

## Performance evaluation of biomass sorghum in Hawaii and Texas



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### ARTICLE INFO

#### Keywords:

Biomass sorghum  
Bioenergy feedstock  
Enrolment and agricultural practice  
Photoperiod sensitive

### ABSTRACT

Although biomass sorghum [*Sorghum bicolor* (L.) Moench] has been identified as a high yielding bioenergy feedstock crop on the continental USA, there is however lack of conclusive data on its performance in Hawaii (HI). The objectives of this study were to (i) determine the adaptability and productivity of two biomass sorghum hybrids, and (ii) identify the associated crop parameter attributes and environmental factors for high biomass yields. Two comparative trials were conducted, one on Maui island, HI and the other at Temple, Texas (TX). At Temple, the biomass sorghum hybrids responded as expected, growing to heights in excess of 3 m and producing average biomass yields of 37.4 Mg ha<sup>-1</sup>. The high leaf area indices (LAI, 7.8–9.8) intercepted over 90% incident photosynthetically active radiation (PAR) at LAI > 4, while the computed average light extinction coefficient (*k*) was 0.48. An average plant growth rate (PGR) of 189 kg dry biomass ha<sup>-1</sup> day<sup>-1</sup> was achieved, while the average radiation use efficiency (RUE) was 2.75 g MJ<sup>-1</sup>. In sharp contrast to the results obtained at Temple, the two sorghum hybrids planted on Maui behaved like photoperiod insensitive short day grain sorghums; lower plant heights (< 2.0 m), LAI (average, 3.8) and PGR prior to heading (average, 41 kg ha<sup>-1</sup> day<sup>-1</sup>), flowered early (~90 days after planting), and had aboveground biomass yields reduced by 76%. The study underscored the importance of not only choosing the right bioenergy crop species, but also the suitability of target environments, planting date and management practices. The crop parameters determined at Temple can be incorporated into crop and environmental simulation models such as ALMANAC, EPIC/APEX and SWAT to model various biomass sorghum cropping systems and their associated environmental impacts.

### 1. Introduction

The state of Hawaii (HI) depends on imported coal and oil for 95% of its energy (US DOE, 2015). Unsurprisingly, its residents pay among the highest prices in the USA for gasoline, residential fuel gas, and electricity (Hawaii State Energy Office, 2015). Faced with this energy challenge, HI has aggressively sought alternative and renewable energy resources to reduce this overdependence on imported energy.

Several US federal and private sector funded projects and demonstrations have been conducted to identify appropriate processes and feedstocks that are economically feasible for producing biofuel in Hawaii (Kinoshita and Zhou, 1999). Although sugarcane (*Saccharum*

*officinatum* L.) is viewed as the ideal sugar-to-ethanol biofuel, its production in HI has declined significantly since the 1970s. This decline is due to a number of factors that include low prices (due to the phasing out of the USA government's protections that limited foreign imports), competition from artificial sweeteners, and low cost production from such countries as Mexico, Brazil, India, and China (Gaddis, 2013; Meki et al., 2015). The total area under sugarcane today is now less than 16,200 ha from a high of 103,275 ha in the 1930s. The large tracts of fallow agricultural lands which used to be under sugarcane production are now transitioning into diversified crops. Other land has been converted to urban developments but still large tracts of prime land now lie fallow or are under pasture (Kinoshita and Zhou, 1999).

**Abbreviations:** DAP, days after planting; FIPAR, fraction of intercepted photosynthetically active radiation; HC & S, Hawaii Commercial & Sugar Company; *k*, light extinction coefficient; LAI, leaf area index; PAR, photosynthetically active radiation; PGR, plant growth rate; RUE, radiation use efficiency

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<http://dx.doi.org/10.1016/j.indcrop.2017.04.014>

Received 28 July 2016; Received in revised form 13 February 2017; Accepted 9 April 2017  
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In HI sugarcane competes with other sectors of the economy for the scarce water resources, and hence the interest in alternatives that optimize water use efficiency. Among the identified potential cellulosic feedstocks, based on their high biomass yields, adaptability to HI conditions, and are relatively drought tolerant, are Napier grass (*Pennisetum purpureum*) (Kinoshita and Stackmann, 1994) and energycane (*Saccharum* hyb.) (Alexander, 1985).

Biomass sorghum hybrids have been demonstrated on the continental USA to produce high biomass yields in as few as 90–100 days, and in addition, are relatively drought tolerant (Rooney et al., 2007; Venuto and Kindiger, 2008; Blade Energy Crops, 2010). To our knowledge only one study (Smith et al., 1987) has evaluated the production potential of sweet sorghum as a renewable biofuel resource for HI. The results of Smith et al. (1987) demonstrated that sweet sorghum is far more widely adapted than was anticipated for a plant of tropical origin and certainly has good potential as a biofuel feedstock in HI. While sweet sorghum has high yields of both fiber and fermentable sugars (15–23%) (Sarath et al., 2008; El Bassam, 2010) biomass sorghums have been bred to specifically maximize cellulosic content (at least 75% cellulosic content) (EPA, 2015). This study was prompted by the lack of conclusive data on the performance of biomass sorghums [*Sorghum bicolor* (L.) Moench] in HI and is a component of a bioenergy project whose overall objective was to evaluate the feasibility and sustainability of producing select bioenergy feedstocks in HI (Meki and Kiniry, 2013; Meki et al., 2015).

The hypothesis being addressed in this paper is that although there is great interest in growing biomass sorghums as a bioenergy feedstock in HI, there is still limited scientific information on how they perform under different environmental and management practices. To this end, we conducted a field study at the Hawaii Commercial & Sugar Company (HC & S) sugarcane plantation, on the Island of Maui, HI, in collaboration with researchers from the University of Hawaii at Manoa to (i) determine the adaptability and productivity of two biomass sorghum hybrids grown as potential biofuel feedstock crops, and make performance comparisons with a similar trial conducted at Temple, TX, a region known to be well adapted for maximum production of biomass sorghums, and (ii) identify the crop parameters and environmental factors that contribute to the high biomass yields.

## 2. Materials and methods

### 2.1. Plant material

Two Wilbur-Ellis Co.<sup>1</sup> high biomass sorghum hybrids Integra 405 (I-405) and Integra 1990 (I-1990)<sup>2</sup> were selected for both field experiments conducted at HC & S, Maui, HI and Temple, TX. When grown at continental USA sites the two hybrids were recognized to have the following characteristics; high biomass yields, drought tolerance, (but are also highly recommended for irrigated production), very tall plants (3.0–3.6+ m) with resistance to lodging, early vigor, high forage quality with a low lignin content. Integra-405 has high sugar content (sweet juicy stalks), while I-1990 is of average sugar content. Integra 405 is a late maturing hybrid while I-1990 is photoperiod-sensitive. Photoperiod sensitive sorghums will not flower when grown when the daylength is more than the photoperiod trigger of 12 h 20 min, and hence produce high biomass through continued vegetative growth.

