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High guayule rubber production with subsurface drip irrigation in the US desert Southwest

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ABSTRACT

Guayule is being produced for natural rubber in US desert areas, where irrigation requirements are high. Improved irrigation practices and methods are required to increase guayule yields and reduce its water use. Presently, there is no information available on guayule produced using subsurface drip irrigation (SDI). Therefore, we conducted an SDI guayule field study in 2012–2015 in Maricopa, Arizona, US. The objectives were to evaluate guayule dry biomass (DB), rubber yield (RY), and crop evapotranspiration (ETc) responses to water application level, and to compare these results to previously reported guayule irrigation studies. Guayule seedlings were transplanted in the field in October 2012 at 0.35-m spacing, in 100-m long rows, spaced 1.02 m apart. The field had 15, 8-row wide plots (5 irrigation treatments x 3 replicates). Irrigation treatments were imposed in a randomized complete block design starting in May 2013. Irrigation scheduling was based on the measured soil water depletion percentage (SWD_p) of a fully-irrigated treatment, defined as 100% ETc replacement, and maintained at ≈20-35% SWD_p. The other treatments received 25%, 50%, 75%, and 125% of irrigation applied to the 100% treatment on each day of irrigation. Destructive samples for dry biomass, rubber, and resin contents were periodically taken from each plot between February and November of each year until the guayule was bulk-harvested in March 2015. Results indicated ETc, DB, and RY increased with total water applied (irrigation + rain), which varied between treatments from 2080 to 4900 mm for the 29-month growing season. Final dry biomass and rubber yields of 61.2 Mg/ha and 3430 kg/ha, respectively, were achieved with the highest irrigation treatment level (125%) and these yields were significantly higher than those under all other irrigation levels. All SDI irrigation treatments except for the lowest 25% level had rubber yields from 24 to 200% greater than the maximum RY achieved under a companion surface irrigation study conducted simultaneously in Maricopa.

1. Introduction

Guayule (*Parthenium argentatum* Gray) is a perennial hardwood shrub native to northern Mexico and the southwestern US deserts whose stem, branches, and roots produce high-quality natural rubber (NR) (Rasutis et al., 2015). It is presently being targeted in the US and other countries as a major source of NR to supplement limited Hevea (*Hevea brasiliensis*) imported rubber, grown primarily in Southeastern Asia (Soratana et al., 2017). Current pressures on NR supplies include rising NR demand from developing countries and potential Hevea plantation destruction due to rising incidents of plant disease (Eranki et al., 2017; Sfeir et al., 2014). Inspired by US tire companies, there is renewed interest in expanding guayule production in the southwestern US desert. A recent USA Today news article reported that General Motors and four of the world's largest tire manufacturers are committed to using sustainable NR for all its tires in the future (Evanoff, 2018). This commitment includes a major focus on utilizing guayule as the cornerstone crop and generating a domestic NR industry in the US.

The need to achieve high yield productivity with efficient irrigation water use is one of several major obstacles impeding the guayule industry. Guayule shrubs are considered drought tolerant, surviving on little or no rainfall for long periods of time (Foster and Coffelt, 2005). The National Academy of Sciences (National Academy of Science (NAS, 1977) recommended that the total water application (TWA), i.e., irrigation water plus rainfall, be limited to 640 mm in desert areas. Increased knowledge on irrigation water use and yield response for guayule was expanded in the mid-1980s. The research included three guayule irrigation studies conducted in Mesa and Yuma, Arizona (Bucks

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et al., 1985a, 1985b, 1985c; Bucks et al., 1985d) and in El Paso, Texas (Miyamoto et al., 1984; Miyamoto and Bucks, 1985). At these locations, where the average yearly rainfall is less than 190 mm/year, the guayule was grown for ≈ two years and then harvested. They reported that maximum dry biomass (DB) and maximum rubber yield (RY) were attained for fully-irrigated treatments whose measured cumulative crop evapotranspiration (ETc) during the second year of growth was 2050, 1950, and 1830 in Mesa, Yuma, and El Paso, respectively. Maximum DB and RY for the three field studies were approximately 22.0 Mg/ha and 1200 kg/ha, respectively, for the Arizona sites and 12.7 Mg/ha and 840 kg/ha, respectively, for the Texas site. These yields were obtained with about 2000–2200 mm/year of TWA for the Arizona studies and with ≈ 1600 mm/year of TWA for the Texas study.

A literature search revealed a few more recent studies regarding guayule yield response to measured water applied have been conducted since the mid-1980s. The relevant papers include guayule research in the Negev desert of Israel (Benzioni et al., 1989) and studies in more humid and cooler climates than US deserts, such as, Zacatecas, Mexico (Rodriquez-Garcia et al., 2002), Queensland, Australia (Dissanayake et al., 2007); northern Texas (Foster et al., 2011), and Southern France and Southern Spain (Sfeir et al., 2014; Snoeck et al., 2015). In all these more recent studies, the TWA reported were 900 mm/year or less and rubber yields were substantially lower than those in the mid-1980s Arizona deserts (Bucks et al., 1985a; and 1985b), except in the Negev desert where RY was 1060 kg/ha. Sfeir et al. (2014), however, estimated after one-year of study that a RY of about 1400 kg/ha could be achieved in Southern Spain with 900 mm/year.

The guayule studies cited above indicate that high yields of rubber can only be achieved with high levels of irrigation. They also showed that guayule biomass production increases directly with increased ETc and irrigation but that percentage of rubber in the plant tends to decrease at higher irrigation levels. In October 2012, we initiated field research to augment existing guayule irrigation information, focusing on a new guayule cultivar (Yulex B; Sanchez et al., 2014) grown under the recommended plant population of 27,000 plants/ha (Ray et al., 1999). We conducted one irrigation study using surface irrigation (SI) grown for 29 months (2012–2015) in Maricopa, Arizona, which evaluated guayule response under five levels of irrigation water application. Results from that study showed that maximum DB and RY were about 30% higher than those in the mid-1980s Arizona studies (Hunsaker and Elshikha, 2017). However, results from Maricopa also indicated that the water productivity (WP) for dry biomass and rubber yield, expressed as the ratio of final DB and RY to TWA, respectively, increased significantly when the TWA level was reduced from the maximum yield TWA level. Thus, under surface irrigation, guayule rubber yield gains became increasingly smaller as total water applied increased.

Subsurface drip irrigation (SDI) is a system used for row crops and trees, which applies water below the soil surface (Lamm et al., 2012). Researchers have reported that SDI (compared to other irrigation methods) has the potential to increase crop quality and yields, reduce irrigation water use, and reduce agronomic costs (Ayars et al., 2015; Colaizzi et al., 2004). Some of the primary crop production advantages attributed to SDI include more frequent, precise, and spatially uniform water and fertilizer applications, ability to maintain soil water content and soil temperatures at stable levels over the season, and reduced irrigation water losses, such as soil evaporation (Ayars et al., 2015; Colaizzi et al., 2004). Lamm et al. (2012) reported that SDI can increase and stabilize crop yield compared to sprinkler when deficit irrigation is practiced due to limited water resources.

However, there is very limited information on the use of SDI for guayule production and virtually no literature that compares guayule responses with SDI to other irrigation systems. Therefore, during 2012–2015 we conducted a SDI guayule study on a nearby field in Maricopa simultaneously with the SI study. A similar range of irrigation levels were also imposed under SDI. The objectives of this paper are to evaluate guayule biomass, rubber yield, and ETc responses to irrigation water application amounts and soil water status with SDI and to compare yield and water productivity of guayule under SDI with the companion study results and those in the literature.

2. Materials and methods

2.1. Experimental details, irrigation system, and plant establishment

A guayule subsurface drip irrigation field study was conducted from October 2012 (planting) through March 2015 (final harvest) within a 1.4-ha field site at The University of Arizona, Maricopa Agricultural Center (MAC), in Maricopa, Arizona, located in the Northeastern Sonoran Desert of the USA. The field-site soil is mapped as a Casa Grande series (Fine-loamy, mixed, superactive, hyperthermic Typic Natrargids) (Post et al., 1988) having 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 less than 100 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). The field site at MAC, located in the Northeastern Sonoran Desert, is characterized by high evaporation rates and low precipitation where historical annual average ETo and rainfall (1990–2014) recorded by AZMET are 1880 and 169 mm/ year, respectively. Typical maximum temperatures in June to August are 40 °C and above. The winter months of December and January can be cold, where minimum temperatures often fall below 0 °C. Details of climatic data during the 29-month study are provided in Fig. 1 (a, b, c, and d). Bi-weekly-averaged climate data for 2012–2013 (Fig. 1a and b) and 2014–2015 (Fig. 1c and d) show that months from January to April were cooler and more humid in 2013 than 2014. Climate data, including ETo and rainfall, for the two years were similar from May to early-July. However, during mid-July to August in 2014 (Fig. 1c and d), higher rates of rainfall and generally lower temperatures, less solar radiation, and lower ETo rates occurred than during the same period in 2013. During the September through December period, 2013 had generally higher temperatures, lower relative humidity, less frequent rainfall, and higher ETo rates than during that period in 2014. Cumulative rainfall for the 2013 and 2014 years was 194 and 207 mm, respectively, while cumulative ETo was 1878 mm and 1855 mm, respectively, both representing typical weather conditions in the central Arizona desert.

