Two-Year Growth Cycle Sugarcane Crop Parameter Attributes and Their Application in Modeling

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ABSTRACT

The renewed interest in the use of sugarcane (*Saccharin officinarum* L.) for biofuel could provide a viable market for potential Hawaiian sugarcane feedstock producers. In Hawaii, sugarcane is grown as an irrigated 2-yr cycle crop. There is however little information on crop parameter attributes of 2-yr cycle sugarcane. This field study on Maui, Hawaii, analyzed the relationship between sugarcane biomass accumulation and specific crop parameters. Overall, the high dry biomass yield (80.20 Mg ha^{-1}) was the result of a high leaf area index (LAI, 7.50) and radiation use efficiency (RUE, 2.06 g MJ^{-1}. The crop growth rate was highly correlated to LAI (R^2, 0.86), and a light extinction coefficient (k) of 0.53 was estimated. Stalk density was estimated at 18 stalks m^{-2}, with a maximum plant height of 3.6 m, and a rooting depth exceeding 2.0 m. When the crop parameters were incorporated into a biological model of Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) the model accurately simulated sugarcane yields across seven different soil types and multiple management scenarios of applied irrigation water, N and P fertilizer inputs and various planting and harvest dates. The mean simulation percent (%) errors ranged from −6.4% to 1.8%, while the calculated Fisher's paired t test of 1.41 with 39 degrees of freedom, showed no significant differences ($P \geq 0.05$) between measured and simulated yields. The ALMANAC model should be useful as a decision support tool for evaluating sugarcane management alternatives that maximize yields while optimizing water, N and P inputs.

Sugarcane production in Hawaii has declined since the 1970s due to a number of factors that include low prices, high labor costs, competition from artificial sweeteners, and low cost production from such countries as Mexico, Brazil, India, and China. Despite these challenges, the Hawaii Commercial & Sugar Company (HC&S) continues to produce approximately 181,400 Mg yr^{-1} of raw sugar on 14,164 ha of land. This company is the last remaining sugarcane plantation in Hawaii and is based on Maui Island. Sugarcane production plays a major role in the island's economy, employing more than 800 people. In addition, the company generates its own electricity and enough energy to meet up to 8% of Maui's total electricity needs through the burning of the residual biomass (bagasse), which is used internally or sold to the county's electricity grid, (HC&S, 2011). Recently, competition for scarce water resources coupled with declining precipitation have become the major constraints to sugarcane productivity and profitability at HC&S. Sugarcane needs 1500 to 2500 mm of water evenly distributed over the growing season (FAO, 2013).

Faced with these multiple challenges, HC&S in collaboration with USDA-ARS implemented a joint project plan to explore the feasibility and sustainability of producing advanced biofuel feedstocks as alternatives to raw sugar production in Hawaii. Among other candidate biofuel crops, sugarcane is an ideal feedstock crop for ethanol production in Hawaii due to its rapid growth, moisture stress tolerance, and high yields (Kinoshita and Zhou, 1999; Grantz and Vu, 2009; Laclau and Laclau, 2009). Furthermore, sugarcane has advantages

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Abbreviations: ALMANAC, Agricultural Land Management Alternatives with Numerical Assessment Criteria; APEX, The Agricultural Policy/Environmental eXtender; DM, dry matter; EPIC, Environmental Policy Integrated Climate; 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; PHU, potential heat units; RUE, radiation use efficiency; SWAT, Soil and Water Assessment Tool.

over other potential biofuel feedstock crops because (i) it is a well-established crop known by both current and previous producers, (ii) it already has an existing sound production and agricultural marketing infrastructure, and (iii) it has a well-established greenhouse gas reduction potential (Goldemberg, 2008; Wang et al., 2012). This renewed interest in the use of sugarcane for biofuel could provide a viable market for potential Hawaiian sugarcane feedstock producers.

At HC&S, and previously elsewhere in Hawaii, sugarcane is grown as an irrigated 2-yr cycle crop. The 2-yr cycle cane and sugar yields (160 Mg ha^{-1} cane yield and 16% sugar yield) are above the national average (79 Mg ha^{-1} cane yield and 12% sugar yield) (NASS, 2013). A recent study by Anderson et al. (2015) also confirmed that Hawaiian sugarcane has a higher net productivity and overall biomass yield than sugarcane grown in other regions of the world. There is however little quantitative information describing the relationship between 2-yr cycle sugarcane biomass yield to important crop parameter attributes that can be utilized in dynamic crop modeling decision support tools to optimize crop management practices and to explore more complex issues of sustainability and long-term environmental impacts of management alternatives. Most studies have tended to focus mainly on the relationship between sugarcane biomass yield and LAI, light interception and radiation use efficiency (RUE) (Bull and Tovey, 1974; Donaldson et al., 2008; Muchow et al., 1994; Robertson et al., 1996; Anderson et al., 2015).

