given 32 kg N/ha and 64 kg N/ha of fertilizer on July 08, 2013 and March 18, 2014, respectively.
Plus and minus (±) one standard deviation for treatments are shown for monthly and yearly totals for irrigation water applied when the SD was greater than one.
Rain provided in year total columns is that from transplanting on October 18, 2012 through final harvest on March 26, 2015.
Average treatment cumulative irrigation totals for the entire 2013–2015 period are followed by TWA for the same period.
Total water applied for treatments is the summation of all irrigation water applied (including for establishment) and all rain from transplanting to final harvest.

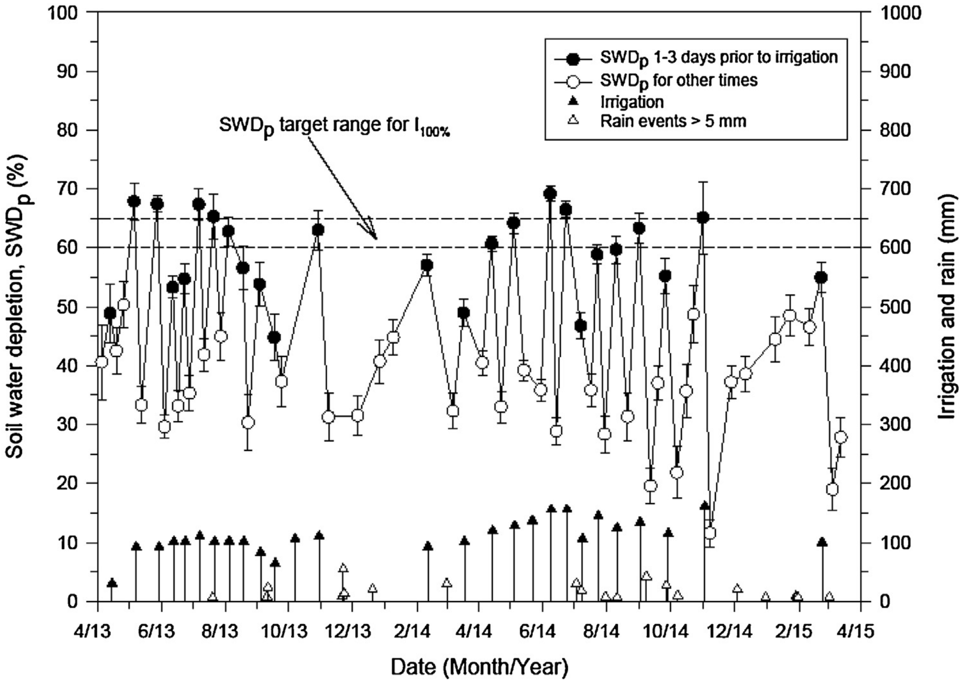

Fig. 1. Periodic changes of measured soil water depletion (SWD_p) and irrigation and rain events measured for the $I_{100\%}$ treatment during the guayule field study at Maricopa, Arizona. Note: error bars for SWD_p represent ± one standard deviation of the treatment average.

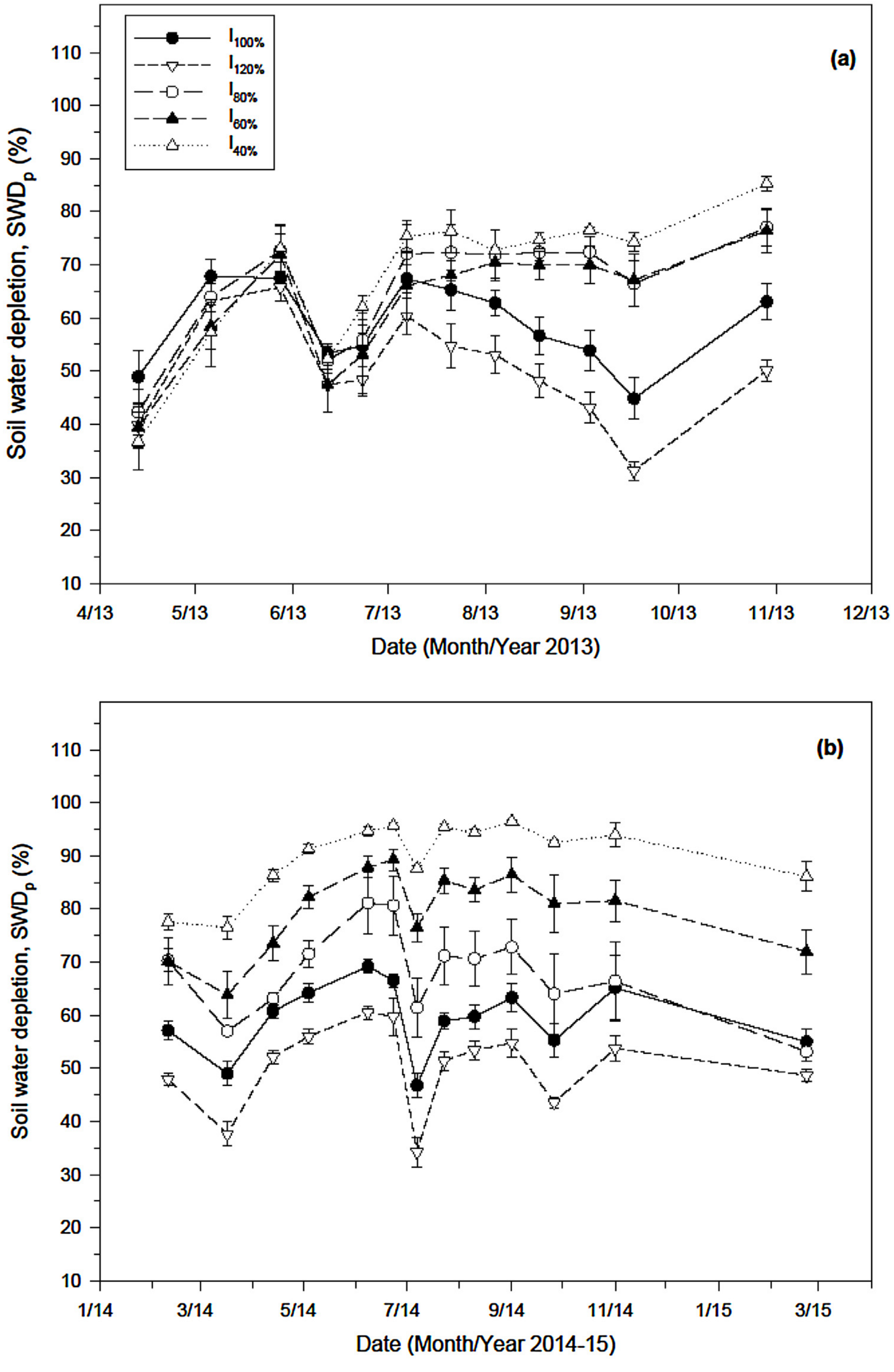

Fig. 2. Periodic changes of soil water depletion (SWD_p) measured one to three days prior to irrigation for all five irrigation treatments during the guayule field study at Maricopa, Arizona. Note: error bars for SWD_p represent ± one standard deviation of the average treatment.

ment (usually made four-five days later) varied from about 12–42% and averaged 31%.