Prior to planting, 120 raised beds were formed every 1.02-m along a length of 100 m. A 15-station, SDI system was then installed in the field during August 2012. The SDI system was designed to provide metered water and fertilizer applications to 15 individual plots, each plot being eight plant beds wide (for a plot size 7.14 m by 100 m). The irrigation flow rate and totalized flow volume for each plot were monitored with flow meters, and pressure heads were monitored using a pressure gauge placed above the irrigation entry point of each plot. Beneath each plant bed, drip tape, 22 mm in diameter and 13 mils (0.325 mm) in thickness, was buried to a depth of 0.20 m. Emitters along the tape were spaced every 0.51 m. The system applied water at a rate of 0.91 l/hr per emitter at a pressure of 100 kPa. In late October of 2012, ≈95-day old greenhouse-grown Yulex-B line guayule seedlings (Sanchez et al., 2014) were transplanted in the raised beds 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 the beds giving an initial transplant population of ≈27,000 plants/ha. Following transplanting, the guayule plants were established by applying alternate-row furrow irrigation five times between October 26 and November 20, 2012. Establishment irrigations were managed by the MAC Irrigation Supervisor who estimated a total of 629 mm of water was applied to the field during 2012. Prior to imposing irrigation treatments on May 21, 2013, the MAC irrigator applied additional furrow irrigations to all plots on February 28 (122 mm) and May 14, 2013 (100 mm).

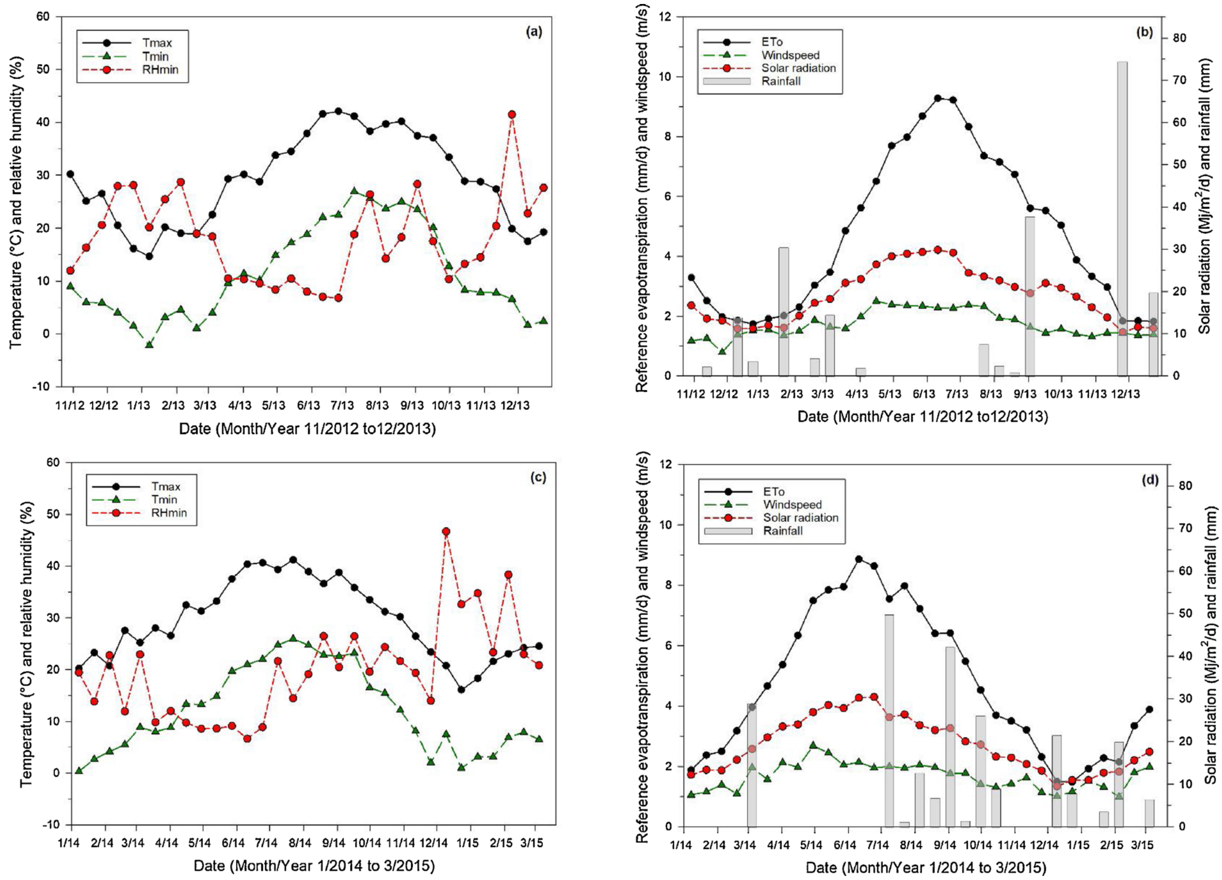

Fig. 1. Bi-weekly-averaged climatic parameters during the SDI guayule experiment, including maximum and minimum temperatures (Tmax and Tmin, respectively), minimum relative humidity (RHmin) (a and c); reference evapotranspiration (ETo), 2-m windspeed, solar radiation, and rainfall (b and d). Data were recorded by the AZMET weather station at Maricopa. Note that **a** and **b** show data for the first 14 months of the experiment (November 2012 to December 2013) and **c** and **d** show data for the last 15 months (January 2014 to March 2015).

Also, SDI was applied four times to all plots between April 10 and May 5 (total averaged ≈35 mm).

2.2. Experimental design, soil water content measurements, irrigation scheduling, and fertilizer applications

The experimental design was a randomized complete block consisting of five irrigation treatments, replicated in three blocks.

Neutron access tubes were installed in all 15 plots in late April 2013 using a tractor-mounted soil sampler. Five, 2.1-m long, metal access tubes were installed vertically in the soil along the length of each of the 15 plots at distances of 10, 30, 50, 70, and 90 m from the irrigation inlet (75 tubes total). The access tubes were placed in the middle row, viz., row 4, in each 8-row plot. Field-calibrated, neutron moisture meters were used to measure volumetric soil water contents (θ_v) from 0.10 to 1.9 m below the surface in 0.20 m increments. Measurements of θ_v were begun on May 9, 2013 and continued through March 13, 2015. From May through early November when guayule growth was active, θ_v measurements were made every 7–14 days at all 75 tube locations. Exceptions occurred during October 2013 when θ_v was measured only once in plots and between late April and mid-May 2014, when time between measurements was 20 days. From mid-November through March, when guayule growth was slow, θ_v was measured about every 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, FC) and lower (permanent wilting point, PWP) volumetric soil water contents. The FC and 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 using SDI were initiated on May 21, 2013, seven months after planting. One irrigation treatment, designated as $I_{100\%}$, served as a control treatment, whose irrigation scheduling was intended to provide ample and uniform available soil water (ASW) within the crop root zone depth (Z_r). The principle used for scheduling the $I_{100\%}$ treatment was to provide irrigation to maintain ASW within an effective Z_r of 1.8 m between 65%–80% 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). Thus, soil water depletion percentage (SWD_p), as calculated by Eq. (1), was to be maintained at 20%–35%.

$$SWD_p = (1\text{- }(ASW/TAW)) \times 100\% \quad (1)$$

where ASW and TAW are in mm and SWD_p is in percent. The 1.8-m depth used for Z_r was based on the extent of measurable guayule soil water extraction determined by Bucks et al. (1985a). The scheduling principle was relaxed from late November through the end of the guayule winter dormancy period in late February, when irrigation was not provided.

For the $I_{100\%}$ treatment, a separate daily soil water balance model was made for each plot replicate. The soil parameter calculations use Eq. (1) and the following equations (Eqs. (2) to (5)). The soil water balance models were initiated on May 9, 2013 with the first set of θ_v measurements and then repeatedly updated after each new set of soil water content measurements was made. The daily soil water balance models for the $I_{100\%}$ treatment were also updated with measured irrigation and rainfall amounts and daily ETo provided by the AZMET station. The measured θ_v were first averaged at each measurement depth for the five tube locations within each replicate and then converted to soil water storage (SWS) over the Z_r of 1.8 m.

$$SWS_m = \sum_{i-1}^{i} 0.2(\theta_{v,i}) \quad (2)$$

where SWS_m is the measured soil water storage over Z_r in mm, $\theta_{v,i}$ are the volumetric soil water contents measured every 0.2-m, from 0.1 m to 1.7 m (j = 8). The TAW for each replicate was determined using the lab analyses of FC and WP, as averaged by depth for each replicate. The amount of soil water storage (SWS) at field capacity over Z_r was calculated by Eq. (3) using the replicate average FC data determined at each sampling depth:

$$SWSFC = \sum_{i=1}^{j} \theta FC,\ i\, Di\, x10 \quad (3)$$

where SWS_{FC} is soil water storage at field capacity over the 1.8-m crop root zone depth in mm, $\theta_{FC,i}$ are the field capacity soil water contents (%) determined at each 0.3-m sample depth (j = 6). Similarly, the SWS at PWP (SWS_{PWP}) over Z_r was calculated using Eq. (3) by replacing $\theta_{FC,i}$ with the replicate average $\theta_{PWP,i}$ for each D_i. Thus, TAW over Z_r for each treatment replicate was computed as the difference between SWS_{FC} and SWS_{PWP}. The available soil water over Z_r (Martin and Gilley, 1983) was calculated as:

$$ASW = SWS_m - SWS_{PWP} \quad (4)$$

and the soil water depletion (SWD) was calculated as

$$SWD = SWS_{FC} - SWS_m \quad (5)$$

where all units for Eqs. (4) and (5) are in mm.

Four other irrigation treatments in the study were governed by the $I_{100\%}$ irrigation dates and application amounts. The four treatments were designated as $I_{25\%}$, $I_{50\%}$, $I_{75\%}$, $I_{125\%}$, and received 25%, 50%, 75%, and 125% of the irrigation amount applied to the $I_{100\%}$ at each irrigation, respectively.