### 2.2. Study sites and cultural practices

Field studies were conducted at the HC & S plantation (lat. 20.89°N,

long. –156.41°W; mean elevation ~100 m asl) and at the USDA ARS, Grassland, Soil and Water Research Laboratory, Temple, TX (lat. 31.09°N, long. –97.36°W; elevation ~219 m asl) during the 2012 and 2013 growing seasons. At HC & S, field trials were established on two fields: field (F) 410 which is a high elevation site (~300 m asl) and is on a Aridisol (Keahua series), which is a fine, kaolinitic, isohyperthermic Ustic Haplocambid; F718 is a low elevation site (~30 m asl) and is on a Mollisol (Ewa series), which is a fine, kaolinitic, isohyperthermic Aridic Haplustolls (USDA NRCS, 2011). Two elevations were chosen due to previous observations which indicated that although certain bioenergy species such as Napier grass are well adapted and yield well at most elevations, sugarcane and energycane are not well adapted to higher elevations and their yields are much lower (Mae Nakahata and Richard Ogoshi, co-authors, pers. comm.). So the two elevations were chosen so as to assess the performance of the two biomass sorghum hybrids at the two elevations. At Temple, the field trials were conducted on a Vertisol (Houston black clay), which is a fine, smectitic, thermic Udic Haplusterts (USDA NRCS, 2011). A few selected key soil properties of the three soils are presented in Table 1. At HC & S and Temple, weather data for the study fields was respectively obtained from an on-field and on-station weather station.

At Temple, a completely randomized repeated measures design with three replicates was used. Overall plot sizes were approximately 12 m by 12 m to allow for unbiased repeated biomass samplings throughout the growing season. Roundup (N-(phosphonomethyl)glycine, C<sub>3</sub>H<sub>8</sub>NO<sub>5</sub>P) herbicide was applied at a rate of 3.51 L/ha to control weeds a week prior to planting. The field was conventionally tilled (plowing followed by disking) and fertilized with 120 and 30 kg ha<sup>-1</sup> of N and P fertilizers, respectively. Fertilization rates were based on data reported in the literature (Blade Energy Crops, 2010; Maughan et al., 2012; Rocatelli et al., 2012; Snider et al., 2011; Undersander et al., 1990). The 2012 and 2013 field plots were established on 19 and 8 April, and final harvests were on 20 and 3 September, respectively. The biomass sorghums were seeded at the recommended seeding rates of 180,000 seeds ha<sup>-1</sup> (Blade Energy Crops, 2010) using the Great Plains 1510 minimum till grain drill (Great Plains Manufacturing, Salina, KS). To ensure near-optimum growing conditions throughout the growing season, limited supplementary irrigation water of 200 mm and 150 mm was applied in 2012 and 2013, respectively.

At HC & S, the sorghum hybrids were planted in a field previously under sugarcane. A group-balanced block experimental design which included three other candidate bioenergy crops: sugarcane, energycane and Napier grass was used. Fields were subsoiled with a deep ripper (60 cm depth), followed by disc harrowing (45 cm). Trial plots were established on September 9, 2011, with final harvests on September 11, 2012 (F410) and September 12, 2012 (F718). Experimental plots in both Temple and at HC & S were replicated three times. At HC & S individual plots (15 m × 11 m) consisted of four rows of grass, centered on a drip irrigation line, the distances between rows and drip lines were 0.23 m and 2.7 m as described in Meki et al. (2015). This design was used to accommodate the sugarcane infrastructure of drip lines already in place. A pre-emergence herbicide mix containing atrazine (1-chloro-3-ethylamino-5-isopropylamino-2, 4, 6-triazine), 2, 4-D (2, 4-dichlorophenoxyacetic acid), Prowl (N-1-ethylpropyl)-3, 4-dimethyl-2, 6-dinitrobenzenamine), Rifle (3, 6-dichloro-2-methoxybenzoic acid), and Velpar (3-cyclohexyl-6-dimethylamino-1-methyl-1, 3, 5-triazine-2, 4(1H,3H)-dione) was applied to control weeds. Seeds were hand sowed into the rows at a target seeding rate of 143,000 plants ha<sup>-1</sup>. Although the hand sowed seeding rate at HC & S was lower than that at Temple, sorghums have the ability to compensate (or self-thin) the plant population through tillering (Snider et al., 2011; Gerik and Neely, 1987), especially under drip and fertigated field conditions. Annual rainfall varied from 250 to 1500 mm in the irrigated plots (92% of total cultivated area). Plants were drip-irrigated weekly as needed to prevent any water stress. The amount of water applied was determined by the plantation's crop production managers who controlled the whole

<sup>1</sup> <http://ag.wilburellis.com/Products/Pages/Home.aspx> (Accessed 17 May 2016).

<sup>2</sup> Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

**Table 1**

Initial soil conditions for a few selected key soil variables for the Houston black clay (0–1%), Ewa silty clay loam (0–3%), and Keahua silty clay loam (3–7%). The soil properties were compiled from the USDA NRCS SSURGO database: <http://sdmdataaccess.nrcs.usda.gov/http://sdmdataaccess.nrcs.usda.gov/> (accessed March 2016).

Soil layer	Houston black clay (0–1%)			Ewa silty clay loam (0–3%)			Keahua silty clay loam (3–7%)			
	1	2	3	1	2	3	1	2	3	4
Soil variable										
Depth (m)	0.01–0.15	0.15–1.12	1.12–2.03	0.01–0.46	0.46–0.99	0.99–1.52	0.01–0.25	0.25–0.84	0.84–1.57	1.57–1.78
Porosity (mm)	0.53	0.50	0.44	0.55	0.53	0.53	0.55	0.57	0.53	0.53
Field Capacity (mm)	0.45	0.42	0.40	0.37	0.36	0.36	0.29	0.32	0.32	0.14
Wilting Point (mm)	0.32	0.30	0.28	0.23	0.22	0.22	0.18	0.21	0.21	0.10
Soil Water (mm)	0.43	0.40	0.38	0.34	0.33	0.33	0.26	0.29	0.29	0.13
Saturated Conductivity (mm/h)	1.46	1.46	1.46	32.40	32.40	32.40	82.80	25.20	9.00	25.20
BD 33kPA ( $\text{t m}^{-3}$ )	1.22	1.31	1.43	1.20	1.20	1.20	1.10	1.10	1.20	1.20
BDD Oven dry soil ( $\text{t m}^{-3}$ )	1.22	1.31	1.43	1.25	1.26	1.26	1.15	1.15	1.26	1.34
Sand (%)	17	17	17	5.8	5.1	5.1	18.5	17	27.6	23.7
Silt (%)	28	28	28	42.2	37.9	37.9	44	40.5	29.9	28.8
Clay (%)	55	55	55	52	57	57	37.5	42.5	42.5	47.5
Rock (%)	2	2	4	0	3	3	6	3	3	3
pH	7.90	7.90	7.90	7.60	7.40	7.40	6.30	6.30	7.00	7.00
CEC ( $\text{cmol kg}^{-1}$ )	45.00	45.00	32.50	21.00	15.00	15.00	22.50	17.50	15.00	15.00
Soil organic carbon (%)	1.32	0.23	0.03	1.76	0.65	0.65	1.76	0.74	0.24	0.18