With this in mind, we conducted a field study at the HC&S plantation to (i) collect data for analyzing the relationship between sugarcane biomass accumulation and specific crop parameter attributes, such as LAI, light extinction coefficient (*k*), fraction of intercepted photosynthetically active radiation (FIPAR), RUE, maximum plant height and rooting depth, and stalk density, and (ii) evaluate the accuracy of the developed crop parameters in calibrating the biological model of ALMANAC (Kiniry et al., 1992) for simulating 2-yr cycle sugarcane management practices and yields. The model has been extensively validated and applied to analyze crop grain and bioenergy feedstock yields, plant community dynamics, phenology, water, nutrient and RUEs, hydrology, erosion, soil organic carbon, and nutrient cycling (Behrman et al., 2013; Engel et al., 2010; King et al., 1998; Kiniry et al., 1996, 2005, 2008, 2012; Meki et al., 2013; Persson et al., 2011).

MATERIALS AND METHODS

Study Site and Cultural Practices

Sugarcane crop data was collected from a field experiment conducted at HC&S plantation, Field no. 609 (20.89° N, –156.41° W; elevation ~ 100 m asl). The field soil belongs to the Molokai series, and is a kaolinitic, isohyperthermic Typic Eutrotorox (USDA NRCS, 2011). The soil is very-fine, well drained and has deep, well-defined horizons below the plow layer. Field plots were established on 26 June 2011 for the 24 mo cropping cycle ending May 2013. The field had been continuously cropped with sugarcane for well over 100 yr. A repeated measures design with three replicates was used. Overall plot sizes were approximately 15 by 10 m. The space between plots was 3 m. The sugarcane plots were planted with seed cane variety H65-7052 (Heinz et al., 1981). Seed billets were planted by a machine that in one pass digs the furrow, drops the cane pieces, injects the irrigation tubing, and covers the furrows. Each plot was made up of six rows with a row planting scheme consisting of two narrow rows at 0.91 m apart and an interval row spacing between each two narrow rows of 1.82 m. Drip irrigation lines were laid out in the middle of each of the two narrow rows (Fig. 1). All plots were adequately fertigated with urea (46–0–0) at a rate of 345 kg N ha^{-1}. At HC&S fertilizers are applied only during the first year of growth. In total 3520 mm of water was drip-applied during the 2-yr growth cycle. 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 during the early establishment stage. Crop parameter data was collected from the two middle narrow rows with the two narrow outer rows acting as borders. No water or N stress conditions were observed throughout the crop growth cycle and hence the plants were able to express their full genetic potential. Soil moisture was monitored with a Stevens Hydra Probe II soil sensor (Stevens Water Monitoring Systems, Inc., Portland, OR).Weather data was collected at the field site by a portable automatic weather station (HOBO logger model H-21, Onset Computer, Bourne, MA).

For model simulations the length of the growing season at the study site was calculated in accumulated potential heat units (PHU) (sometimes referred to as growing degree days) using the equation:

$$\mathrm{PHU} = \Sigma\,[(T_{\mathrm{max.}} + T_{\mathrm{min.}})/2 - T_{\mathrm{base}}] \qquad [1]$$

where $T_{\mathrm{max.}}$ and $T_{\mathrm{min.}}$ are the averages of the daily maximum and minimum temperatures compared to a base temperature, T_{base}, in °C (10°C for sugarcane and many other tropical crops).

Field Measurements

Sugarcane cultivars grown in Hawaii over a 24 mo growth cycle have two distinct growth patterns. During the first 12 mo the cultivars exhibit a growth pattern similar to that of 12 to 18 mo cultivars grown on the U.S. mainland and elsewhere in the world. Plants grow tall and straight with little or no lodging (Fig. 2a). After 12 mo the plants start to lodge due to the high biomass accumulation and in some cases lodging is exacerbated by high winds (Fig. 2b).

Lodging seems to have the positive benefit of exposing the sugarcane plants to more sunlight and hence allowing for more biomass and sugar accumulation (Mae Nakahata, HC&S agronomist, personal communication, 2011). Biomass sampling of the lodged crop does however present some challenges when matching harvested biomass to corresponding LAI and intercepted light measurements. To overcome this challenge we devised two protocols for biomass sampling, LAI determination and taking light interception measurements during the first 12 mo (Protocol I), and thereafter from 12 to 24 mo (Protocol II).