The average SWD_p measured one to three days prior to irrigation are shown together for all treatments in Fig. 2a (2013) and b (2014–15). Separation of the prior-to-irrigation SWD_p between the $I_{100\%}$ and two drier treatments, $I_{80\%}$ and $I_{40\%}$, and the wettest treatment, $I_{120\%}$, was evident starting in mid-July 2013 (Fig. 2a). However, SWD_p separation between the $I_{100\%}$ and the drier, $I_{60\%}$ treatment, did not clearly appear until mid-August 2013. Unexpected trends in SWD_p occurred between $I_{60\%}$ and the $I_{80\%}$ treatment (which had more irrigation applied than $I_{60\%}$, but higher SWD_p) during 2013 (Fig. 2a) and persisted until mid-March 2014 (Fig. 2b). These trends in SWD_p could be attributed to lower available soil water for the $I_{80\%}$ than the $I_{60\%}$ treatment (Table 2), but also suggest that the $I_{80\%}$ treatment consumed proportionately more of its applied water in ETc than did the $I_{60\%}$ during the first year. By early-May 2014, the measured SWD_p had clearly separated among all treatments in a manner consistent to treatment irriga-

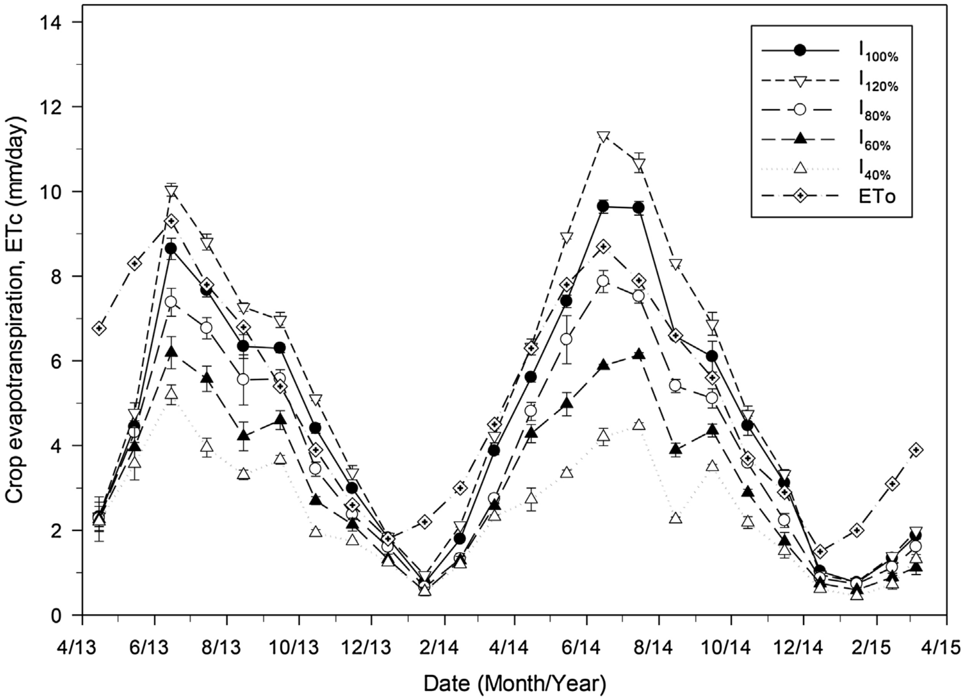

Fig. 3. Monthly ETc rates measured for five irrigation treatments and monthly ETo rates during the guayule field study at Maricopa, Arizona. Note: error bars for ETc represent ± one standard deviation of the average treatment. Data for April 2013 begins on April 5 and data for March 2015 ends on March 12.

tion amounts, and these treatment separations remained through late-September 2014 (Fig. 2b). For 2013, the SWD_p measured prior to irrigation for the $I_{120\%}$, $I_{80\%}$, $I_{60\%}$, and $I_{40\%}$ averaged 50%, 68%, 65%, and 71%, respectively, which compares to 60% for the $I_{100\%}$ treatment in 2013. While the average measured pre-irrigation SWD_p for the $I_{100\%}$, $I_{120\%}$, and $I_{80\%}$ treatments for the 2014–15 period (59%, 50%, and 68%, respectively) were almost identical to those in 2013, the average pre-irrigation SWD_p for the two driest irrigation treatments ($I_{60\%}$, and $I_{40\%}$) increased in 2014-15 to 80 and 90%, or by 15 and 19%, respectively. The SWD_p trends for the two driest treatments indicate higher water use in 2014 as plants in these treatments got larger and cumulative effects of continual low irrigation became more pronounced. For the $I_{120\%}$, pre-irrigation SWD_p was often below the two-year average of 50% throughout the study, and in some instances as low as 30–40% before irrigation. These lower SWD_p values prior to irrigation when coupled with the additional ≈20% in the irrigation amount over the $I_{100\%}$ suggest that DP occurred during some of the $I_{120\%}$ irrigations. Results on DP for treatments will be presented in Section 3.3.

3.3. *Crop evapotranspiration and soil water balance components*

Crop evapotranspiration (ETc) rates, presented as monthly averages (Fig. 3), varied from less than 1.0 mm/d during January in 2014 and 2015 to nearly 10.0 mm/d during June and July 2014 for the $I_{100\%}$ treatment. Monthly ETc rates were the highest among all treatments for the $I_{120\%}$ treatment from June through November 2013 and again from April through September 2014 (Fig. 3). The highest ETc rates for the $I_{120\%}$ treatment occurred in June in both 2013 and 2014. It was evident that more irrigation to the $I_{120\%}$ increased ETc rates over $I_{100\%}$ during most of 2013 and 2014. During the guayule growing period from May to August in 2014, ETc rates for the $I_{120\%}$ treatment were from 1.1 to 1.7 mm/d higher than for the $I_{100\%}$ treatment. During this period, the monthly ETc rates for the $I_{120\%}$ were 15–30% higher than the ETo rates, while they were 0–20% higher than the ETo for the $I_{100\%}$ during the same period (Fig. 3). This suggests that some reduction in full ETc due to soil water stress occurred for the $I_{100\%}$. A clear separation between daily ETc rates for the $I_{100\%}$ and $I_{80\%}$ also began in June 2013 and continued through November (Fig. 3). Similarly, from June through October 2013, ETc rates were higher for the $I_{80\%}$ than $I_{60\%}$, while the $I_{60\%}$ treatment also had higher ETc than for the $I_{40\%}$ during that same period. Monthly ETc rates for treatments were consistently separated based on irrigation treatment levels from May through September 2014. All treatments experienced a sharp decline in ETc rates during August in both 2013 and 2014 from the higher ETc rates that occurred during June and July (Fig. 3). The treatment ETc rates rapidly decreased starting in October in both 2013 and 2014, which coincided with decreased ETo.