plantation drip irrigation system. A total of 640 mm was applied during the study period. Liquid urea (46–0–0) and phosphorus fertilizers were applied monthly through the drip irrigation system at rates of 345 kg N ha<sup>-1</sup> and 45 kg P ha<sup>-1</sup>. The timing and rate of fertilizer application were based on HC & S plantation practices and the need to accommodate the fertilizer requirements of the two-year cycle sugar-cane.

### 2.3. Plant growth measurements

At Temple aboveground biomass measurements and sampling began 35 and 45 days after planting (DAP) in 2012 and 2013, respectively. Thereafter biomass measurements and sampling occurred every two weeks. Plant height was measured before each biomass harvest, from the ground to the tip of the longest leaf. Biomass samples were collected from a randomly chosen representative area of 0.5 m x 1 m = 0.5 m<sup>2</sup>, avoiding previously sampled areas or plot edges. Three samples were collected at each harvest. A total of seven biomass harvests were made for each year. The photosynthetically active radiation (PAR) intercep-

tion was measured with a 0.8 m AccuPAR LP-80 Ceptometer (Decagon, Pullman, WA) as described in Meki et al. (2015). In the laboratory, the samples were weighed and then separated into stem, leaves and panicle (head), when present. The leaf area was determined with a LiCor LI-3100 leaf area meter (LiCor Inc., Lincoln, NE) and used to determine leaf area index (LAI). Dry biomass was measured after drying all harvested plant materials in a forced-air drying oven at 70 °C to constant weight which also allowed the determination of percent moisture content at final harvest. The light extinction coefficient (*k*) values for each biomass harvest stage were calculated using Beer's law (Monsi and Saeki's, 1953):

$$k = [\ln (1.0 - \text{FIPAR})]/\text{LAI} \quad (1)$$

where FIPAR is the fraction of intercepted photosynthetically active radiation. The radiation use efficiency (RUE) of the two hybrids was calculated as the slope of the regression equations for dry biomass as a function of accumulated intercepted PAR.

Similar procedures were used to take plant growth measurements from F410 and F718 HC & S: biomass yield (stem, leaves and head), leaf



**Fig. 1.** In Hawaii, both the biomass sorghum hybrids (I-405 and I-1990) behaved like photoperiod insensitive short day grain sorghums, heading in approximately 96 days after planting (DAP) (left photo). In Texas, the two hybrids continued to grow vegetatively (middle photo), and only the late maturing I-405 hybrid flowered late in the season (right photo).

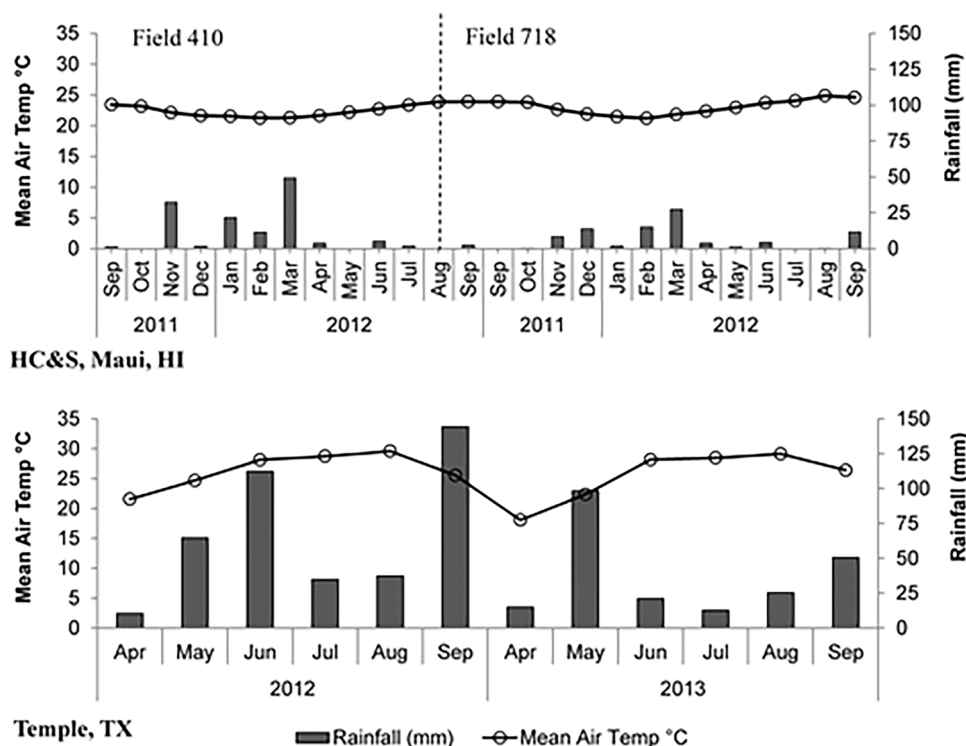


Fig. 2. Mean monthly air temperature and total precipitation for HC & S, Maui, HI Field nos. 410, 718 (during the study period: September, 2011 to September, 2012), and Temple, TX (during the study periods: April to September, 2012 and 2013).

area for LAI determinations, plant height and percent moisture content. Only a limited number of field measurements could be taken in Hawaii due to labor bottlenecks and costs. Field measurements were taken every three months during a 12 month period.

#### 2.4. Data analysis

Statistical analyses for the two experimental sites were performed

using SAS version 9.3 (SAS Institute, 2011). Standard and repeated Measures ANOVA using SAS PROC GLM was performed on the measured and derived variables: plant height, dry biomass (stem, head and leaves), percent moisture content, LAI,  $k$ , FIPAR, and RUE. The SAS REG procedure was used to conduct regression analyses to describe the relationship between aboveground dry biomass vs. accumulated intercepted PAR. Differences between means of measured and derived variables were separated by standard errors for the mean at  $P < 0.01$ .

### 3. Results and discussion

#### 3.1. Temperature, precipitation, and irrigation

The mean monthly air temperature and total precipitation at HC & S during the study period (September, 2011 to September, 2012) for Field 410 were respectively, 22 °C and 112 mm (Fig. 2). The dotted line separates the weather data for Field 718 whose mean monthly air temperature and total precipitation were respectively, 23 °C and 88 mm. The mean monthly air temperature and total precipitation for Temple during the study periods were respectively, 26 °C and 404 mm (2012), and 25 °C and 223 mm (2013).