Prior to initiating irrigation treatments on May 21, 2013, urea-ammonium-nitrate (UAN) was injected during irrigation by SDI on April 19, 2013 to uniformly apply 32 kg N/ha to all plots. A second application of UAN (32 kg N/ha) was given to all plots during treatment irrigations on 10 July 2013. A third and final UAN application of 64 kg N/ha was applied to all plots during irrigations in March 2014. Soil tests for P and K indicated adequate levels so no P or K fertilizer was applied.

2.3. Crop evapotranspiration for treatments

In this section, methods are presented for the estimation of the actual ETc that occurred for irrigation treatments, where ETc was calculated separately at each of the five access tube locations within a treatment plot replicate. These ETc calculations were begun on May 17, 2013, following a final flood irrigation to all plots on May 14. The ETc was determined as the residual of the soil water balance equation (Jensen et al., 1990) shown in Eq. (6) over time-periods between two consecutive soil water content measurement dates.

$$ET_c = (SWD_2 - SWD_1) + IW + R - DP \quad (6)$$

where ET_c is the total evapotranspiration (mm) between two consecutive water measurement dates, SWD_1 and SWD_2 are the measured root zone soil water depletion (mm) on first and second dates, respectively, and IW, R, and DP are the measured irrigation water (mm), measured rainfall (mm), and the estimated deep percolation (mm) that occurred during the time-period between the two soil water measurements, respectively. For Eq. (6), SWD was calculated over a Z_r of 1.8 m by Eqs. (2),(3), and (5) using the lab-analyzed field capacity values determined for each tube location. Measurement of DP was not made. However, thorough evaluation of the measured SWD with time indicated an assumption of negligible DP was valid for all locations within $I_{25\%}$, $I_{50\%}$, and $I_{75\%}$ treatments. Evaluation of the measured SWD for the $I_{125\%}$ treatment plots indicated significant DP was certain, particularly during the 2014, and therefore ETc calculations were omitted for the $I_{125\%}$ treatment. Examination of SWD for $I_{100\%}$ plots suggested DP likely occurred at some tube locations during a period in early July 2014 when measured SWD approached values near zero (i.e., field capacity) after a 29-mm rain occurred on July 3, one day after full irrigation had been applied. Consequently, an estimated DP of about one-half the rain amount (15 mm) was uniformly applied to all $I_{100\%}$ plots in the soil water balance calculation of ETc for the period from July 3 to July 10, 2014.

2.4. Plant growth and destructive sampling

Guayule canopy height and canopy cover measurements commenced in April 2013. Measurements were made for three to six plants in each plot ≈ every 25 days from April to November 2013, ≈ every 36 days from February to September 2014, and on March 16, 2015. Three to six 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 five whole plants was made on March 16, 2015, just before a final bulk harvest was made. 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 3, 4, and 5) of each 8-row plot to minimize the influence on plant growth due to irrigation from adjacent treatment plots. Fresh biomass weights obtained from whole plant harvests were immediately measured and then dried in open greenhouses for 2–4 weeks Each biomass sample was periodically weighed until there was no significant change in dry weight (Mohammadi Shad and Antungulu, 2019). 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, Plant Science Department, in Tucson, Arizona. Resin and rubber concentrations were determined through a sequential extraction protocol that closely followed the methods recommended by Cornish et al. (2013).

2.5. Final harvest

Final bulk harvest occurred on March 17 and 18, 2015 when entire 100-m lengths of two plant rows (rows 4 and 5) were bulk-harvested for each of the 15 plots. The equipment used was a modified potato-digger harvester that pulled the two rows of plants including main roots up to the surface. The trailer load for each plot harvest was then immediately weighed on a large truck-scale on the MAC farm. The content of moisture in the fresh weights of the bulk final harvests and the rubber and resin contents were determined from the mean values obtained from the destructive samples within each plot taken during hand-harvests on March 16, 2015. The dry biomass (DB) in kg/ha was multiplied by the rubber and resin contents to obtain final rubber and resin yields (Ray et al., 2005), respectively. The WP of the total water applied was calculated as the ratio between yield and TWA (kg/m^3) using the dry biomass and rubber and resin yield data obtained from final bulk harvest.

2.6. Statistical analyses

Irrigation treatment effects for measured total water applied, plant height, DB, rubber and resin contents, final yields, water productivity, and cumulative ETc were analyzed statistically using a randomized

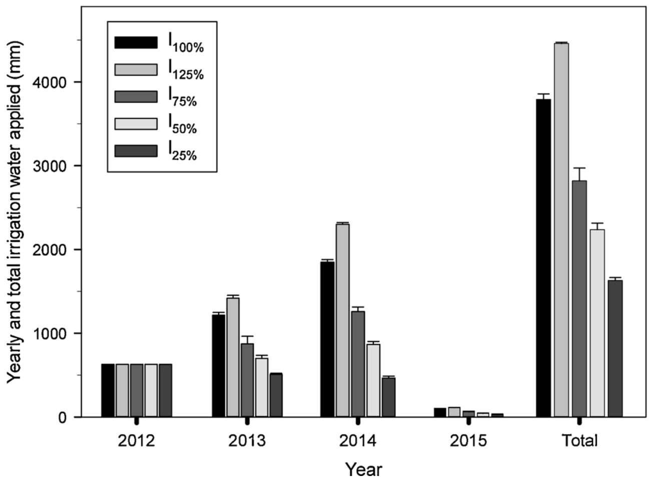

Fig. 2. Irrigation water applied (cumulative) by year and total from 2012–2015 for five subsurface drip irrigation treatments in Maricopa, Arizona. Year 2015 includes one irrigation applied to each treatment before final harvest.

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. Treatment means were separated using the Pdiff (least significance difference, LSD, at $p = 0.05$) option.

3. Results

3.1. Irrigation

Fig. 2 shows the irrigation totals for treatments by year, including the 629 mm estimated for plant-establishment irrigations in Oct.-Nov. 2012. Monthly and yearly irrigation amounts for treatments and rain data are summarized in Table 1. The yearly total for irrigation water applied to the $I_{100\%}$ treatment in 2013 averaged 1215 ± 33 mm, which included furrow-applied irrigations of 122 mm (late Feb.) and 100 mm (early May), also equally applied to the four other treatments. Because differential irrigation to treatments did not start until May 21, 2013, yearly total irrigation applied to the $I_{125\%}$ treatment in 2013 (1418 mm; Table 1) was only 17% greater than that for the $I_{100\%}$, while the $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$ received about 72%, 58%, and 42% of that applied to the $I_{100\%}$. Yearly total irrigation to the $I_{100\%}$ averaged 1848 mm in 2014, while the 2014 yearly irrigation amounts to other treatments were generally commensurate with treatment target rates. The total yearly irrigation applied to the $I_{125\%}$, was 24% greater than for the $I_{100\%}$, while the $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$ treatments total irrigation were 68%, 47%, and 25% less, respectively. The lower than intended irrigation for the $I_{75\%}$ treatment, which was only 68% of that for the $I_{100\%}$ in 2014, was affected by greater variability in irrigation amounts among replicates then for other treatments (e.g., the greater standard deviation (SD) for $I_{75\%}$ in Table 1 and fig.1). One replicate in the $I_{75\%}$ was consistently less than the target irrigation rate by about 10% throughout the study, thus, lowering the average intended for the treatment. $I_{75\%}$. Only one irrigation was applied to treatments in 2015 (Feb). Compared to the amount applied to the $I_{100\%}$ in 2015, other treatments were somewhat less than intended amount, except for the $I_{25\%}$ treatment (Table 1). Considering the entire 29-month guayule growing period between planting (Oct. 2012) and final harvest (March 2015), total irrigation water applied to the $I_{100\%}$ was 3791 mm and the total water applied, including the 452 mm of rain for the period, was 4243 mm (Table 1). Relative to the TWA for the $I_{100\%}$ over the entire growing period, TWA was 16% greater for the $I_{125\%}$, while TWA for the $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$ were 77%, 63%, and 49% of the $I_{100\%}$ TWA. Statistical analyses indicated TWA was significantly different between all irrigation treatments. Derivation of the TWA at an annual basis, i.e., considering the entire 29-month growing period, gave an annual TWA for treatments of 2032, 1756, 1354, 1112, and 861 mm/year for the $I_{125\%}$, $I_{100\%}$, $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$.

3.2. Soil water properties and soil water depletion

Irrigation treatment averages for soil texture fraction, field capacity, permanent wilting point, and soil water holding capacity were not appreciably different (Table 2). Sand fraction for a 1.8-m soil depth varied from 59 to 63%, silt fraction from 12 to 15%, and clay fraction from 23 to 26%. The soil water contents determined for FC and PWP were notably uniform for treatments varying from 26 to 28% for FC and from 14 to 15% for PWP. Average soil water holding capacity was highest for the $I_{50\%}$ treatment (130 mm/m) and lowest for the $I_{25\%}$ treatment (122 mm/m). There was also comparable within-treatment variability in soil water holding capacities for treatments, as indicated by a range in the SD of 14–19 mm/m for the treatments (Table 2).