The soil water balance equation components (Table 4) are presented for the 23-month period of the study from April 2013 through March 2015, during which cumulative ETc was determined. Cumulative ETc was significantly different between each irrigation treatment level in 2013, 2014, 2015, and for the total period from 2013 to 2015. This result agreed with significant treatment differences in irrigation water and TWA for the same measurement periods for each year (Table 4). Cumulative ETc was higher for all treatments in 2014 than 2013 and the increase varied from 8% ($I_{40\%}$) to 37% ($I_{120\%}$). Total cumulative ETc (April 2013 through March 2015) for the $I_{100\%}$ treatment was 19% higher than that for the $I_{80\%}$ treatment, though TWA for the $I_{100\%}$ for this period was 22% higher than for the $I_{80\%}$ TWA. On the other hand, the total cumulative ETc for the $I_{100\%}$ treatment was significantly less by 12% than for the $I_{120\%}$, again suggesting an occurrence of some soil water stress for the $I_{100\%}$.

The change in soil water storage over the 2.0-m guayule root zone (ΔS) from April 2013 to the end of 2013 correlated well with irrigation treatment levels during that period, where depletion of stored soil water (i.e., positive ΔS) increased significantly at decreased irrigation treatment level, except that between the two highest irrigation levels (Table 4). However, in 2013, the $I_{120\%}$ treatment had significantly more deep percolation from the root zone

Table 4

Treatment means for soil water balance components in 2013, 2014, 2015, and for total period from 2013 to 2015, where ETc is total crop evapotranspiration, IW is measured irrigation water, TWA is total water applied (irrigation plus measured rainfall), ΔS is the measured change in soil water storage of the root zone, and DP is measured deep percolation below the root zone.

Year[a]	Treatment	ETc (mm)	IW (mm)	TWA (mm)	ΔS (mm)	DP (mm)
2013	$I_{120\%}$	1533a	1416a	1561a	24d	52a
	$I_{100\%}$	1359b	1193b	1338b	34d	13b
	$I_{80\%}$	1189c	961c	1106c	90c	6c
	$I_{60\%}$	992d	733d	878d	122b	8bc
	$I_{40\%}$	809e	525e	670e	142a	3c
2014	$I_{120\%}$	2097a	2010a	2217a	5b	126a
	$I_{100\%}$	1830b	1673b	1880b	−3b	47b
	$I_{80\%}$	1483c	1322c	1529c	−37c	9c
	$I_{60\%}$	1199d	977d	1184d	16ab	2c
	$I_{40\%}$	880e	634e	841e	39a	0c
2015	$I_{120\%}$	89a	120a	152a	−40c	23a
	$I_{100\%}$	85a	100b	132b	−35c	11b
	$I_{80\%}$	74c	79c	111c	−34c	3c
	$I_{60\%}$	59d	60d	92d	−26b	7bc
	$I_{40\%}$	51d	40e	72e	−16a	5c
Total	$I_{120\%}$	3719a	3546a	3930a	−10d	201a
	$I_{100\%}$	3274b	2965b	3349b	−3d	71b
	$I_{80\%}$	2746c	2362c	2745c	18c	18c
	$I_{60\%}$	2250d	1771d	2155d	112b	17c
	$I_{40\%}$	1740e	1199e	1583e	166a	8c

For each year, different lower-case letters in a column indicate significant differences in treatments at the 0.05 level of significance.

[a] Data for soil water balance components began on April 5 and ended on December 31 for 2013; data began on January 1 and ended on March 13 for 2015.

(52 mm) than for all other treatments (Table 4). A small amount of DP (less than 10 mm) detected for drier treatments in 2013 occurred primarily during irrigations in April and May of that year. By the end of 2014, the three driest treatments ($I_{80\%}$, $I_{60\%}$, and $I_{40\%}$) had each gained substantial root zone soil water (less positive ΔS), albeit there were minimal DP losses from the root zone for those treatments. Increased root zone soil water storages at the end of 2014 occurred for the $I_{120\%}$ and $I_{100\%}$ but were small compared to those for drier treatments. However, both the $I_{120\%}$ and $I_{100\%}$ lost significant amounts of irrigation water from the root zone due to DP in 2014 (Table 4). Most of the DP losses for the $I_{120\%}$ and $I_{100\%}$ treatments in 2014 occurred during irrigations in late-March, mid-July, and late-September, periods when the root zone soil water depletion was particularly less than at other times (Fig. 2b). All treatments gained stored root zone soil water and lost water to DP to some extent when final soil water balance measurements were made in 2015. Both the ΔS and DP components for treatments in 2015 were effected by occurrences of rainfall in January and early February 2015, which were then followed by irrigation to treatments in late February 2015. These results indicate that the TWA provided to each treatment was more than needed to meet the treatment crop evapotranspiration during this short early 2015 period. Since final harvest occurred in late March 2015, the final irrigations to treatments in February 2015 may not have been needed.

The change in root zone soil water storage for the total measurement period was significantly affected by irrigation treatment (Table 4). The change in soil water storage from beginning to end of measurements was small for the three wettest treatments, though significantly different for the $I_{80\%}$ than the $I_{120\%}$ and $I_{100\%}$ treatments. The $I_{60\%}$ had significantly greater soil water depletion than the $I_{80\%}$, whereas the $I_{40\%}$ depletion was significantly greater than for $I_{60\%}$. In comparison of the two wettest treatments, the $I_{120\%}$ had 130 mm more DP than the $I_{100\%}$ treatment, while ΔS was essentially the same for the two treatments. The TWA to the $I_{120\%}$ for the total period was 580 mm more than for $I_{100\%}$. Thus, the additional losses in DP for the $I_{120\%}$ were more than offset by the higher TWA. Thus, the $I_{120\%}$ had significantly greater ETc than $I_{100\%}$.