#### 3.2. Plant height

Differences in plant height and developmental stages of the biomass sorghum hybrids grown at HC & S and Temple are shown in Figs. 1 and 3. At HC & S I-405 and I-1990's final heights were dependent on the date of planting (Fig. 3a). When I-405 and I-1990 were planted before March i.e. daylength hrs < 12 h 20 min, the biomass sorghums behaved like photoperiod insensitive short day grain sorghums. The hybrids had initiated flowering by the first biomass harvest date (96 DAP) (Figs. 1a and 5b) and only grew to final heights of less than 2 m. In contrast, when the two hybrids were planted after March i.e. when daylength hrs exceeded 12 h 20 min (Fig. 3a) their plant heights exceeded 3.0 m.

At Temple, I-405 and I-1990 were not significantly different in plant

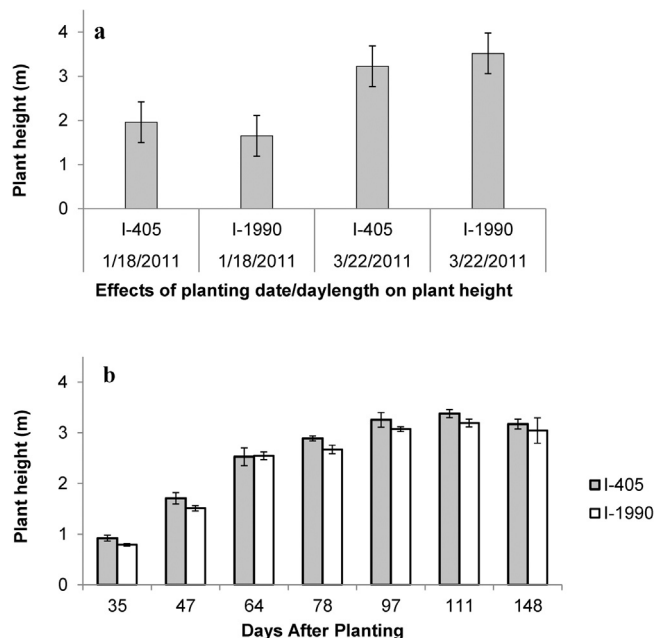


Fig. 3. (a) Effects of planting date/daylength on hybrids I-405 and I-1990 plant heights at HC & S, Maui, HI, during the 2011 growing season, and (b) plant height measurements for I-405 and I-1990 at Temple, TX, averaged across the 2012 and 2013 growing seasons. Vertical bars represent the standard error of the means of the measured data.

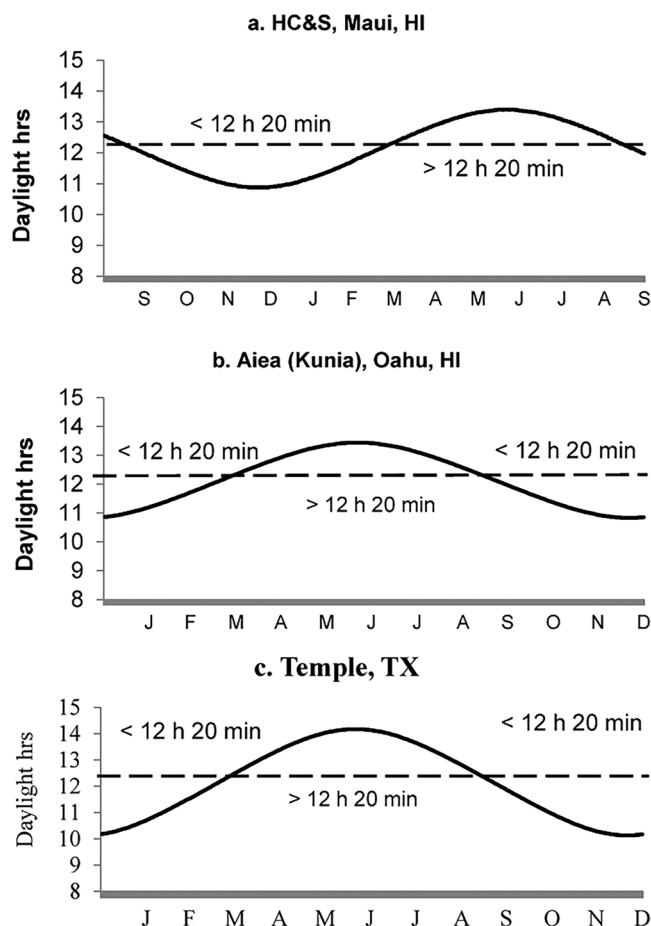


Fig. 4. (a) Daylight hours at HC&S, Maui, HI, (b) Aiea, Oahu, HI, and (c) Temple, TX, during the study periods.

height ( $P < 0.01$ ) across the two growing seasons: 2012 and 2013, reaching maximum plant heights of 3.38 m and 3.19 m, respectively (averaged across years) (Fig. 3b). Overall the plants' prolonged vegetative growth contributed to the high plant heights. Biomass sorghum plant heights exceeding 3 m have also been reported in several studies (Maughan et al., 2012; Rocateli et al., 2012; Carmi et al., 2006; Sakellariou-Makrantonaki et al., 2007).

The daylength effect assumption is corroborated by the results of a study by Smith et al. (1987) at Aiea, HI (23°N latitude) and the response of other measured traits at HC&S. In a 4-year varietal study of four to six sweet sorghum cultivars, Smith et al. (1987) recorded an average maximum plant height of 3.88 m and a biomass yield of 29.61 Mg ha<sup>-1</sup>. Although plant dates are not mentioned in the Smith et al. (1987) paper, it is most likely the two experiments conducted in 1981 and 1983 were planted during the time when daylength hrs were greater than the photoperiod trigger of 12 h 20 min (March 30 and September 1) (Fig. 4b). At Temple, and for most other places on the continental USA, biomass sorghums are planted when daylength hrs exceed the photoperiod trigger of 12 h 20 min (Fig. 4c).

Although no significant lodging was observed in I-405 and I-1990 both at Temple and HC&S, Smith et al. (1987) noticed significant lodging in nearly all the cultivars which had plant heights that exceeded 3 m. Serious problems associated with the lodging of tall plants can lead to reduced biomass yields especially in places such as Hawaii which sometimes experience adverse weather conditions of high winds. More research is needed to determine if it is possible to develop biomass sorghum types of medium height but with wider stem diameters to maintain the high biomass yield.