Measured soil water depletion for treatments with time are shown from May 17, 2013 through Dec. 17, 2013 (Fig. 3a) and from Jan. 30, 2014 through March 12, 2015 (Fig. 3b). Following a flood irrigation to plots on May 14, 2013, all treatments were near field capacity (5 to 6% SWD_p) for measurements made three days later (Fig. 3a). The SWD_p for treatments then increased during the remainder of May through mid-June. Initiation of irrigation treatments on May 21, 2013 led to higher SWD_p for the less-irrigated treatments, $I_{50\%}$ and $I_{25\%}$, than the three higher-irrigated treatments, $I_{75\%}$, $I_{100\%}$, and $I_{125\%}$, starting in early-June. As the differences in irrigation water applications accumulated, SWD_p for the $I_{75\%}$ increased relative to $I_{100\%}$ beginning in late June and decreased for $I_{125\%}$ relative to $I_{100\%}$ beginning in early July 2013. Differences in SWD_p between the $I_{50\%}$ and $I_{25\%}$ treatments also became evident in early July. The trends for treatment separation in SWD_p remained relatively stable throughout the irrigation cycle of 2013 that ended in early November. Soil water depletion for the $I_{100\%}$ treatment, which had been maintained less than 32% through late September, increased to 41% in late October and then increased to 47% at the end of 2013, about six weeks after irrigation had been terminated. During the irrigation period of 2013 (May 17 to November 11), the measured SWD_p for the $I_{100\%}$ varied from 6 to 42% and averaged 25% for all measurements in that period. During the same irrigation period, the SWD_p for the $I_{125\%}$ treatment varied from 6 to 30% and averaged 20%. The average SWD_p for the $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$ treatments in 2013 (May to Nov.) was 37, 44, and 51%, respectively, with a maximum SWD_p of 60, 66, and 73% occurring on November 11, prior to subsequent rain in late November that reduced the soil water depletion for those treatments.

Before resuming irrigation in early February 2014, SWD_p varied between 42 and 64% for irrigation treatments in late January (Fig. 3b). This was followed by decreased SWD_p for all treatments through March 13, 2014, where the average $I_{100\%}$ and $I_{125\%}$ values were 19 and 11%, respectively. The subsequent SWD_p values for $I_{100\%}$ then gradually increased to 30% on April 23, however, SWD_p for $I_{100\%}$ then increased to 44% on May 13, 2014, which was above the target range (i.e., 20–35%). The increased SWD_p for the $I_{100\%}$ indicated that the estimated crop evapotranspiration used to project irrigation amounts had underestimated actual the ETc during the late-April early May timeframe, coinciding with a 20-day period between soil water content measurements. The SWD_p for the $I_{125\%}$, $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$ treatments on May 13, 2014 was 37, 61, 72, and 82%, respectively (Fig. 3b). As for the $I_{100\%}$ treatment, SWD_p for other treatments on May 13 was near to or above the maximum depletion measured for each treatment through the end of 2014 measurement (December 8). The lowest measured

Table 1
Summary of irrigation water applied, and total water applied (TWA) to five irrigation treatments during the 2012–2015 subsurface drip guayule study at Maricopa, Arizona.

Year	Month	Rain (mm)	Irrigation treatments				
			$I_{125\%}$	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$	$I_{25\%}$
			Irrigation water applied (mm)				
2012	Oct.-Nov.	3	629	629	629	629	629
	Year total	20	629	629	629	629	629
2013	Jan.-Feb.	35	122	122	122	122	122
	Mar.-Apr.	16	33 ± 1	37 ± 8	31	33 ± 1	33 ± 1
	May	0	170 ± 3	160 ± 4	141 ± 5	133 ± 2	123 ± 1
	June	0	217 ± 6	175 ± 5	110 ± 16	81 ± 7	49 ± 3
	July	7	300 ± 7	242 ± 4	162 ± 26	113 ± 9	62 ± 3
	August	8	218 ± 5	184 ± 8	116 ± 17	83 ± 7	46 ± 2
	September	33	179 ± 7	150 ± 8	96 ± 14	68 ± 6	38 ± 2
	October	0	142 ± 5	116 ± 2	85 ± 12	60 ± 6	32 ± 2
	Nov.-Dec.	95	36 ± 1	29 ± 1	9 ± 1	7 ± 1	4
	Year total	194	1418 ± 35	1215 ± 33	872 ± 91	700 ± 38	508 ± 13
2014	Jan.-Feb.	0	113 ± 2	106 ± 3	70 ± 11	52 ± 2	27 ± 1
	March	29	106 ± 2	96 ± 3	55 ± 7	40 ± 3	21 ± 1
	April	0	217 ± 2	169 ± 2	116 ± 11	79 ± 6	44 ± 2
	May	0	344 ± 10	268 ± 10	192 ± 3	129 ± 4	67 ± 2
	June	0	439 ± 5	348 ± 7	238 ± 6	163 ± 9	88 ± 5
	July	58	377 ± 13	299 ± 7	201 ± 11	143 ± 5	75 ± 4
	August	13	324 ± 8	254 ± 6	174 ± 5	117 ± 6	64 ± 4
	September	70	153 ± 5	125 ± 4	90 ± 5	60 ± 2	35 ± 2
	October	8	159 ± 2	128 ± 3	84 ± 3	56 ± 2	29 ± 2
	Nov.-Dec.	29	68 ± 1	54 ± 2	37 ± 2	26 ± 1	13 ± 1
	Year total	207	2300 ± 22	1848 ± 31	1257 ± 56	865 ± 37	464 ± 24
2015	Jan.-Feb.	24	111 ± 2	99 ± 3	61 ± 8	43 ± 5	27 ± 7
	March	7	0	0	0	0	0
	Year total	31	111 ± 2	99 ± 3	61 ± 8	43 ± 5	27 ± 7
Total	2012-2015	452	4458 ± 16	3791 ± 67	2820 ± 152	2236 ± 79	1629 ± 35
Total water applied (mm)			4910 ± 16	4243 ± 67	3272 ± 152	2688 ± 79	2081 ± 35

Notes: Establishment flood irrigation amounts were equally applied to all treatments in Oct.-Nov., 2012 and in Feb., 2013.
Differential irrigation treatments were begun on May 21, 2013.
Irrigation was not applied during the months of December and January in any year.
Each treatment received 32, 32, and 64 kg N/ha of fertilizer in April of 2013, July of 2013, and March of 2014, respectively.
Values following the ± sign are the standard deviations of the treatment means.
Rain amounts are shown from transplanting on October 26, 2012 through final harvest on March 18, 2015.
Treatment means of cumulative irrigation totals for the entire 2012–2015 period are followed by TWA for the same period.
TWA is the summation of all irrigation water applied (including for establishment) and all rain from transplanting to final harvest.

Table 2
Soil texture fractions and soil water retention properties for five guayule subsurface drip irrigation treatments at Maricopa, Arizona.

Soil property	Irrigation treatment[a]				
	$I_{125\%}$	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$	$I_{25\%}$
Sand (%)	62 ± 7	59 ± 8	62 ± 7	63 ± 7	63 ± 8
Silt (%)	15 ± 5	15 ± 4	14 ± 3	13 ± 4	12 ± 5
Clay (%)	23 ± 5	26 ± 6	24 ± 6	24 ± 6	25 ± 5
Field capacity (%)	27 ± 3	27 ± 3	28 ± 2	28 ± 3	26 ± 2
Permanent Wilting point (%)	15 ± 3	14 ± 2	15 ± 2	14 ± 2	14 ± 2
Water Holding Capacity (mm/m)	124 ± 17	123 ± 19	128 ± 15	130 ± 19	122 ± 14

[a] Irrigation treatment data for soil texture fractions, field capacity, and permanent wilting point are means over a soil depth from 0 to 1.8-m depth for 15 locations per treatment. Soil water holding capacity was calculated for locations as SWS_{FC} minus SWS_{PWP} over a crop root zone depth of 1.8 m and are presented as means for each treatment. Values following the ± sign are the standard deviations of the treatment means.

SWD_p for the $I_{100\%}$ in 2014 was 10% and occurred on July 10 (Fig. 3b). The lowest soil water depletion coincided with significant rain events following irrigation just prior to July 10 water content measurements. After August 6, 2014, SWD_p for the $I_{100\%}$ treatment was maintained between about 19–36% until irrigation termination. For the period of irrigation in 2014 measurement (early Feb. to early Nov.), the average SWD_p for the $I_{100\%}$ was 27%, slightly higher than during irrigation period in 2013. Between early June through mid-November 2014, measured SWD_p on many dates were in the range of -5 to 5% for the more heavily-irrigated $I_{125\%}$ treatment, indicating deep percolation occurred in these plots. During the irrigation period of 2014, the average SWD_p for the $I_{125\%}$, $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$ was 12, 54, 66, and 78%, respectively, which was slightly lower than in 2013 for the $I_{125\%}$ but much higher in 2014 than 2013 for the three drier treatments. As rainfall between late-November 2014 through mid-February 2015 was light, soil water depletion increased for treatments during that period, until reduced following irrigation, applied for five days in late February 2015. The SWD_p measured during the short irrigation period of 2015 (late Feb. through March 12, 2015) varied from 27% ($I_{125\%}$) to 79% ($I_{25\%}$) for treatments (Fig. 3b).