3.4. Treatment growth and rubber and resin contents

Fig. 4a and b illustrate the development of guayule treatment plants over the course of the study. Plant height means (Fig. 4a) increased from ≈0.3 m in April 2013–0.62 to 0.68 m for the three wettest irrigation treatments ($I_{120\%}$, $I_{100\%}$, and $I_{80\%}$) by the end of July 2013. For the same period, plant heights increased to 0.45–0.51 m for the $I_{40\%}$ and $I_{60\%}$ treatments, respectively. Plant heights were significantly greater for the three wettest compared to the two driest treatments starting in mid-July 2013. However, plant measurements at the end of July and the end of August 2013 revealed slower growth in height occurred for the three wettest treatments during August compared to those for the $I_{60\%}$ and $I_{40\%}$ treatments (Fig. 4a). Little to no difference in plant height occurred among the three wettest treatments during 2014, nor at the last measurement date in March 2015. Plant height for the $I_{60\%}$ treatment was significantly greater than for the $I_{40\%}$ treatment during 2014 and 2015. Canopy cover (Fig. 4b) increased more rapidly for the $I_{80\%}$ than all other treatments through the end of July 2013, while mean differences in cover between the $I_{120\%}$ and $I_{100\%}$ treatments versus the $I_{60\%}$ treatment were not significant until the end of September 2013. However, as with plant height, the lack of increase in percent cover during August 2013 was apparent for the three wettest treatments, but not for the two driest treatments (Fig. 4b). As mentioned earlier, decline in ETc rates from July to August 2013 occurred for all treatments (Fig. 3). However, the reduced ETc during August appeared to be more associated to plant growth retardation for the three wetter than two drier treatments. Between February and May 2014, the rate of increase in canopy cover was much more rapid for the three wettest treatments compared to the $I_{60\%}$ and the $I_{40\%}$ treatments and the mean differences in cover during this period were significant. With the exception of the $I_{40\%}$, all treatments achieved cover of 90% or more by mid-June to early-July and the treatment differences in cover were small from this point on.

There were no treatment effects with time for guayule dry biomass (DB) until mid-November 2013 (Fig. 5). At mid-November, the $I_{40\%}$ treatment mean was significantly lower in DB than for the three wettest treatments, but it was not lower than mean DB for the $I_{60\%}$. The effects of irrigation treatment on DB occurred later in 2013 than those for plant height (i.e., mid-July), while the DB treatment trend was similar to the canopy cover trend during 2013. The DB for the three wettest treatments were significantly different from the two driest treatments for the February 2014 sampling, and the differences remained significant through the last destructive plant sampling in March 2015. In late April 2014, the $I_{80\%}$ had a significantly lower DB than both $I_{120\%}$ and $I_{100\%}$ treatments. However, the $I_{80\%}$ treatment subsequently achieved the same DB as $I_{120\%}$ and $I_{100\%}$ in July 2014 and beyond. Plant dry biomass for the three wettest treatments on the last sampling in March 2015 varied from 1.36 to 1.51 kg/plant and the DB means for these three treatments were not significantly different (Fig. 5). The final bulk harvest results, presented below in Section 3.5, revealed substantially lower dry biomass weights per plant for all treatments compared to the DB made at the last sampling in March 2015. While the periodic sampling of three to six plants per plot was useful for showing treatment effects on DB over the course of the study, greater emphasis is given to final treatment yields based on DB data obtained during final bulk harvest, where an average of 388 ± 29 plants were harvested for each plot.

Mean percent rubber for the $I_{40\%}$ was significantly higher than the other treatments on July 30, 2013 sampling (Fig. 6a). The $I_{60\%}$ treatment also had a significantly higher rubber content than the

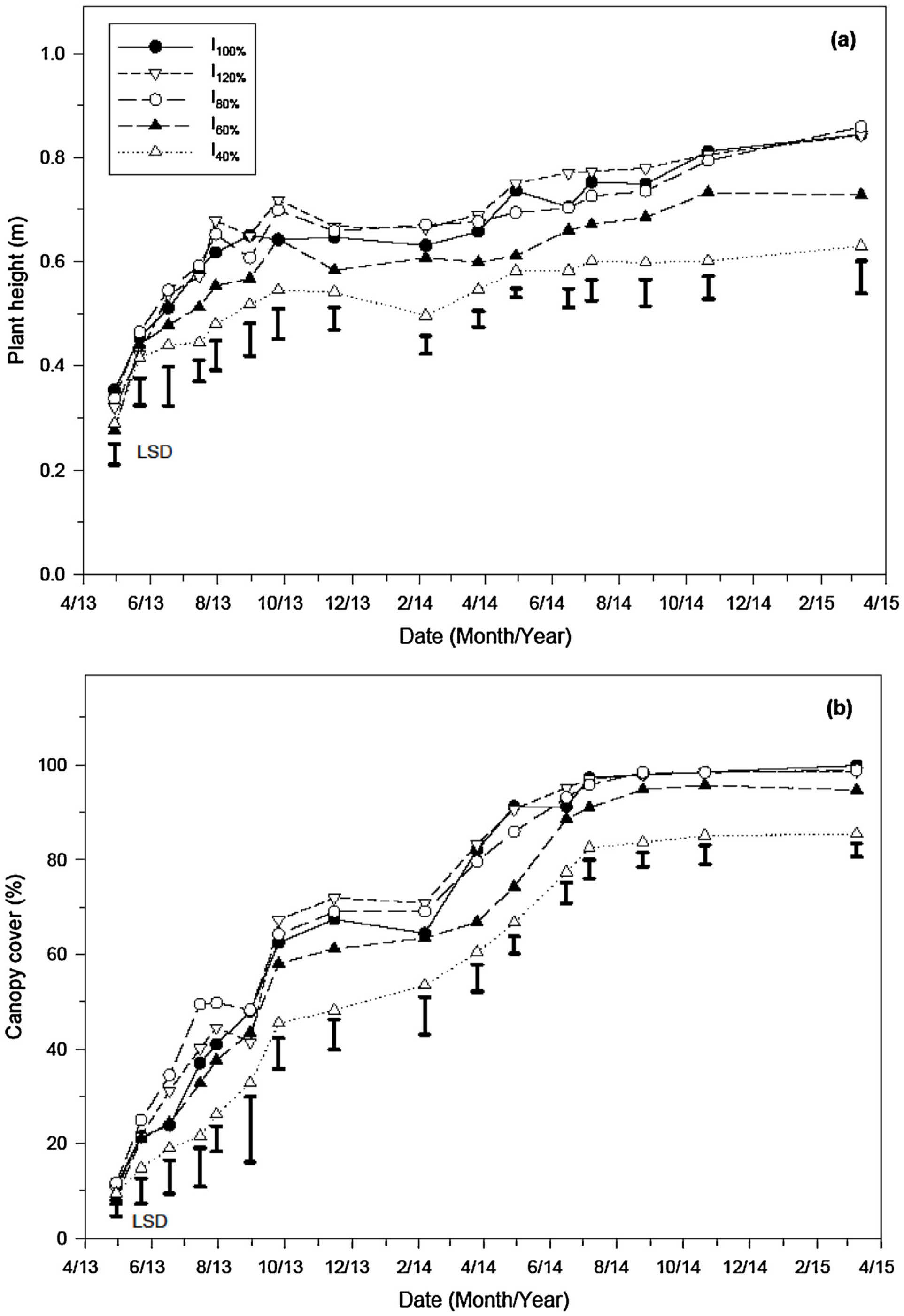

Fig. 4. Mean plant height (a) and mean percent cover (b) with time for five irrigation treatments in the guayule field study at Maricopa, Arizona. The least significant difference (LSD) at p = 0.05 is shown below the data for each measurement date.