### 3.3. Dry biomass yields

The total, stem, leaves and head dry biomass yields differed greatly between hybrids and years during the 2012 and 2013 growing seasons at Temple, TX (Fig. 5a). There were significant biomass yield differences ( $P < 0.01$ ) between the I-405 and I-1990, across harvest dates and the 2012 and 2013 growing seasons. The two hybrids performed as expected of high biomass sorghums, with I-405 and I-1990 reaching maximum biomass yields of 37.9 Mg ha<sup>-1</sup> and 36.9 Mg ha<sup>-1</sup> in 2013, respectively (Fig. 5a). These biomass sorghum yields are comparable to those reported in College Station, TX by Miller and McBee (1993), Rooney et al. (2007), and Olson et al. (2012). Despite the supplemental irrigation at Temple, overall dry biomass yields were 50% lower in 2012 due to the comparably lower rainfall during the rapid growth phase of biomass sorghum.

Both I-405 and I-1990 initially had a rapid accumulation of leaf biomass before it was overtaken by stem biomass at about 50 DAP. By the time of the final harvest (148 DAP) stem biomass comprised approximately 73% of the total dry biomass. In a similar study, Olson et al. (2012) reported an end of season stem biomass partitioning of 83%, while Smith et al. (1987) reported a percent stalk harvest weight of 79%. Flowering in I-405 resulted in a 7% and 25% decline in total biomass yield in 2012 and 2013, respectively. Despite the flowering (approximately 78 and 97 DAP in 2012 and 2013, respectively), the grain yield of I-405 at the final harvests was only 2.3% of the total biomass. As expected I-1990 did not flower at all continuing to grow vegetatively until the final harvest at 148 DAP.

In sharp contrast to the results obtained at Temple, overall dry biomass yields of both I-405 and I-1990 were 76% lower at HC&S (Figs. 1 and 5b). Interestingly, sweet sorghum biomass yields at Aiea, HI (29.61 Mg ha<sup>-1</sup>) (Smith et al., 1987) were within the range for biomass sorghum yields reported for the continental USA and other regions of the world (Habyarimana et al., 2004a,b; Ra et al., 2012; Ceotto et al., 2013). Despite there being no significant differences ( $P < 0.01$ ) between I-405 and I-1990 biomass yields, the hybrids at HC&S had a growth pattern which was distinctively different from that at Temple. Similar to the plant height responses, the growth pattern seemed to have somewhat been influenced by the date of planting and daylength hrs during emergence. Although both hybrids were planted on September 9 when the daylength hrs were 12 h 24 min (Fig. 4a), the daylength only four days after planting was less than the photoperiod trigger hrs of 12 h 20 min. Even though I-405 is considered late maturing and I-1990 photoperiod-sensitive, both hybrids behaved like photoperiod insensitive short day grain sorghums. The hybrids initiated flowering by the first biomass harvest date (96 DAP) (Figs. 1 and 5b). Planting biomass sorghums during inappropriate daylength periods will trigger early flowering and heading, and will result in low biomass yields (Blade Energy Crops, 2010). Heading diverts assimilates from the vegetative parts, primarily stems and leaves to the grain resulting in low biomass accumulation and overall biomass yields. Even though both I-405 and I-1990 were still at the soft dough stage (Zadoks et al., 1974) when they were harvested at 96 DAP they already had reduced biomass accumulation and had started to senesce resulting in a drop in biomass yield at the second harvest date (172 DAP). Similar results have been reported for grain sorghum by Gutjahr et al. (2013) in Mali and by Olson et al. (2012) in College Station, TX.

After the second biomass harvest date (172 DAP) daylength started to increase (Fig. 4a), while there was also a slight increase in the mean daily air temperature (Fig. 2). Given these conditions plus the continued drip irrigation and fertigation, both hybrids started tillering which increased total biomass accumulation throughout the rest of the growing period. While the growth pattern and biomass yields of I-405 and I-1990 in F718 are very much similar, their growth responses in F410 are slightly different, in particular at the last harvest (368 DAP) at which I-1990 had a 59% higher biomass yield than I-405. In F410, and although small, I-1990 flowered and produced some head at the 368