3.3. Guayule crop evapotranspiration (ETc)

Crop evapotranspiration rates are shown for irrigation treatments from May to December in 2013 (Fig. 4a) and from January 2014 to March 2015 (Fig. 4b). As mentioned in Section 2.3, ETc data were not calculated for the $I_{125\%}$ treatment due to uncertainty of the DP quantity in that treatment's soil water balance. Seasonal variation in ETc was apparent for all treatments but varied more for the $I_{100\%}$ treatment,

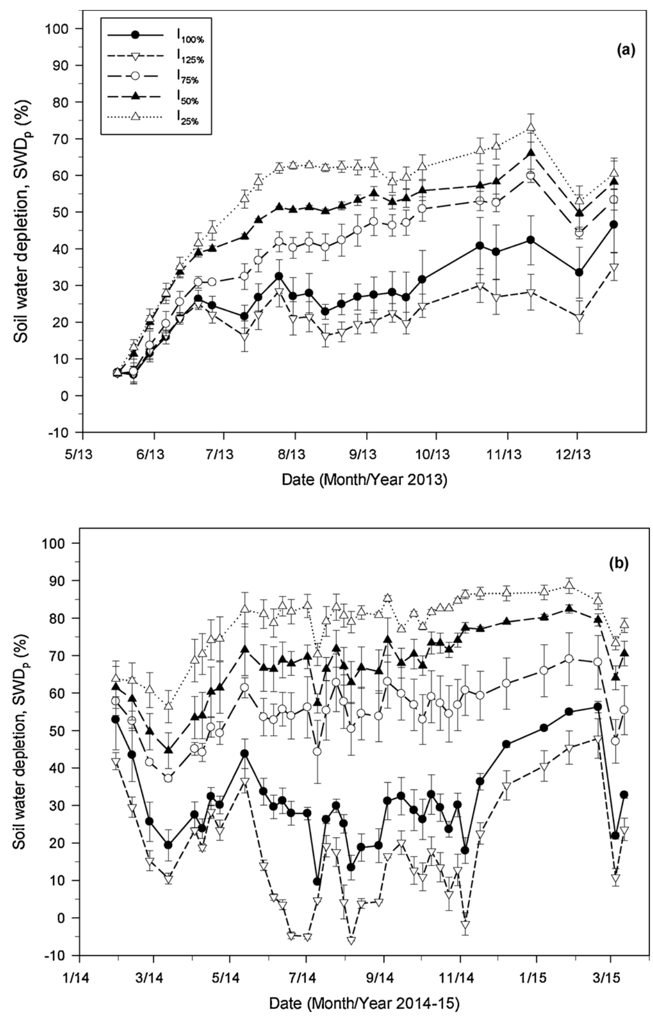

Fig. 3. Periodic changes of measured soil water depletion (SWD_p) for five subsurface drip irrigation treatments during (a) 2013 and (b) 2014–2015 in Maricopa, Arizona. Note: treatment bars for SWD_p give the means ± the standard deviation of the mean (n = 3).

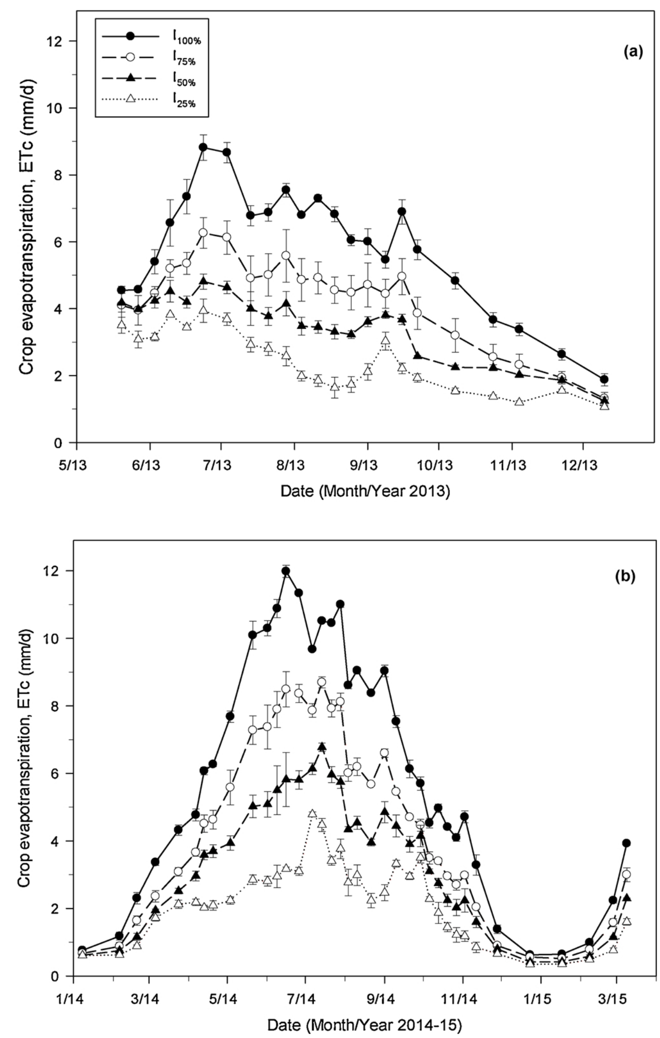

Fig. 4. Periodic changes of measured crop evapotranspiration (ETc) for four subsurface drip irrigation treatments during (a) 2013 and (b) 2014–2015 in Maricopa, Arizona. Note: treatment bars for ETc give the means ± the standard deviation of mean (n = 3).

where the ETc extremes were less than 1.0 mm/d during winter months (late December through January) and as high as 12.0 mm/d during a mid-June period in 2014. During 2013, ETc rates for the $I_{100\%}$ were at a yearly maximum of about 9.0 mm/d during late June to mid-July, declined to about 7.0 mm/d during late July through August, and then progressively declined from 7.0 mm/d to 2.0 mm/day between mid-September to late December (Fig. 4a). Noticeably higher ETc rates for $I_{100\%}$ than $I_{75\%}$ occurred in early June about two weeks after initiation of irrigation treatments. It was evident that the higher application of irrigation for the $I_{100\%}$ treatment corresponded to increased ETc rates over the $I_{175\%}$ during the remainder of the irrigation period (early November 2013), though the treatment ETc rates converged by January 2014. Similarly, a clear separation in ETc rates between the $I_{75\%}$ and $I_{50\%}$ and those between the $I_{50\%}$ and the $I_{25\%}$ began by mid-June 2013 and separation remained through late October (Fig. 4a). Resumption of irrigation treatments in early February 2014 resulted in treatment separation for ETc in late February ($I_{100\%}$) and in early March for $I_{75\%}$ vs $I_{50\%}$, as well as for $I_{50\%}$ vs $I_{25\%}$ (Fig. 4b). During 2014, ETc rates for the $I_{100\%}$ varied from 9.7–12.0 mm/d between late May through the end of July, declined to 8.4–9.0 mm/d during August, and then steadily declined from 9.0–1.4 mm/d between early September and late November 2014. All treatments experienced a decline in ETc rates during August in both 2013 and 2014 from the higher ETc rates that occurred during June and July. The reduction in August guayule ETc rates corresponded to reduced ETo during the August monsoon season, where average ETo for August was 6.8 and 6.6 mm/d in 2013 and 2014, respectively, compared to ETo for June (9.3 and 8.7 mm/d) and July (7.8 and 7.9 mm/d), respectively. Similarly, average ETo declined monthly from 5.4 and 5.5 mm/d in September 2013 and 2014, respectively, to 1.8 and 1.5 mm/d in December.

The yearly average cumulative ETc for the $I_{100\%}$ was 1159 mm for 2013, where the periodic ETc water balance were summed for all periodic ETc determinations from May 17 to December 18 in 2013 (Table 3). Obviously more ETc occurred during the 6.5 months between October 26, 2012 (planting) and the first soil water content measurements on May 17 but this ETc was not determined by a soil water balance. For 2014, average cumulative ETc for the $I_{100\%}$ treatment (summed from Dec. 19, 2013 to Dec. 9, 2014) was 2057 mm. A short final period of average cumulative ETc for $I_{100\%}$ was 109 mm, determined between Dec. 10, 2014 and March 12, 2015, just prior to final harvest. Thus, total cumulative ETc for the 22-month period of soil water balance measurement averaged 3325 mm for the $I_{100\%}$ treatment. Statistical analyses of the data in Table 3 indicated all treatment means for cumulative ETc were significantly different from one another, whether yearly or total. For the 22-month period of ETc measurement, total cumulative ETc for the three treatments $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$ were 73%, 56%, and 38%, respectively, of that for the $I_{100\%}$.These treatment

Table 3
Means of yearly and total cumulative crop evapotranspiration (ETc) in mm determined by soil water balance for four[a] irrigation treatments under subsurface drip at Maricopa, Arizona.

Dates for cumulative ETc	Irrigation treatments[a]			
	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$	$I_{25\%}$
May 17, 2013 to Dec. 18, 2013	1159 ± 43	843 ± 89	674 ± 24	483 ± 17
Dec. 19, 2013 to Dec. 9, 2014	2057 ± 21	1496 ± 54	1128 ± 52	737 ± 26
Dec. 10, 2014 to March 12, 2015	109 ± 4	85 ± 4	64 ± 3	49 ± 3
Total (May 17, 2013 to March 12, 2015)	3325 ± 59	2424 ± 146	1866 ± 75	1269 ± 36

[a] ETc data for irrigation treatment $I_{125\%}$ was not presented due to expected but un-measured deep percolation. The ETc for the $I_{100\%}$ treatment in 2014 included 15 mm of estimated DP and DP was assumed to be negligible for all drier treatments. Values following the ± sign are the standard deviations of the treatment means.

differences in total ETc reflect a linear response to the TWA during the same 22-month period, where the TWA for the $I_{100\%}$ was 3273 mm, while the $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$ were 70%, 53%, and 34% of that for the $I_{100\%}$, respectively. Prorated on an annual basis, considering the 22-month period of ETc measurement, gave an annual ETc of 1820, 1390, 1060, and 680 mm/year for the $I_{100\%}$, $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$ treatments, respectively.