Protocol I (0–12 mo). Monthly biomass samplings were made during the first 12 mo of the growth cycle. We used a rectangular PVC pipe frame open on one end (1.25 by 0.8 m = 1.0 m^2)

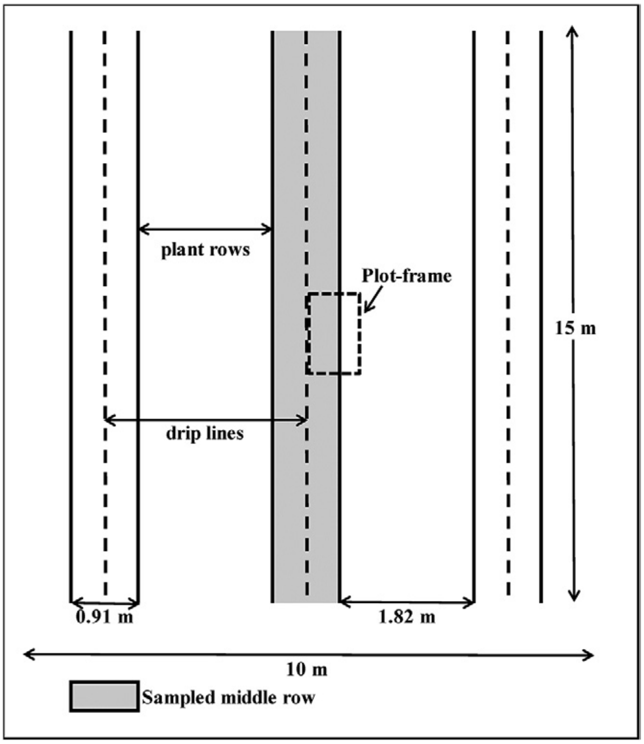

Fig. 1. Plot layout showing sugarcane row spacing in relation to drip line placement.

(Fig. 1 and also see pointed arrow in Fig. 2a) to demarcate the sampling area. The frame was placed on the ground with the long edge (1.25 m) onto and parallel to the drip line and plant rows as shown in Fig. 1 and 2. The plant height was measured from the base of the stool (i.e., sugarcane shoots growing out of buds on the joints of the billets) to the top of the longest leaf. The stalks within the frame area that were greater than one-fourth of the maximum plant height were recorded for estimation of stalk density. The PAR interception was measured with a 0.8 m AccuPAR LP-80 Ceptometer (Decagon, Pullman, WA) between 1000 and 1300 h–the times when incident solar radiation was usually relatively stable. Two ceptometers were used to take concurrent above and below canopy PAR readings after "test matching" PAR readings from both ceptometers on an open space. These readings should match or have a difference of <100 μmol m^{-2} s^{-1}. When they differed by more, we recalibrated the sensors and took the measurements again. The open space PAR readings represent the above canopy PAR readings. Below

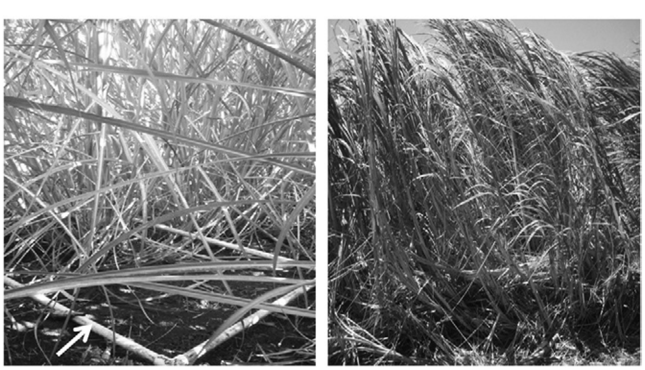

Fig. 2(a) Eight-month sugarcane showing no signs of lodging, and (b) Lodged sugarcane at 23 mo lodging can be exacerbated by high winds.

canopy PAR measurements were taken 10 cm above the ground while moving the ceptometer across the plant row and along the 1.25 m length of the frame. Sampled row areas were chosen at random but making sure they were not next to any previously sampled area. The FIPAR was calculated with the mean of at least five PAR measurements above and below the canopy.

A representative subsample of three to five cane stalks (based on visual observations of plant height) was harvested from within the frame for LAI determination in the laboratory. The rest of the plant material within the frame was harvested and weighed in the field to get the total weight. In the laboratory, the subsample was weighed and then separated into green leaves, dead leaves, green photosynthetic stalks and brown non-photosynthetic stalks. The leaf area was determined with a LiCor LI-3100 leaf area meter (LiCor Inc., Lincoln, NE). The LAI was calculated as the area of the subsample multiplied by the ratio of the total fresh weight/subsample fresh weight divided by sampled ground area. An important model parameter associated to LAI is the rate of LAI decline between the maximum LAI and harvest time–between 15 to 24 mo. This parameter was determined by systematically adjusting model pre-set values; 1.0 is linear; >1 accelerates decline; <1 retards the decline rate, until the simulated decline rate matched the measured LAI data values. The *k* values for each biomass harvest stage were calculated by changing Beer's law, as originally described by Monsi and Saeki's (1953):

$$\text{FIPAR} = 1 - \exp^{(-k \times \text{LAI})} \qquad [2]$$

Into:

$$k = [\text{Ln}\,(1.0 - \text{FIPAR})]/\text{LAI} \qquad [3]$$

Subsample total dry matter was measured after drying all harvested plant materials in a forced-air drying oven at 70°C to constant weight.