$I_{100\%}$ and $I_{120\%}$ on that date. Differences in percent rubber for treatments were also significant in mid-November 2013, where the $I_{40\%}$ and $I_{60\%}$ had mean rubber percentages that were from 1 to 2% higher than for the three wetter treatments. Rubber content was significantly greater for the three driest versus the two wettest treatments ($I_{120\%}$ and $I_{100\%}$) in early February 2014. Significant differences between treatments for rubber content were not found for the remaining sample dates of 2014, though the trend was clearly for higher concentrations of rubber for the $I_{40\%}$ in 2014. On March 9, 2015, just before final bulk harvest, each treatment achieved its maximum rubber content (6.0–7.8%) (Fig. 6a). On this sample date, mean rubber content was highest for the $I_{40\%}$, followed by the $I_{60\%}$ and $I_{80\%}$ treatments, respectively. The rubber content for these three treatments was not significantly different, whereas only the $I_{40\%}$ had significantly greater rubber content than for the two wettest treatments (treatment data for the March 2015 rubber content sample is also presented in Table 5).

Resin concentrations were generally higher for the wetter irrigation than drier treatments during 2013, though the only significant difference among treatments occurred between the $I_{100\%}$ and $I_{40\%}$ in mid-November (Fig. 6b). Higher resin percentage was generally associated with increased irrigation during 2014, however, significant treatment differences were few. On March 9, 2015, resin percentage was similar among the three wettest treatments and

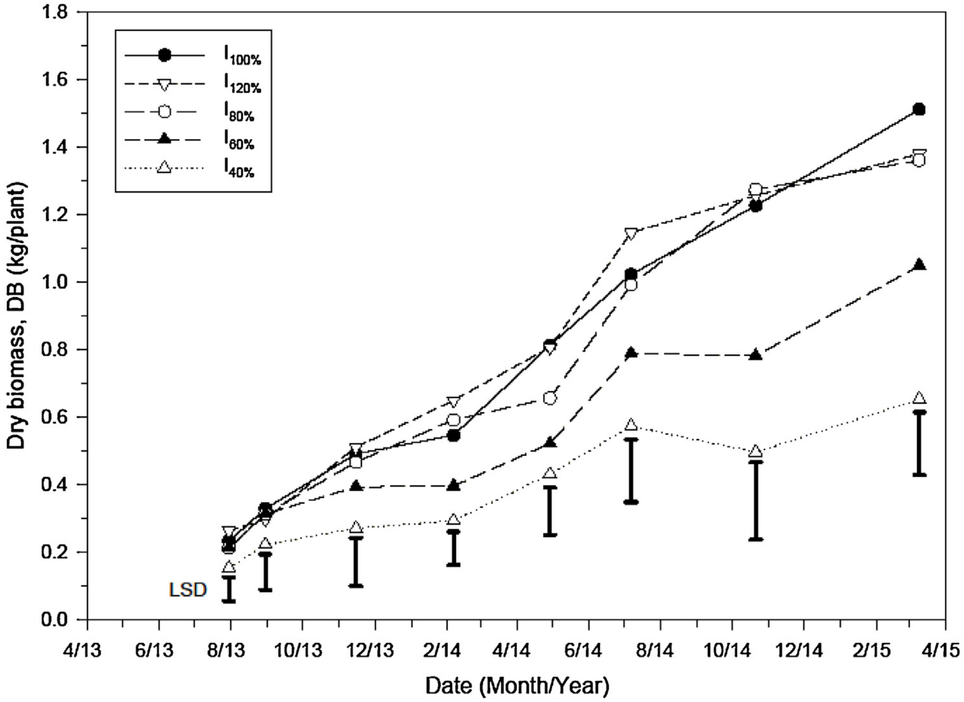

Fig. 5. Mean dry biomass with time for five irrigation treatments in the guayule field study at Maricopa, Arizona. The least significant difference (LSD) at $p = 0.05$ is shown below the data for each measurement date.

Table 5
Means for dry biomass, rubber and resin contents and yields, and the water productivity (WP) for dry biomass and yield at final harvest in March 2015 for five guayule irrigation treatments under surface irrigation in Maricopa, Arizona.

	Irrigation treatment				
	$I_{120\%}$	$I_{100\%}$	$I_{80\%}$	$I_{60\%}$	$I_{40\%}$
Variable					
Dry biomass (Mg/ha)[a]	27.9a	24.5b	22.64b	20.3c	15.7d
WP–dry biomass (kg/m^3)[b]	0.59b	0.59b	0.64ab	0.69a	0.67a
Rubber content (%)	6.02b	6.24b	6.82ab	6.97ab	7.79a
Rubber yield (kg/ha) [a]	1680a	1529ab	1547ab	1418bc	1221c
WP–rubber yield (kg/m^3) [b]	0.036b	0.037b	0.044ab	0.048a	0.052a
Resin content (%)	9.75a	9.06a	8.62ab	6.73b	8.17ab
Resin yield (kg/ha) [a]	2723a	2222ab	1942b	1362c	1285c
WP–resin yield (kg/m^3) [b]	0.058a	0.054a	0.055a	0.046a	0.055a

abcd indicate treatment variables followed by a different letter in a row were significantly different at the 0.05 level.

[a] Data based on a plant population of 27,000 plants/ha.

[b] WP is the ratio of dry biomass or yield per unit total water applied (TWA) from October 2012 through March 2015.

the means for $I_{120\%}$ and $I_{100\%}$ were significantly higher than for the $I_{60\%}$ but not the $I_{40\%}$ treatment (Table 5). Seasonal variations in resin content for treatments differed from those for rubber content during 2014 where resin content means sharply rose from 5 to 6% in late April to 7–10% in early July. This coincided with a large increase in the DB of treatments (Fig. 5) during the same period.

3.5. *Final yield and water productivity*

Means for final dry biomass after 29 months were significantly different among treatments with a near two-fold increase in mean DB from $I_{40\%}$ to $I_{120\%}$ (Table 5). Final yield of all 15 plots for DB for was highly linear with TWA, having a regression coefficient of determination (r^2) of 0.91 (Fig. 7a). The $I_{120\%}$ treatment achieved the maximum DB in the study with a mean of 27.9 Mg/ha. This was 14% greater than the mean DB for the $I_{100\%}$ and was achieved with 14% more TWA than that for $I_{100\%}$. For the three drier treatments ($I_{80\%}$, $I_{60\%}$, and $I_{40\%}$), final mean DB was 8, 17, and 36% lower than for $I_{100\%}$, respectively. However, final DB for the $I_{80\%}$ treatment was not significantly lower than that for the $I_{100\%}$ (Table 5), although the $I_{80\%}$ received 15% less TWA than $I_{100\%}$. Water productivity for dry biomass was significantly lower for the two wettest versus the two lowest irrigation treatments (Table 5), while the WP for DB under the $I_{80\%}$ treatment was not significantly different from that for any other treatment.