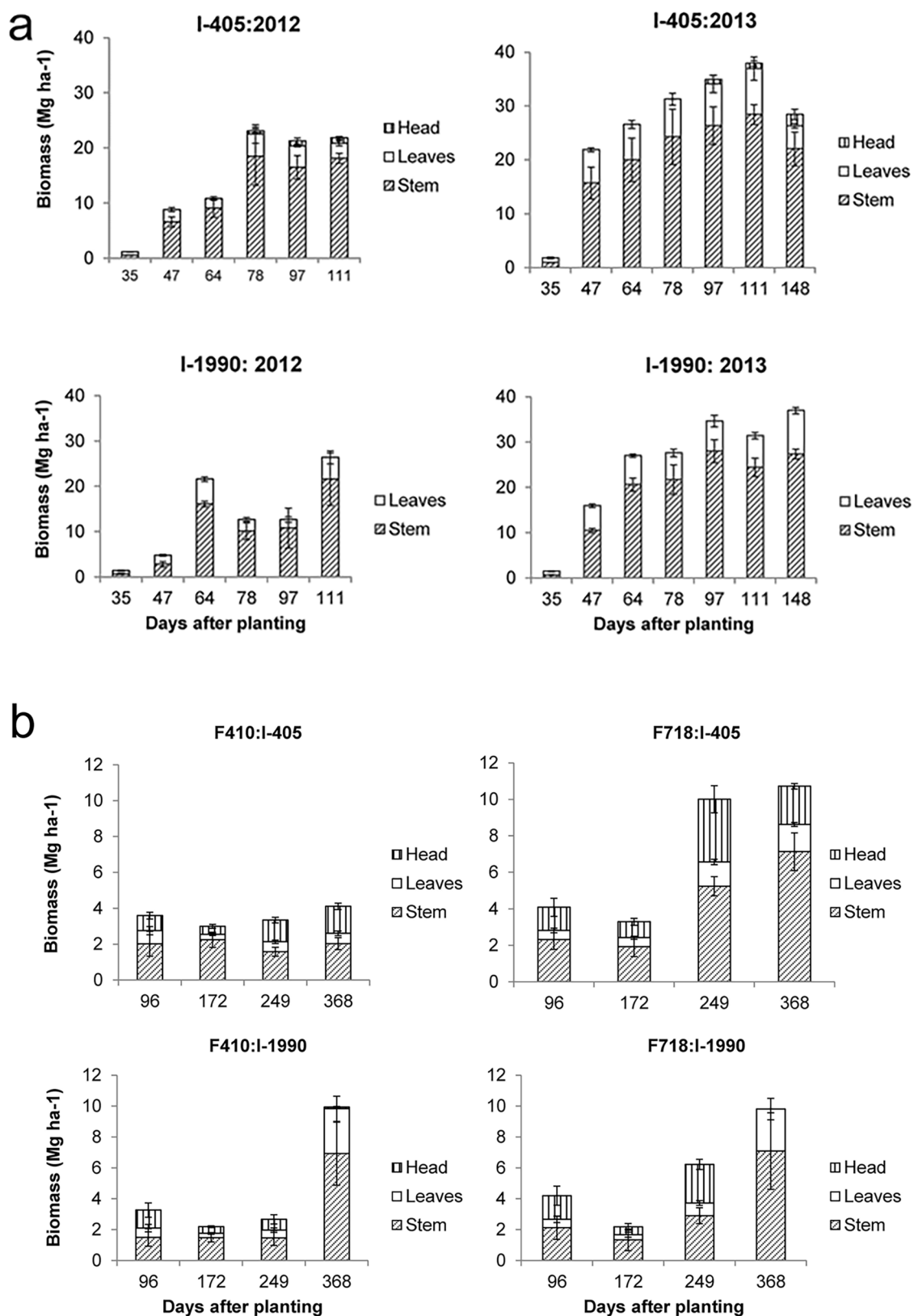


Fig. 5. (a) Total, stem, leaves and head dry biomass yields of biomass sorghum hybrids I-405 and I-1990 during the 2012 and 2013 growing seasons at Temple, TX, and (b) fields (F) 410 and 718 at HC & S, Maui, HI. Vertical bars represent the standard error of the means of the measured data.

DAP harvest, while in F718, I-1990 did not produce any head at all. We could not find any reasonable explanation of this difference, except to speculate that it could have been due to sampling errors. We did however notice that overall, plants did not all flower and head at the

same time, raising questions of the genetic purity of the hybrid.

Although the total accumulated biomass at HC & S was much lower than that at Temple, grain biomass partitioning for both hybrids was much higher, which on average was 30% for I-405 and 26% for I-1990,

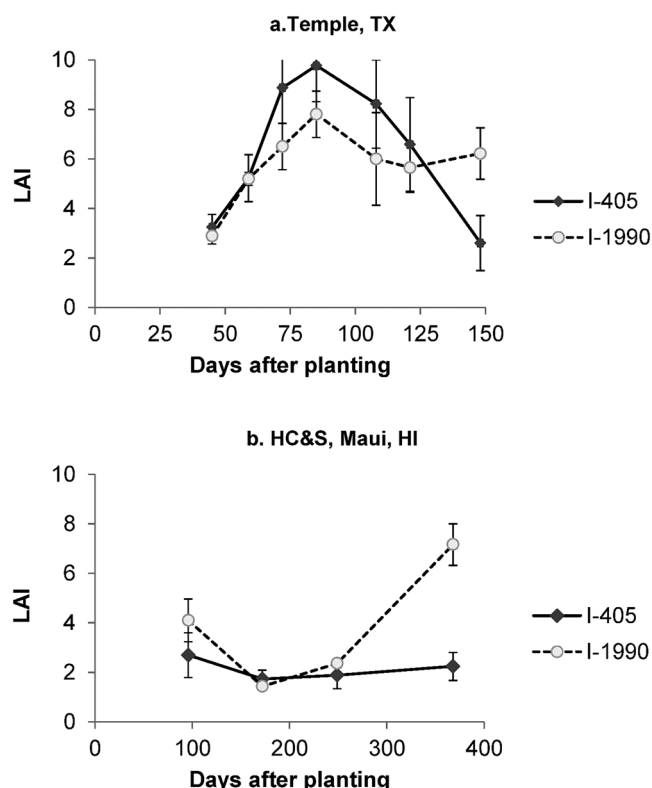


Fig. 6. (a) Measured leaf area index (LAI) at Temple, TX and (b) HC & S plantation, Maui, HI. Vertical bars represent the standard error of the means of the measured data.

respectively. Again partitioning of stem biomass to total biomass increased over time, and was similar for both hybrids and respectively reaching peak values of 58% (I-405) and 71% (I-1990) at the last harvest (368 DAP).

While high biomass yields are deemed essential for lignocellulosic bioenergy feedstock production, a study by Mohammed et al. (2014) showed that sometimes less harvested biomass could produce more energy, with the added advantages of reduced biomass ash, soil nutrient uptake, transportation costs, and storage. However, the biomass yield reduction due to the inappropriate date of planting and daylength photoperiodic effects in HI was such that biomass quality alone would not offset the bioenergy output from the high biomass yields obtained in Texas. Both direct combustion and cellulosic ethanol production from high biomass sorghum requires the maximization of cellulosic biomass yields (Rooney et al., 2007; Carpita and McCann, 2008).

Although it can be argued that the low biomass yields in HI were due to the lower seeding rates, studies by Snider et al. (2011) showed

that increasing seeding rate from 116,000 to 291,000 seeds  $\text{ha}^{-1}$  did not affect biomass sorghum yields. High seeding rates produce tall plants with thinner stem diameters, while lower seeding rates produce shorter plants with thicker stem diameters (Blade Energy Crops, 2010; Snider et al., 2011). Snider et al. (2011) also noticed that under low seeding rates, stem density was higher than the number of seeds sown, suggesting that tillering compensated for the low seeding rates. Similarly, Gerik and Neely (1987) observed increased tiller production under low plant densities in grain sorghum, therefore suggesting that plant compensation via tillering may maintain stem density in some instances.

### 3.4. Leaf area index (LAI) and light interception

The LAI, light interception and dry biomass data collected at Temple were used to derive some of the crop parameter attributes of high biomass sorghums. For most crops LAI is a key driving variable for plant growth rate (PGR) and biomass accumulation especially before full crop canopy closure when light interception by individual leaves is at its maximum (Evans, 1993). In addition LAI determines the amount of intercepted radiation and hence RUE, which in turn is an important function that is basic to plant growth. A linear relationship between LAI and PGR was reported by Tsuni and Fujisi (1965) and Meki et al. (2015). There were significant differences ( $P < 0.01$ ) in LAI between I-405 and I-1990 at Temple. Averaged across the two years maximum LAI values for I-405 and I-1990 were 9.8 and 7.8, respectively (Fig. 6a). Similar biomass sorghum LAI values have been reported by Olson et al. (2012) (LAI = 8.4) and Ceotto et al. (2013) (LAI = 7.0–8.5). The high LAI resulted in greater light interception as shown by the relationship between LAI and FIPAR for I-405 and I-1990 (Fig. 7). Both I-405 and I-1990 intercepted more than 90% of the incident PAR. A similar relationship was observed by Bégué (1993), Cieto et al. (2013), and Olson et al. (2012). As pointed out by Bégué (1993), plants with LAI  $> 4$  intercept more than 90% of incident PAR. Maximum LAIs were reached 85 DAP. Thereafter LAI started to decline even though both hybrids maintained some green foliage up to the last harvest (148 DAP). According to Williams and Izaurrealde (2013) the LAI of vegetative crops reaches a plateau at which time the rates of senescence and growth of leaf are approximately equal.