3.4. Guayule growth measures and rubber and resin contents

Fig. 5a and b illustrate the development of guayule plants over the course of the study. Measured plant height averages for treatments

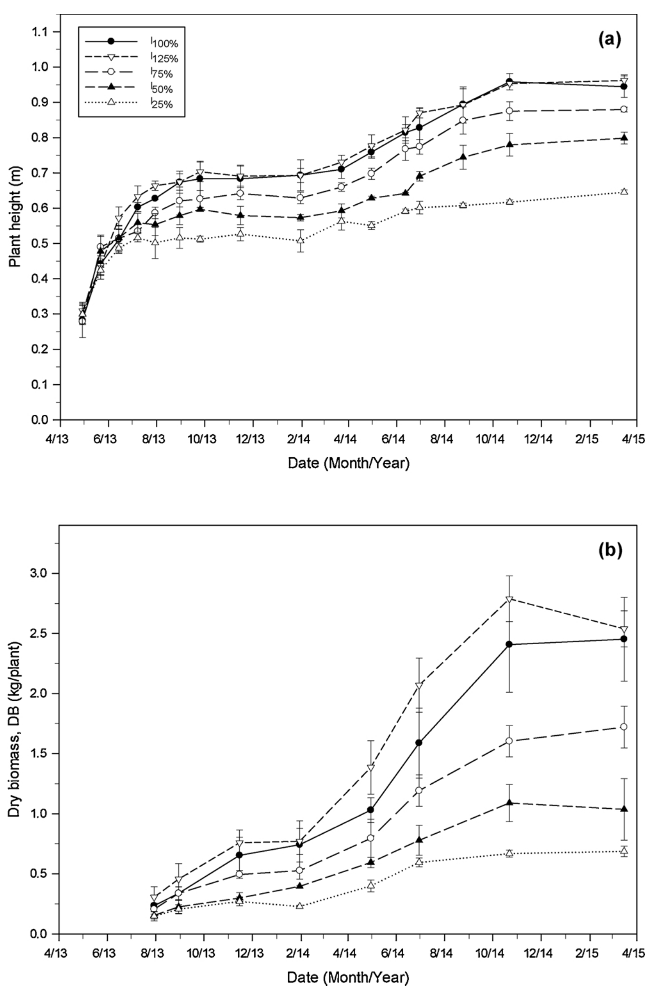

Fig. 5. Measured (a) plant height and (b) dry biomass (DB) with time for five subsurface drip irrigation treatments from July 2013 to March 2015 in Maricopa, Arizona. Note: treatment bars for plant height and DB give the means ± the standard deviation of the mean (n = 3–6).

(Fig. 5a) increased from ≈ 0.3 m in late April 2013 to 0.63 to 0.66 m for the two wettest irrigation treatments ($I_{100\%}$ and $I_{125\%}$, respectively) by the end of July 2013. For the same period, plant heights increased to 0.59, 0.55, and 0.50 m for the $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$ treatments, respectively. However, plant height measurements through mid-November 2013 revealed only slight changes in height occurred during the remainder of 2013 for the $I_{125\%}$ (+0.03 m), $I_{50\%}$ (+ 0.03 m), and the $I_{25\%}$ (+0.015 m) treatments. During the same period, plant height increased at a higher rate for the $I_{75\%}$ (+ 0.04 m) and even greater rate for the $I_{100\%}$ (+0.07 m). Plant height averages on November 15, 2013 were not significantly different ($p < 0.05$) between the three wettest treatments, $I_{75\%}$, $I_{100\%}$ and $I_{125\%}$, while heights for these three treatments were significantly greater than those for $I_{50\%}$ and $I_{25\%}$, though $I_{50\%}$ was significantly greater than for $I_{25\%}$. During 2014, plant heights increased rapidly for the two wettest treatments beginning in late March 2014 (Fig. 5a), and the heights were not significantly different between $I_{100\%}$ and $I_{125\%}$ throughout 2014 and on the final measurement made on March 16, 2015. For most measurements made in 2014, plant height was significantly greater for the two wettest treatments than for the $I_{75\%}$ treatment, which in turn had significantly greater height than the two driest treatments ($I_{50\%}$ and $I_{25\%}$), while height was also greater for $I_{50\%}$ than $I_{25\%}$ from late April 2014 through the final plant measurement in 2015. On March 16, 2015, plant height averaged 0.96 m, 0.94 m, 0.88 m, 0.80 m, and 0.65 m for $I_{125\%}$, $I_{100\%}$, $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$, respectively.

There were significant treatment effects for guayule dry biomass (DB) for all destructive plant sampling dates, which began on July 30, 2013 (Fig. 5b). For the first two sampling dates in 2013, treatment mean comparison tests revealed significant differences between the $I_{125\%}$ treatment and the drier $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$ means with no difference detected between the $I_{125\%}$ and the $I_{100\%}$ DB. At mid-November 2013, the dry biomass for $I_{125\%}$ was 0.76 kg/plant compared with a DB of 0.65 kg/plant for the $I_{100\%}$ treatment, although the difference was not significant. However, both $I_{125\%}$ and $I_{100\%}$ had significantly greater DB than the $I_{75\%}$, whose DB was also significantly greater than the DB for the $I_{50\%}$ and $I_{25\%}$ treatments in November 2013. A similar trend in treatment differences occurred for the first DB sampling date in 2014, on January 30. However, for samples taken on April 30 and June 30, 2014, DB increased at a higher rate for the $I_{125\%}$ than $I_{100\%}$ and mean DB was significantly different between the two treatments. On June 30, 2014 the DB for the $I_{125\%}$ was just over 2.0 kg/plant versus 1.59 kg/plant for the $I_{100\%}$. However, towards the end of 2014 and through the March 16, 2015 sample, the $I_{100\%}$ DB appeared to have caught up to that in the $I_{125\%}$ treatment and differences were not statistically significant. For samples made in 2014 through March 2015, the general trend was greater DB for $I_{100\%}$ than the $I_{75\%}$ and greater biomass for $I_{75\%}$ than both the $I_{50\%}$ and the $I_{25\%}$. Though the $I_{50\%}$ had higher mean DB than that for the $I_{25\%}$ during this same period, significant differences between the two only occurred on the October 22, 2014 date. On March 16, 2015, treatment DB, determined from the destructive made just before final bulk harvest, was 2.54, 2.45, 1.72, 1.04, and 0.69 kg/plant for the $I_{125\%}$, $I_{100\%}$, $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$, respectively.

Table 4
Means of rubber and resin contents by sampling date for five subsurface drip irrigation treatments at Maricopa, Arizona.

	Rubber content (%) for irrigation treatments				
Date sampled	$I_{125\%}$	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$	$I_{25\%}$
July 30, 2013	1.2 d	1.4 cd	1.6 bc	1.7 b	2.1 a
August 30, 2013	1.6 b	1.8 b	2.1 ab	2.3 ab	2.7 a
November 15, 2013	2.4 b	2.4 b	2.9 ab	3.6 ab	4.2 a
January 30, 2014	4.6 a	4.6 a	4.7 a	5.2 a	5.4 a
April 30, 2014	3.7 a	4.3 a	4.6 a	4.5 a	4.6 a
July 8, 2014	3.3 a	3.5 a	3.4 a	4.2 a	3.8 a
October 22, 2014	3.2 c	3.4 c	3.5 bc	4.0 ab	4.3 a
March 16, 2015	5.6 d b	6.0 b	6.6 b	7.6 a	8.6 a
July 30, 2013	4.6 a	4.6 a	4.7 a	5.3 a	5.4 a
August 30, 2013	4.6 a	2.4 b	4.5 ab	3.9 ab	4.1 ab
November 15, 2013	3.3 a	4.2 a	4.3 a	3.5 a	4.1 a
January 30, 2014	4.5 b	7.3 a	5.8 ab	6.8 ab	6.6 ab
April 30, 2014	4.6 a	4.6 a	4.7 a	5.3 a	5.4 a
July 8, 2014	7.0 a	7.2 a	7.9 a	8.1 a	7.0 a
October 22, 2014	7.3 a	6.2 a	6.7 a	6.5 a	8.5 a
March 16, 2015	6.2 b	7.9 ab	8.6 a	6.5 b	6.3 b

abcd indicate treatment means of rubber or resin contents were significantly different at the 0.05 level when followed by a different letter in a row.

Rubber and resin contents are shown for treatments in Table 4. A general trend for all treatments was to increase the rubber content of plants with time starting at low initial values of 1.2–2.1% in late July 2013 to 4.6 to 5.4% on January 30, 2014. After January 2014, subsequent treatment rubber contents gradually decreased through the remaining sample dates in 2014 (to 3.2–4.3%, Table 4). However, by late winter of 2015, i.e., March 16, 2015, rubber content for each treatment had increased to their maximum (5.6–8.6%). Significant treatment differences for rubber contents occurred during all three sample dates of 2013, where the driest treatment, $I_{25\%}$, had higher rubber than the two wettest treatments, $I_{125\%}$ and $_{I100\%}$, though there were no differences in average rubber content between $I_{25\%}$ versus the $I_{50\%}$ and $I_{75\%}$, except on July 30, 2013. During 2014, there were no treatment differences in rubber content until late October. However, at the final sampling on March 16, 2015, significantly higher rubber content was attained for the $I_{25\%}$ and $I_{50\%}$ than for all three wetter treatments.

Treatment trends for resin content with time were different than for rubber content (Table 4), where resin content generally decreased from July 2013 to November 2013. Highest resin content in 2014 occurred in July for the $I_{100\%}$, $I_{75\%}$, and $I_{50\%}$ treatments, however, it was in October 2014 for the $I_{125\%}$ and $I_{25\%}$ treatments. On March 16, 2015, resin content for the $I_{100\%}$ and $I_{75\%}$ was at the maximum for the study (7.9 and 8.6%, respectively), while $I_{125\%}$, $I_{50\%}$, and $I_{25\%}$ had significantly lower resin content on that last sampling date.

3.5. Final yields and water productivity

Means for the final bulk-harvested dry biomass after 29 months of growth were significantly different among all treatments with a near four-fold increase in mean DB from $I_{25\%}$ to $I_{125\%}$ (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 0.90 (Fig. 6a). The $I_{125\%}$ treatment achieved the maximum DB in the study with a mean of 61.2 Mg/ha. This was 29% greater than the mean DB for the $I_{100\%}$ and was achieved with only 16% more TWA than that for $I_{100\%}$. Final mean DB for the three drier treatments ($I_{75\%}$, $I_{50\%}$, and $I_{25\%}$) was 81%, 57%, and 34% the DB attained for the for $I_{100\%}$, respectively. Water productivity for dry biomass averaged $I_{125\%}$ (1.25 Mg/m^3) and the mean was significantly greater than that for both $I_{50\%}$ and $I_{25\%}$, while the mean WP for the $I_{100\%}$, and $I_{75\%}$, and $I_{50\%}$ treatments were each significantly greater than for $I_{25\%}$ (Table 5). A maximum rubber yield (RY) of

Table 5
Final harvest means for dry biomass, rubber yield, resin yield, and water productivity (WP) for dry biomass, rubber yield, and resin yield for five guayule subsurface drip irrigation treatments at Maricopa, Arizona.