A maximum rubber yield of 1680 kg/ha for the $I_{120\%}$ treatment was significantly greater than RY for $I_{60\%}$ and $I_{40\%}$, whereas the RY means for the three wettest treatments were not significantly different (Table 5). However, RY for both the $I_{100\%}$ and $I_{80\%}$ were significantly greater than for the $I_{40\%}$. It is noteworthy that the $I_{80\%}$ treatment achieved a final mean rubber yield 92% of that for the $I_{120\%}$, while receiving 25% less total water applied. Similar to DB, the trend in RY was also linear with TWA with a regression r^2 of 0.48 (Fig. 7b). The higher within-treatment variation shown for rubber yield than for DB (Fig. 7a) was related to the treatment replicate differences in rubber contents. However, final RY was correlated significantly ($p < 0.01$) to final DB with an r value of 0.83 (data not shown). The mean WP for RY was greatest for the $I_{40\%}$ and $I_{60\%}$ treatments, and both were significantly greater than those for the $I_{100\%}$ and $I_{120\%}$ but not the $I_{80\%}$ (Table 5). Final resin yields also increased with irrigation level (Table 5). The three wettest treatments in Maricopa had significantly higher resin yield than the two driest treatments, but the WP of resin yield was not statistically different among treatments.

4. Discussion

The estimated 585 mm of irrigation used for guayule transplant establishment represented a significant portion of the total irrigation water applied to treatments during the study. However, guayule transplants in the US Southwest desert were more efficiently established using sprinkler irrigation, where only 380 mm of irrigation was applied for establishment in Yuma, Arizona (Bucks et al., 1985d). Guayule growers using surface irrigation should con-

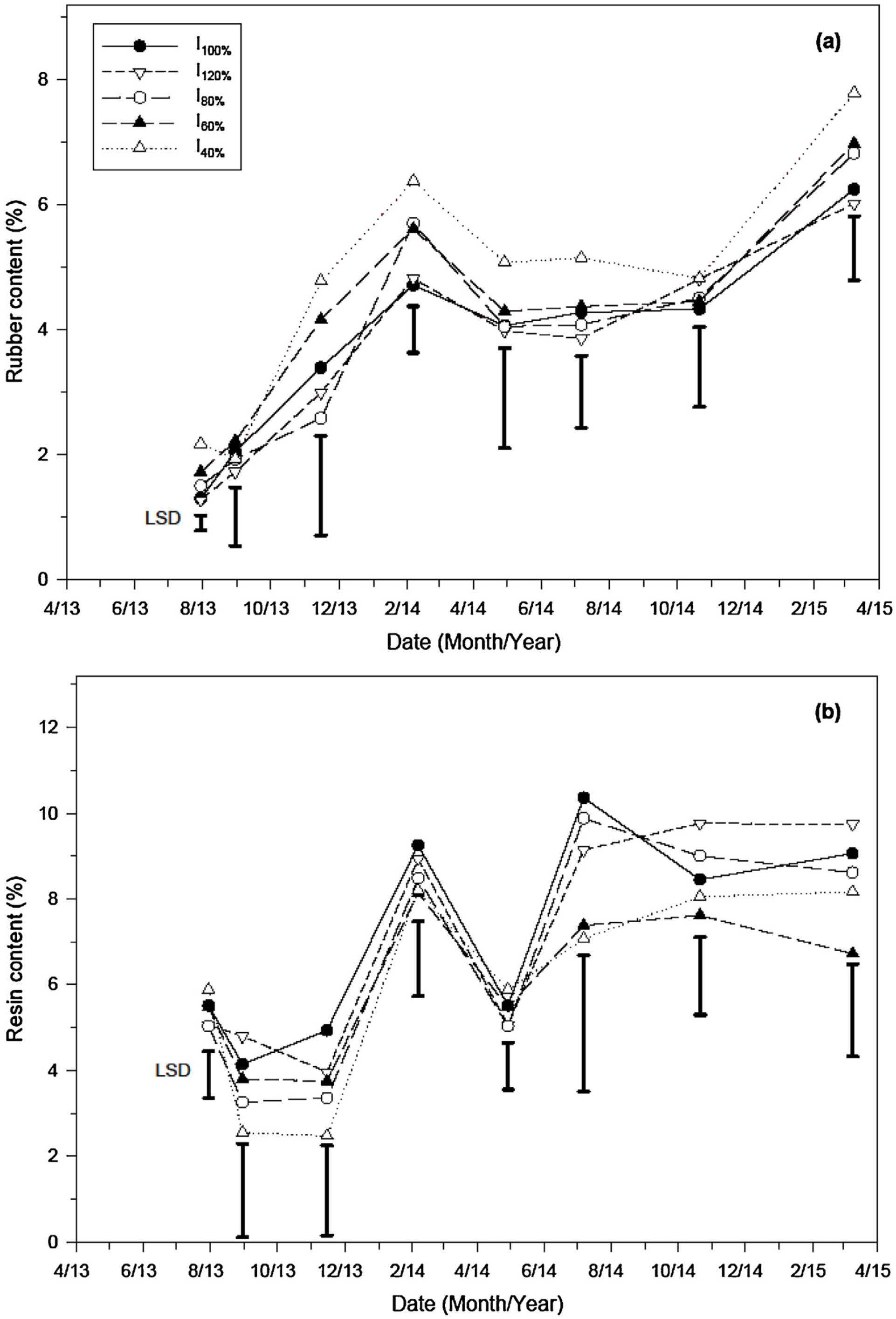

Fig. 6. Mean rubber content (a) and mean resin content (b) with time for five irrigation treatments in the guayule field study at Maricopa, Arizona. The least significant difference (LSD) at p = 0.05 is shown below the data for each measurement date.

sider the deployment of portable sprinkler systems as a means to reduce irrigation water used in plant establishment. On an annual basis, TWA for the $I_{100\%}$ and the $I_{120\%}$ treatments were 1770 and 1950 mm/year, respectively, somewhat less than the 2000–2220 mm annual TWA for the wetter treatments in the previous Arizona studies in the 1980s (Bucks et al., 1985a,d). While guayule is considered drought tolerant, it clearly requires significant irrigation in the US Southwest desert to achieve high biomass and rubber yields. Study results indicate irrigation requirements for guayule are similar to that for alfalfa (Erie et al., 1982), a major crop grown year-round in the area. Due to high evaporative water demand in the US Southwest desert, potential exists to reduce guayule irrigation water use by using sub-surface drip irrigation systems. Though soil evaporation was not measured separately from ETc in our study, it can be a large contributor to crop evapotranspiration when using surface irrigation systems, particularly before crop cover is complete. Burt et al. (2005) estimate that subsurface drip could reduce the evaporation from irrigation by about one-half.