At Temple, the average light extinction ( $k$ ) values were 0.43 and 0.53 for I-405 and I-1990, respectively. Our values compare well with the values derived by Curt et al. (1998) ( $k = 0.57$ ), Varlet-Grancher et al. (1992) ( $k = 0.59$ ) and Perniola et al. (1996) ( $k = 0.62$ ). A higher value of  $k$  infers a higher incident PAR capture.

At HC & S LAI values were comparably lower, with I-405 and I-1990 respectively reaching maximum LAIs of 4.5 and 3.0 at the last harvest (368 DAP) (Fig. 6b). The LAIs were significantly different ( $P < 0.01$ ) at the first harvest (96 DAP) and last harvest 368 DAP, while at 172 DAP and 249 DAP there were non-significant. The increase in LAIs after dropping at 172 DAP was due to an increase in tillering.

### 3.5. Plant growth rate (PGR)

As expected, the computed PGRs ( $\text{kg dry biomass ha}^{-1} \text{ day}^{-1}$ ) from the data presented in Fig. 5 show that Temple had much higher PGRs than HC & S. Even with the limited irrigation applied at Temple, the PGRs in 2012 ( $153.20 \pm 20.91 \text{ kg ha}^{-1} \text{ day}^{-1}$ ) were still lower than in 2013 ( $224.96 \pm 24.76 \text{ kg ha}^{-1} \text{ day}^{-1}$ ) due to the adverse drought conditions. The hybrid I-405 had a higher PGR ( $200.81 \pm 24.50 \text{ kg ha}^{-1} \text{ day}^{-1}$ ) than I-1990 ( $177.35 \pm 21.17 \text{ kg ha}^{-1} \text{ day}^{-1}$ ). As with the biomass yields PGRs at HC & S were drastically lower than those at Temple. The PGR for I-405 and I-1990 prior to heading (96 DAP) were very much similar ( $41.65 \pm 7.71 \text{ kg ha}^{-1} \text{ day}^{-1}$  and  $40.44 \pm 10.01 \text{ kg ha}^{-1} \text{ day}^{-1}$ , respectively). Thereafter the PGRs were drastically reduced to an average of  $8 \text{ kg ha}^{-1} \text{ day}^{-1}$ . The low elevation field 718 had a slightly higher

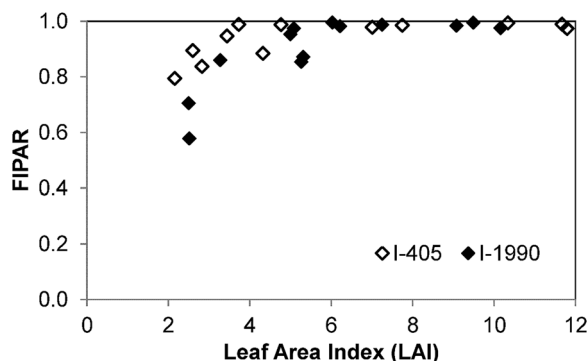


Fig. 7. Relationship between the fraction of intercepted photosynthetically active radiation (FIPAR) and leaf area index (LAI) of biomass sorghum hybrids I-405 and I-1990 at Temple, TX.

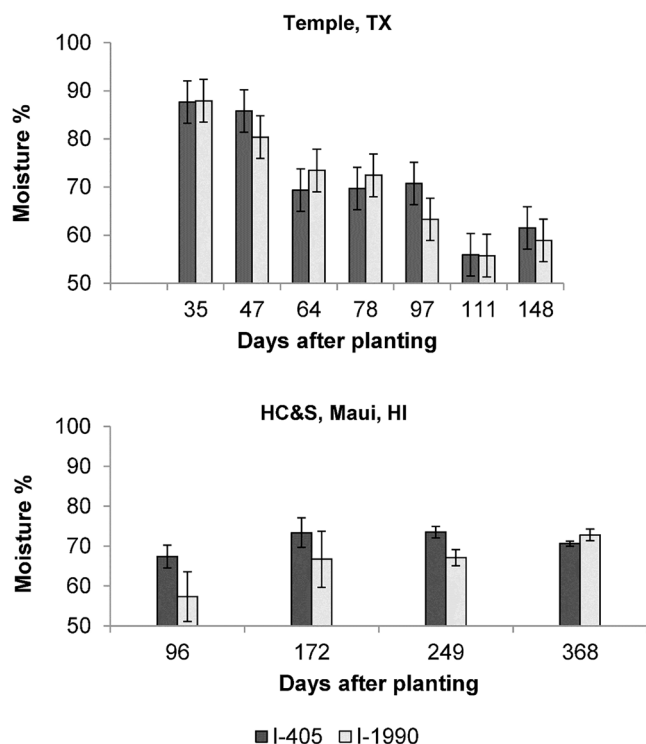


Fig. 8. (a) Biomass sorghum moisture content at each harvest date at Temple, TX and (b) fields (F) 410 and 718 at HC & S, Maui, HI. Vertical bars represent the standard error of the means of the measured data.

overall biomass accumulation rate of  $28 \text{ kg ha}^{-1} \text{ day}^{-1}$  ( $R^2 = 0.79$ ) due to the slightly warmer air temperature compared to the rate of  $17 \text{ kg ha}^{-1} \text{ day}^{-1}$  ( $R^2 = 0.56$ ) for the high elevation field 410. Not surprisingly, final dry biomass yields (368 DAP) for both hybrids were slightly higher in field 718 than in 410 (Fig. 5b).

The maturation of late maturing and photoperiod sensitive sorghum hybrids is regulated entirely by either thermal time accumulation (degree days) or daylength photoperiod triggers. According to Childs et al. (1997) daylength is the most important environmental factor that regulates flowering in sorghum genotypes. A thermal time accumulation trigger is found in grain sorghums in which maturity will only be reached after a specified accumulation of heat units. Photoperiod sensitive sorghums will not flower and hence produce high biomass through continued vegetative growth if sown when the daylength is more than the photoperiod trigger of 12 h 20 min. However, growth in the more recently developed hybrids is regulated by a combination of varying degrees of both thermal time and day-length (Blade Energy Crops, 2010). The regulation of flowering time in sorghum genotypes has been widely studied and identified as being genetically and environmentally controlled (Childs et al., 1997; Murphy et al., 2011; Yang et al., 2014). According to Morgan and Finlayson (2000) the stage of plant development, daylength period, temperature, plant hormones such as gibberellins are all integrated to regulate flowering time in sorghum.