	Irrigation treatment				
Variable	$I_{125\%}$	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$	$I_{25\%}$
Dry biomass (Mg/ha)[a]	61.2 a	47.4 b	38.6 c	27.2 d	15.7 e
WP–dry biomass (kg/m^3)[b]	1.25 a	1.12 ab	1.18 ab	1.02 b	0.76 c
Rubber yield (kg/ha)[a]	3429 a	2830 b	2528 bc	2080 c	1352 d
WP–rubber yield (kg/m^3)[b]	0.070 a	0.067 a	0.077 a	0.078 a	0.065 a
Resin yield (kg/ha)[a]	3781 a	3740 a	3307 a	1797 b	993 c
WP –resin yield (kg/m^3)[b]	0.077 ab	0.88 ab	0.101 a	0.067 bc	0.048 c

abcd indicate treatment means for 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 (in kg/ha) or yield per unit total water applied (TWA) from October 2012 through March 2015.

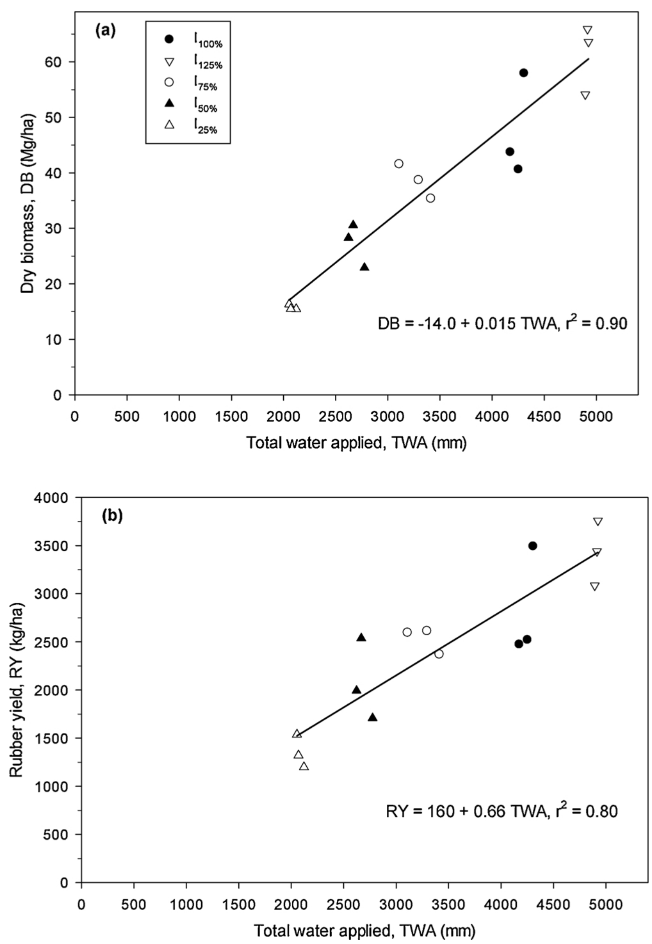

Fig. 6. (a) Dry biomass (DB) and (b) rubber yield (RY) as a function of total water applied (TWA) for final bulk-harvested data (March 16 and 17, 2015) for five subsurface drip irrigation treatments in Maricopa, Arizona. Note: graphs show DB and RY data for three replicates within each treatment.

3429 kg/ha for the $I_{125\%}$ treatment was significantly greater than the RY for all other treatments and was two and a half times greater than for the $I_{25\%}$ treatment (Table 5). The $I_{125\%}$ RY was 21% greater than the RY for $I_{100\%}$ and the increased rubber yield for $I_{125\%}$ was slightly greater than the 16% increase in TWA for $I_{125\%}$ over $I_{100\%}$. The 11% higher RY for the $I_{100\%}$ over the $I_{75\%}$ was not significant and the increase in RY was much less than the 23% increase in TWA for $I_{100\%}$ over

$I_{75\%}$. Similarly, an 18% increase in RY for the $I_{75\%}$ over the $I_{50\%}$ could not be excepted as significant. However, all treatments were found to have significantly greater RY than the $I_{25\%}$ treatment. Regression of rubber yield data for all 15 plots (Fig. 6b) also reveals an overall linear relationship with TWA. While WP for RY was highest in the $I_{50\%}$ and $I_{75\%}$ treatments, statistical differences in mean WP for treatments did not occur (Table 5). Mean resin yields from 3300 to 3780 kg/ha were achieved by the $I_{75\%}$, $I_{100\%}$, and $I_{125\%}$ treatments and differences between the treatment means for these three treatments were not significant (Table 5). Also, all three treatments had significantly greater resin yield than the $I_{50\%}$ and $I_{25\%}$, while $I_{50\%}$ resin yield was significantly greater than for $I_{25\%}$. The water productivity of resin yield was highest for the I75% treatment, but not enough to be significantly greater than either $I_{100\%}$ and $I_{125\%}$.

4. Discussion

The estimated 629 mm of irrigation water applied using furrow irrigation for guayule transplant establishment represented a significant portion of the total irrigation water applied to treatments during the SDI 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 SDI should consider the deployment of portable sprinkler systems to reduce irrigation water use for plant establishment. On an annual basis, TWA for the $I_{100\%}$ and the $I_{125\%}$ treatments in the SDI study were 1760 and 2030 mm/year, respectively, somewhat less than the 2000–2220 mm annual TWA for the wetter treatments in the previous 1980s studies in Arizona (Bucks et al., 1985a, d). Annual TWA for the $I_{75\%}$, $I_{50\%}$, and $I_{25\%}$ in the SDI study were 1350, 1110, and 860 mm/yr. For the companion study conducted simultaneously in Maricopa using surface irrigation (Hunsaker and Elshikha, 2017), annual TWA for five similar irrigation treatments, i.e., $I_{120\%}$, $I_{100\%}$, $I_{80\%}$, $I_{60\%}$, and $I_{40\%}$) were 1950, 1770, 1460, 1210, and 980 mm/year, respectively. Considering guayule research conducted outside the US deserts, in which irrigation and rainfall were measured, a maximum amount of ≈ 900 mm/year of total water was applied in Mediterranean studies (Sfeir et al., 2014; Snoeck et al., 2015) and in Israel (Benzioni et al., 1989). These amounts of TWA were comparable to our lowest TWA in the SDI study ($I_{25\%}$). The $I_{25\%}$ treatment attained DB and RY of 15.7 Mg/ha and 1350 kg/ha, respectively, which are similar values reported by Sfeir et al. (2014) for guayule grown for two years in Spain. Even less TWA (600–700 mm/year) was provided in studies in Australia (Dissanayake et al., 2007), northern Texas (Foster et al., 2011), and Mexico (Rodriquez-Garcia et al., 2002). In the latter three studies, rubber yields reported after two years of growth were on the order of 600–700 kg/ha.

Regarding irrigation scheduling and soil water depletion, the average measured SWD_p for the SDI $I_{100\%}$ treatment during irrigation periods was 27%. For the $I_{100\%}$ treatment, the target SWD_p (20–35%) was both somewhat exceeded and somewhat reduced on several measurement dates but overall the fluctuations in SWD_p were small in comparison to those usually encountered under surface irrigation (SI) methods. In the companion study in Maricopa with SI, the measured SWD_p for the $I_{100\%}$ treatment went from 12% measured shortly after irrigation to as high as 69% just prior to irrigation. Overall, the measured SWD_p for the 100% SI treatment in Maricopa averaged 46% over irrigation periods (Hunsaker and Elshikha, 2017). Bucks et al. (1985a) did not provide detailed SWD_p data for the SI treatments in Mesa but did report that the depletion measured prior to irrigation for their wettest treatment averaged about 72% for the two years of study. Benzioni et al. (1989) reported that guayule plants showed signs of visible wilting and had increased plant temperatures beginning at 60% SWD_p in the Negev desert of Israel. A study by Veatch-Blohm et al. (2006) in Tucson, Arizona found a 50% reduction in rubber yield when soil water depletion was increased to ≈ 75% before irrigating. The ability to apply frequent but light irrigation amounts using SDI allowed uniformly-high available soil water for guayule throughout the irrigation season for the three wettest treatments in Maricopa. Because higher irrigation was applied to the $I_{125\%}$ than $I_{100\%}$ treatment in the SDI study, the average measured SWD_p for the $I_{125\%}$ over irrigation periods for the three years was only 16%. For the SDI irrigation periods, average SWD_p for the $I_{75\%}$ and $I_{50\%}$ treatments were 47% and 57%, respectively.

During the second year (2014) of the SDI study, the annual ETc was 2050 mm for the $I_{100\%}$ treatment. This result shows that cumulative ETc increased about 12% using SDI over the 2014 annual ETc of 1830 mm for the $I_{100\%}$ treatment under surface irrigation in Maricopa (Hunsaker and Elshikha, 2017). This was close to the 9.0% higher TWA for SDI than the SI in 2014. The current study and the companion SI study results clearly demonstrated that guayule ETc responses will be closely proportional to the amount of total water applied. Other studies that reported measured ETc for guayule in arid climates showed similar maximum ETc values to the SDI cumulative ETc, varying from 1950 to 2050 during the second year (Bucks et al., 1985a, d; Miyamoto et al., 1984). However, Benzioni et al. (1989) reported maximum cumulative ETc for the second year of guayule was about 1300 mm, though the experiment used deficit irrigation for the highest treatment. Other research found on this subject applied much less total water than in our studies and thus cumulative ETc would be much smaller. For example, Rodriquez-Garcia et al. (2002) calculated a maximum annual ETc of 690 mm but the combined irrigation plus rainfall was only slightly higher than that amount. Although the $I_{125\%}$ treatment under SDI had obvious deep percolation during some periods in 2014, we would expect the ETc of that treatment to be about the TWA minus any DP that occurred. This would give an estimated cumulative ETc during the second year about 17–20% higher than for $I_{100\%}$, or about 2300 mm.