In regards to irrigation scheduling, the SWD_p measured prior to irrigation for $I_{100\%}$ varied from 45 to 69% and averaged 59%, considerably lower than the Bucks et al. (1985a) average measured SWD_p

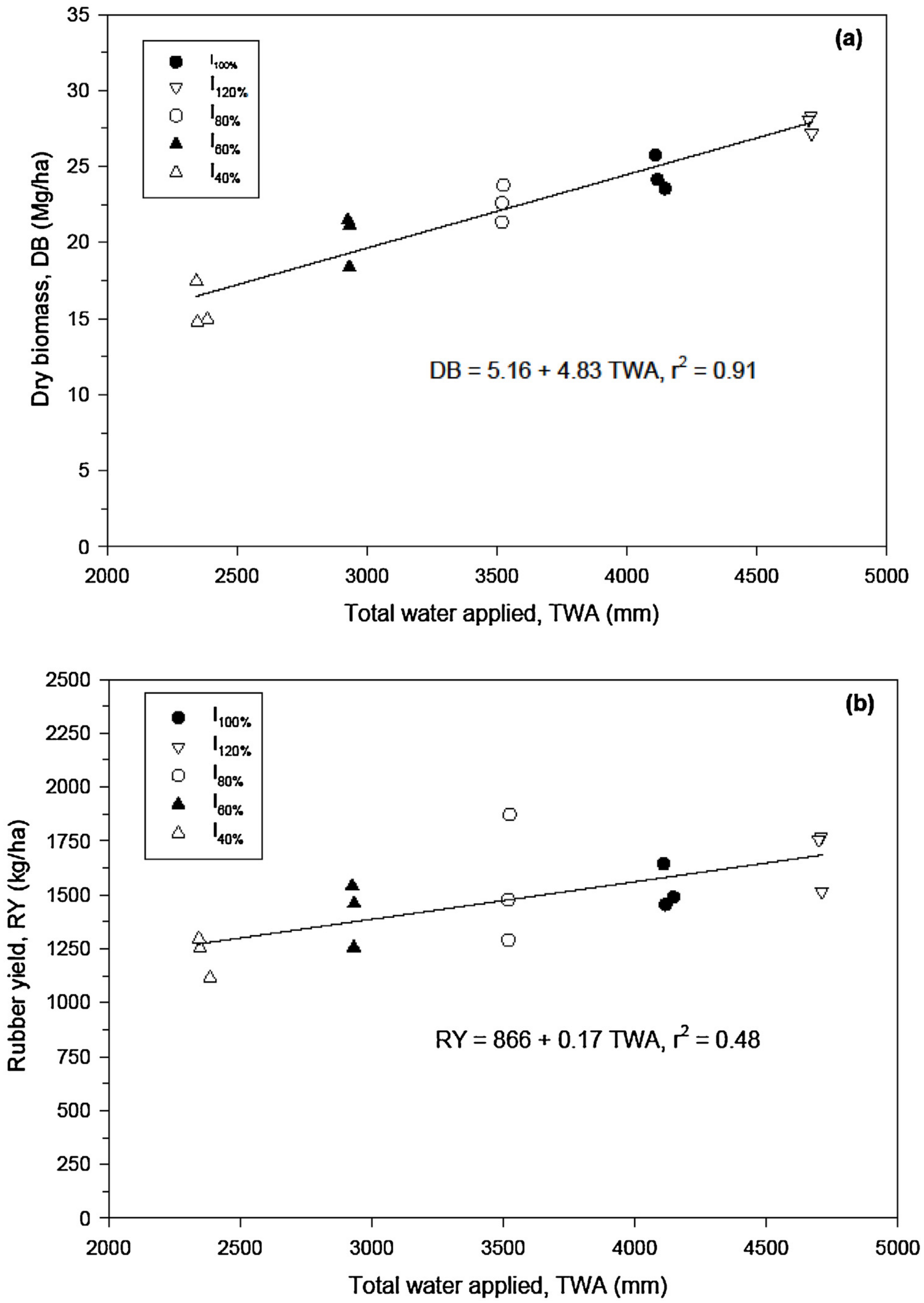

Fig. 7. Final dry biomass (a) and rubber yield (b) plotted against total water applied for five irrigation treatments in the guayule field study at Maricopa, Arizona. Regression functions in figures were derived from data for all 15 plot replicates.

of 72% for the wettest treatment. Miyamoto et al. (1984), however, reported significantly increased biomass and rubber yields when using SWD_p of about 45% versus using SWD_p of 60%. Benzioni et al. (1989) suggested that SWD_p for guayule should be less than 60%, although they did not report average SWD_p prior to irrigation. Because higher irrigation was applied to the $I_{120\%}$ than $I_{100\%}$ treatment, average SWD_p for the $I_{120\%}$ treatment prior to irrigation was 50%. In good agreement with Miyamoto et al. (1984), our results indicate that maintaining SWD_p at 50% rather than 60% would increase guayule biomass. The average SWD_p for the $I_{80\%}$ treatment (68%) was slightly less than for Bucks et al. (1985a), while the drier $I_{60\%}$ and $I_{40\%}$ treatments had average SWD_p before irrigation of 80% and 90% in 2014, respectively.

Bucks et al. (1985a) reported measured guayule ETc rates in previous experiments in the US Southwest desert on the order of 9–11 mm/d from late-June to mid-July for their highest irrigation treatment level. The ETc rates from Bucks et al. above refer to data obtained during the second full year of guayule growth. In our study, ETc rates during 2014 (i.e., second year of growth) for the $1_{120\%}$ treatment during June and July were similar. However, during the months of April and May 2014, the ETc rates for our $I_{100\%}$ treatment were similar to those by Bucks et al. during those months (≈5.5 and 7.4 mm/d, respectively), whereas rates for our

$I_{120\%}$ treatment were 1.0 and 1.5 mm/d higher, respectively. Bucks et al. (1985a) also noted reduced ETc rates for guayule beginning in late July through the end of August. They linked this occurrence to reduced flower production, slower growth, as well as some loss of leaves during these higher air temperature periods of summer. In our study, the occurrence of slower plant height and canopy cover for treatments during late summer, particularly in 2013, coincided with reduced ETc rates in August compared to those in June and July.