### 3.6. Biomass moisture content

Overall there were no statistically significant differences between I-405 and I-1990 in biomass moisture contents (Fig. 8). At Temple, biomass moisture content reached a maximum of 88%, 35 DAP, after which it started to decline, reaching an average of 60% at the last harvest (148 DAP). Interestingly, biomass moisture contents at HC & S actually seemed to slightly increase at each harvest. The increase in biomass moisture content over the growing season could be associated

with continued tillering over the growing season. Furthermore, there was little to no relationship between biomass moisture and rainfall/temperature. Lower biomass moisture contents at harvest are highly recommended for reduced transportation costs and storage (Mohammed et al., 2014), and also ensure feedstock quality during storage (Rocateli et al., 2013).

### 3.7. Radiation use efficiency (RUE)

Radiation use efficiency varied from 2.39 to 3.04 at Temple (Fig. 9). The RUE values in 2012 were lower than those in 2013 partly due to the lower biomass yields as a result of the drier 2012 season (Fig. 2). The average RUE of  $2.75 \text{ g MJ}^{-1}$  is within the range of values for biomass sorghums reported by Rinaldi and Garofalo (2011) ( $2.91 \pm 0.54 \text{ g MJ}^{-1}$ ), and Olson et al. (2012), ( $2.2\text{--}2.3 \text{ g MJ}^{-1}$ ). Slightly higher RUE values have also been reported:  $3.4 \text{ g MJ}^{-1}$  (Mastorilli et al., 1995),  $3.48 \text{ g MJ}^{-1}$  (Ceotto et al., 2013),  $3.6 \text{ g MJ}^{-1}$  (Varlet-Grancher et al., 1992), and  $3.55 \text{ g MJ}^{-1}$  (Dercas and Liakatas, 2007). According to Rinaldi and Garofalo (2011), RUE can vary depending on experimental conditions, especially the amount of crop available soil moisture and plant nutrients. Similarly, Demetriades-Shah et al. (1992) stressed that comparisons of RUE should only be made when measurements are made under similar conditions.

## 4. Conclusion

From a practical standpoint, the performance of the biomass sorghum hybrids used in this study was largely affected by the time of planting and daylength effects. At Temple, TX, the late maturing biomass sorghum hybrid I-405 and the photoperiod-sensitive hybrid I-1990 were planted at the beginning of April when daylight hrs exceeded 12 h 20 min. The two hybrids performed as expected: grew to heights in excess of 3 m and produced average biomass yields of  $37.4 \text{ Mg ha}^{-1}$ . At Temple, and for most other places on the continental USA, biomass sorghums should be planted when daylength hrs exceed of 12 h 20 min, which allows the hybrids to continue growing vegetatively for longer periods (up to six months) before harvest. In Maui, HI, the biomass sorghum hybrids were planted in September when the daylength hrs were less than 12 h 20 min, resulting in the hybrids flowering as early as 90 days after planting. For most grain crops, flowering diverts assimilates from the vegetative parts, primarily stems and leaves to the grain, resulting in low biomass accumulation and overall biomass yields. In the HI experiment, overall plant heights and biomass yields were reduced by 44% and 76%, respectively. Not surprisingly, final dry biomass yields for both hybrids were slightly higher in the low elevation F718 than in the higher elevation F410 (Fig. 5b).

Crop parameter attributes for high biomass yields for the two hybrids planted at Temple indicated: high leaf area indices (LAI, 7.8–9.8) which intercepted over 90% incident PAR at  $\text{LAI} > 4$ , and an average light extinction coefficient ( $k$ ), PGR, and RUE of 0.48,  $189 \text{ kg dry biomass ha}^{-1} \text{ day}^{-1}$ , and  $2.75 \text{ g MJ}^{-1}$ , respectively. In sharp contrast to the results obtained at Temple, the two sorghum hybrids planted on Maui had lower leaf area indices (average LAI, 3.8) and PGR prior to heading (average,  $41 \text{ kg ha}^{-1} \text{ day}^{-1}$ ).

Besides determining crop parameter attributes and environmental factors for high biomass yields, the study provides valuable crop coefficients that can be incorporated into field and regional/watershed process-based models, such as ALMANAC, EPIC/APEX and SWAT to simulate biomass sorghum growth, and associated environmental impacts. These models can be used as tools for assessing the feasibility and potential sustainability of biomass sorghum biofuel feedstock cropping systems in various target environments.

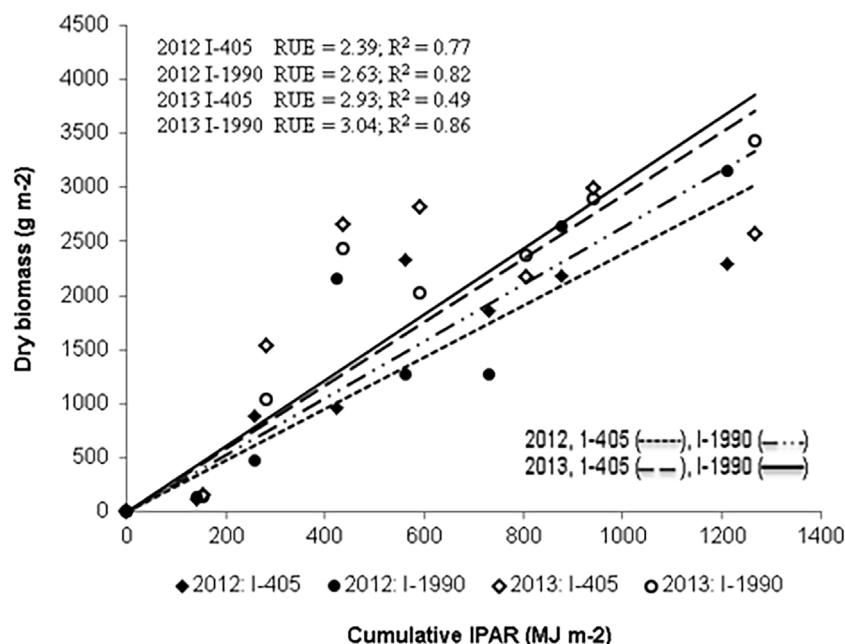


Fig. 9. Radiation use efficiency (RUE) of biomass sorghum hybrids I-405 and I-1990 at Temple, TX during the 2012 and 2013 growing seasons.

## Acknowledgements

Preparation of this manuscript supported by the USDA-ARS, Grassland, Soil and Water Research Laboratory, and Texas A & M AgriLife Research, Temple, TX, through Specific Cooperative Agreement: 58-6206-1-053, and was funded by the U.S. Navy, Office of Naval Research (ONR). This work was also partly funded by an ONR GrantN00014-12-1-0496 and USDE Award DE-FG36-08G088037 to the University of Hawaii. We appreciate the support by the USDA National Institute of Food and Agriculture: Hatch project TEX09514. Finally, we thank Jason Drogowski, Daniel Richardson and HC & S staff for field work and research support. USDA is an equal opportunity provider and employer.

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