In the two Maricopa studies, ETc rates for the 100% treatments occurred in June and July 2014 during the second year of growth. Between mid-June to the end of July 2014, the ETc for the $I_{100\%}$ treatment under surface irrigation varied from 9.5–10.8 mm/d and averaged 9.9 mm/d. However, for the SDI study, the ETc was increased during this same period where the rates for the $I_{100\%}$ varied from 9.7–12.0 mm/d (Fig. 4b) and averaged 10.8 mm/d. Differences in ETc rates between the SI and SDI fully-irrigated treatments were considerable in 2014 where the average ETc rate for the $I_{100\%}$ SDI treatment between early May through the end of August was 9.9 mm/d, or 1.6 mm/d higher daily ETc than for the 100% under SI. The higher ETc rate and cumulative ETc for SDI than for SI under full-irrigation is contrary to the often-heard theory that SDI may decrease ETc for crops due to less evaporation (Burt et al., 2002). However, a detailed analysis of crop evapotranspiration under different irrigation methods in California by Burt et al. (2002) showed that for a wide variety of crops, SDI tends to increase ETc by 6–10 % over ETc using surface and sprinkler irrigation methods. In the case of guayule in Maricopa, it is most likely that the higher frequency irrigation under SDI allowed more available soil water use by plants than SI, since relatively less of the irrigated water is lost to evaporation. Ayars et al. (2015) and Colaizzi et al. (2004) suggested that higher ETc for SDI than under SI or other irrigation methods is mainly due to increased transpiration, which is also associated with decreased evaporation. Because guayule is drought tolerant, even the extreme and prolonged soil water depletion of > 80% that occurred from June to September in 2014 for the driest treatment ($I_{25\%}$) in the SDI study (Fig. 3b) did not further reduce the $I_{25\%}$ ETc rate during summer relative to the $I_{100\%}$ treatment ETc rate (Fig. 4b). This would not be the case for many annual crops, as reported by Butt et al. (2017).

Periodic sampling of plant dry biomass indicated that the DB for the $I_{100\%}$ and $I_{125\%}$ treatments were no different than the DB of the two highest irrigation levels ($I_{120\%}$ and $I_{100\%}$) under SI in Maricopa through early February 2014. However, DB differences dramatically increased starting with samples collected on April 30, 2014, where $I_{100\%}$, and

$I_{125\%}$ had DB between 1.0–1.4 kg/plant versus about 0.8 kg/plant for the two highest irrigation levels under SI. The differences grew larger through the end of 2014. Final DB from destructive sampling in March 2015 was about 2.5 kg/plant for both the SDI $I_{125\%}$ and $I_{100\%}$ treatments for SDI, while, notably, the DB for the $I_{75\%}$ was 1.7 kg/plant (Fig. 5b). These compare to DB of 1.4–1.5 kg/plant for the high irrigation levels under SI after 29 months of growth. Thus, even the less-irrigated $I_{75\%}$ treatment under SDI produced DB greater than the $I_{120\%}$ and $I_{100\%}$ treatments under surface irrigation.

The dry biomass of the final bulk harvest made after 29 months of growth was maximum for the $I_{125\%}$ treatment (61.2 Mg/ha). This DB yield was 2.2 times greater than the maximum DB realized in the SI study in Maricopa (also at 29 months). A comparison of final DB for the $I_{100\%}$ treatments in the two Maricopa studies shows DB for SDI (47.4 Mg/ha) was 1.9 times higher than that with SI (24.5 Mg/ha). 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 guayule cultivars grown in Maricopa under surface irrigation and a plant population of 27,000 plants/ha, as used in the present study. More recently, however, at the same plant population, Abdel-Haleem et al. (2018) grew improved lines of guayule in Maricopa using SI and achieved an average DB of 27.2 Mg/ha after two years. Thus, dry biomass yield for the $I_{125\%}$ and $I_{100\%}$ treatments achieved with SDI was substantially greater than all recent guayule SI irrigation studies at the same location in Maricopa. At two locations in Australia (Dissanayake et al., 2007), maximum final DB for well-watered guayule after 32 months was 14.1–20.3 Mg/ha. Also, for well-watered and fertilized treatments in France, Snoeck et al. (2015) reported guayule DB after one year averaged 9.0 Mg/ha. However, in Zacatecas. Mexico, well-watered guayule achieved only 15.0 Mg/ha in dry biomass after 30 months (Rodriquez-Garcia et al., 2002).

Because the relationship between DB and TWA was linear (Fig. 6a and b), with no leveling off at the highest TWA in the SDI study, we submit that possibly higher DB could have been realized with increased irrigation applications under SDI. This is supported by the trend found for water productivity for dry biomass under SDI that increased rather than decreased with TWA, unlike WP with surface irrigation (Hunsaker and Elshikha, 2017). The water productivity for dry biomass production under the three highest irrigation levels under SDI (1.12–1.25 kg/m^3) are the highest reported for guayule to date. For the companion study in Maricopa, WP for DB for all treatments (0.59 to 0.69 kg/m^3) were about half that of the $I_{125\%}$ treatment under SDI.

The findings concerning irrigation effects on final rubber contents were generally consistent with previous research, which has mainly revealed rubber content increases as irrigation and available soil water decrease. Peak rubber concentrations occurred at the end of the guayule winter dormancy period (i.e., February and March) versus other times of the year and similar trends for rubber with time were reported by others (Coffelt et al., 2009; Veatch et al., 2005; Hunsaker and Elshikha, 2017). Low temperatures during winter months induce biochemical reactions in the guayule plant that stimulate rubber biosynthesis and accumulated rubber content (Benedict et al., 2013). Final rubber contents (Table 4) for the three highest irrigation levels under SDI (5.6–6.6 %) were slightly lower than those for the three highest irrigation levels under SI in Maricopa (6.0–6.8 %), whereas rubber contents were higher at the two lowest irrigation levels under SDI (7.6 and 8.6%) than those for SI. Maximum guayule rubber contents found in the literature vary from 4.1–12.0% (Rasutis et al., 2015). However, we found that final resin content was generally not related to irrigation level in a consistent manner. This result was consistent to data provided by Rodriquez-Garcia et al. (2002). However, Hunsaker and Elshikha (2017) found that resin content was generally higher for the three wettest than two driest treatments under surface irrigation, though significant differences were only between the two wettest versus the second driest treatment.

The rubber yield for the $I_{125\%}$ treatment (3429 kg/ha) was 21% higher than the $I_{100\%}$ treatment, which in turn was only 12% higher than that for the $I_{75\%}$ and the difference was not significant (Table 5). Rubber yield was 2080 kg/ha for the $I_{50\%}$ and not significantly different than that for $I_{75\%}$, due to higher percent rubber for the $I_{50\%}$ treatment (Table 5). Remarkably, the $I_{50\%}$ SDI treatment RY was 24% higher than maximum rubber yield in the companion study using SI (1680 kg/ha for the $I_{120\%}$) but the $I_{50\%}$ treatment received 57% less TWA than that SI treatment. The $I_{125\%}$ using SDI was twice the $I_{120\%}$ RY using SI even though TWA for $I_{125\%}$ was only 200 mm more. The highest rubber yield for guayule after two years of growth reported in previous literature was 2006 kg/ha (Abdel Haleem et al., 2018). A vast improvement in the WP for RY compared to previous results was achieved under SDI, where values ranged from 0.067 to 0.078 kg/m^3 (Table 5). This is especially pertinent for higher irrigation levels, which were only 0.036 to 0.037 kg/m^3 for the two highest irrigation levels under SI in Maricopa and comparable to the WP for RY at the two highest irrigation levels in the mid-1980s' studies in Mesa, Yuma, and El Paso (0.029 to 0.035 kg/m^3). Similarly, resin yield (3600 kg/ha) and WP of resin yield (0.089 kg/m^3) when averaged for the three highest irrigation levels under SDI were 56% and 59% greater than those based on the average of the three highest irrigation levels under SI in Maricopa, respectively.

5. Conclusions

A major challenge in commercializing guayule for natural rubber is to improve yield and water productivity under cropped conditions. This is particularly true for the irrigated-guayule crops that are envisioned for US deserts areas. This study was conducted to evaluate guayule responses to water applied by subsurface drip irrigation in the Southwestern US. The results provide strong evidence that guayule yield and irrigation water productivity can both be vastly improved using subsurface drip instead of surface irrigation. Both dry biomass and rubber yield were the highest ever reported when guayule was irrigated to maintain soil water depletion less than 35%. Rubber yield for fully-irrigated guayule using subsurface drip irrigation was about double the rubber yield attained by surface irrigation with similar amounts of total water applied. We attribute the higher yield to more uniform readily available soil water at the upper soil profile for crop water use, resulting in more rapid biomass production. Rubber content generally decreases with irrigation amount, however, under subsurface drip irrigation, rubber yields are substantially increased with irrigation amount because of the significantly higher dry biomass produced. Moreover, this study suggests that irrigation water use for guayule could be drastically reduced using subsurface drip and still achieve higher rubber yields than guayule grown with surface irrigation. To further improve water savings using subsurface drip, more efficient establishment irrigation practices need to be developed.

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