For the soil water balance measurement period from April 2013 to March 2015 (≈two years), cumulative ETc for each year and total cumulative ETc for the entire period increased significantly with irrigation treatment level. Notable deep percolation occurred for the $I_{120\%}$ treatment (200 mm) and to a lesser extent for the $I_{100\%}$ treatment (70 mm). At the end of the period, the $I_{40\%}$ treatment had depleted 166 mm of soil water from the root zone depletion. The ΔS for the $I_{100\%}$ and $I_{120\%}$ treatments for the measurement period were near zero, indicating that except for DP losses these wetter treatments had used all the total water applied during the period in ETc.

In the second full year of past guayule irrigation studies in Mesa and Yuma, Arizona (Bucks et al., 1985a,d), the measured ETc for fully-irrigated treatments were 2050 and 1950 mm, respectively. These results of ETc were somewhat higher than for the $I_{100\%}$ in the second year of 2014 (1830 mm, Table 4) but somewhat less than for the $I_{120\%}$ treatment in 2014 (2097 mm). For 2014, the ratio of cumulative ETc to annual ETo (1855 mm) was 1.13 for the $I_{120\%}$ and 0.99 for $I_{100\%}$. The ratio for the $I_{120\%}$ treatment implies an average crop coefficient (Kc) less than that for alfalfa in this arid environment (≈1.2, Allen et al., 1998, pg. 67). In the present study, higher ETc for the $I_{120\%}$ over the $I_{100\%}$ might suggest an increase in soil evaporation for the $I_{120\%}$. However, the significantly higher biomass achieved for $I_{120\%}$ implies that transpiration was higher for the $I_{120\%}$. The differences in the ETc rates observed between these treatments during 2013 and 2014 plus 14% higher total cumulative ETc for $I_{120\%}$ than $I_{100\%}$ suggest the occurrence of soil water stress for the $I_{100\%}$ at average measured SWD_p of about 59%.

The findings on irrigation effects on rubber contents were generally consistent with previous research. Peak rubber concentrations at the end of the guayule winter dormancy period (i.e., February and March) versus other times of the year were reported by others (Bucks et al., 1985b; Benzioni et al., 1989; Jasso Cantu et al., 1997). During the dormancy period, rubber synthesis occurs when little guayule biomass is being accumulated (Jasso Cantu et al., 1997). The small treatment differences for resin content in our study were similar to previous studies that showed little change in resin content due to irrigation (Miyamoto and Bucks, 1985; Jasso Cantu et al., 1997).

The maximum final dry biomass for the $I_{120\%}$ treatment in the present study was about 25–28% greater than the highest final DB obtained in the 1980s' Mesa (Bucks et al., 1985b) and Yuma (Bucks et al., 1985d) studies after two years. The highest DB obtained in El Paso (Miyamoto et al., 1984) and the Negev (Benzioni et al., 1989) studies in the 1980s were 3.0 and 5.0 Mg/ha lower than that for the DB for the $I_{40\%}$ treatment in Maricopa, respectively, though the TWA for the $I_{40\%}$ was less than that in El Paso and about the same as that in the Negev. Coffelt and Ray (2010) reported dry biomass yields of 21.6 Mg/ha after 24 months and 29.7 Mg/ha after 36 months for newer guayule cultivars grown in Maricopa under flood irrigation and plant population of 27,000 plants/ha, as used in the present study. Thus, dry biomass yield for the $I_{100\%}$ treatment (24.5 Mg/ha) considering 29 months of growth was comparable with DB achieved by Coffelt and Ray (2010). The dry biomass water productivities based on total applied water where significantly higher for the two driest than two wettest irrigation levels in Maricopa. This result was different than found in three previous studies (Mesa, El Paso, and the Negev), which indicated that WP for DB was either lower or about the same for drier than wetter treatments. However, the trend for WP for the Yuma study, under sprinkler irrigation, was similar to the trend in the present study. Increased WP for DB with decreased TWA for the present and Yuma studies were obtained when timing of irrigation (though not irrigation amount) was the same for the treatments. The variable irrigation timing for the treatments in the other earlier studies may explain why assorted trends of WP with TWA were obtained. The maximum final rubber yield for the $I_{120\%}$ treatment in our study was eight to nine percent higher than for our $I_{80\%}$ and $I_{100\%}$ treatments. However, with a similar level of TWA, RY for the $I_{120\%}$ was from 29 to 54% greater than the highest final RY obtained in the 1980s' Yuma and Mesa studies after two years of growth. The $I_{100\%}$ and $I_{120\%}$ treatments achieved WP for RY of 0.036–0.037 kg/m^3, which were considerably higher than those at the wettest irrigation levels in the 1980s' studies in Mesa, Yuma, and El Paso (≈0.030 kg/m^3) but not in the Negev study (0.047 kg/m^3). The newer guayule cultivar grown in Maricopa appears to be of higher quality than the guayule used several decades ago. It not only increased dry biomass from earlier guayule but also improved rubber concentrations leading to higher rubber yields.

5. Conclusions

Responses of a guayule cultivar commercially grown in the Southwestern US desert to variable irrigation treatment levels were investigated in a field study conducted with surface irrigation from 2012 to 2015 in central Arizona. The study confirms that both guayule biomass and rubber yields responded linearly to total water applied. Reduction in rubber content with increased water occurred, but greater dry biomass led to greater rubber yield. Monthly ETc rates and cumulative ETc also increased significantly with each irrigation level and support the linear relationship between dry biomass production and water input. Significant differences in the ETc and dry biomass between the two wettest irrigation treatments suggest that soil water stress occurred to some extent for the second wettest treatment, which averaged 59% in measured soil water depletion just before irrigation. However, the wettest irrigation treatment was maintained at an average depletion of 50%, a depletion level often used for irrigation scheduling of field crops grown under surface irrigation. To achieve the highest potential guayule yields, it is recommended to use 50% soil water depletion for irrigation scheduling purposes. This would require irrigation frequency of about every 10–11 days in sandier soils during peak ETc periods from mid-May to mid-August, rather than irrigation every 12–14 days as used in this study. For fall-planted guayule, typical irrigation amounts in summer months would increase from about 120 mm during the first full year of growth to about 160 mm in the second full year. Starting in mid-August, irrigation intervals can be increased to coincide with subsequent declining guayule ETc rates. If minimizing irrigation water use is the management goal, significantly greater water productivity for guayule can be achieved by reducing total water applied well below the yield maximizing level. The results show that 92% of maximum rubber yield was achieved with 25% less total water applied. For reduced irrigation management, the irrigation scheduling frequency should be maintained at regular intervals during summer months, rather than extending the irrigation interval over long periods. Recommendations for achieving high water productivity would include irrigation frequency of 15 days or less during the summer months and maintaining soil water depletion at 70% or less. Irrigation amounts could be lighter than needed to replace full

ETc during summer months, but the irrigation frequency should be maintained.

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