Protocol II (12–24 mo). In 2-yr growth cycle sugarcane biomass accumulation slows down (reduced growth phenomena) in the second year even though growth conditions such as water availability, nutrient status, and temperature are all favorable (Muchow et al., 1997; Park et al., 2005). Hence biomass samplings after the first year of growth were only made every 2 mo. As pointed out earlier, this growth period presents many challenges in accounting for all the trash (crop residues composed of plant tops and dry leaves that are left above the ground; these residues form a mat known in the sugarcane industry as trash) biomass from senesced leaves and stalks for inclusion in the calculation of the total aboveground biomass and accurately estimating RUE. Furthermore, lodging of the cane (Fig. 2b) makes relating this biomass to the corresponding LAI and FIPAR difficult. To this end, we applied the following modification to Protocol I; The rectangular frame was used to demarcate the sampling area as in Protocol I. The plant height was measured and below canopy PAR interception measurements taken at a height just below the green leaves (~1 m above the ground). A representative subsample of three to five cane stalks was harvested from within the frame for LAI determination as detailed in Protocol 1. However, and unlike in Protocol I, the corners of the frame were pinned off using four 30-cm metal pins. To accurately estimate stalk density, sugarcane stalks originating from outside the pinned area were slashed and cleared to enable easy recording of only those stalks originating from within the pinned area. All the plant material within the frame–stalks and cane trash mat was cut, collected, and weighed in the field. A representative subsample of the stalks and cane trash mat were collected, weighed in the lab, and oven-dried to constant weight at 70°C. This subsample dry matter weight was used to estimate the total dry biomass yield.

The RUE was calculated as the slope of the regression equation of the sugarcane aboveground dry matter (including the trash cane mat) and accumulated intercepted PAR.

ALMANAC Model Description

For a more detailed description of the ALMANAC model, refer to Kiniry et al. (1992). The model was developed for use in field management; several fields may be simulated to comprise a whole farm up to about 100 ha. The model can be used to compare management systems and their effects on yields, N, P, C, pesticides, and sediment. The management components that can be changed include irrigation scheduling, crop rotations, tillage operations etc. In summary, the model uses a daily time step to simulate various biophysical processes including plant growth. Radiation interception and RUE are the drivers of plant growth or biomass accumulation which are in turn a function of the LAI and k for FIPAR as described by Monsi and Saeki's (1953) Beer's law in Eq. [2] above. RUE is a function of the vapor pressure deficit and atmospheric CO_2 (Kemanian et al., 2004; Stöckle and Kiniry, 1990), while LAI evolution is simulated with a daily heat unit system that correlates plant growth with temperature.

To accurately estimate total plant biomass the model takes into account the contribution of root biomass in calculations of RUE. According to Jones (1985) the fraction of total biomass partitioned to the root system of most crops normally decreases from 0.30 to 0.50 in the seedling to 0.05 to 0.20 at maturity. The model simulates this partitioning by decreasing the fraction linearly from emergence to maturity. We applied the maximum root biomass fraction at maturity of 0.20. Daily incident PAR values were taken as 45% of the total solar radiation (Meek et al., 1984; Monteith, 1965) which was measured on-site with the portable automatic weather station.

Other important model parameters included maximum plant height and rooting depth, percent moisture content in biomass at harvest, N and P nutrient contents at early, mid- and late crop growth stages. Various stresses that include temperature, soil moisture, plant nutrients (N and P), aeration, salinity, pH, and soil compaction limit plant growth (Kiniry et al., 1992; Meki et al., 2013).

Model Calibration and Crop Parameter Fine-tuning

A new crop for 2-yr growth cycle sugarcane was created in the ALMANAC Crops database by modifying crop parameter data for a 1-yr growth cycle sugarcane crop from the Environmental Policy Integrated Climate (EPIC) model (Williams, 1995) with our field gathered data. The ALMANAC and EPIC models have similar crop growth models but each also has subroutines describing different biophysical processes: both models contain detailed functions for water balance, nutrient cycling, and plant growth, but with ALMANAC having additional detail for light competition, population density effects, and vapor pressure deficit effects which enable it to simulate the growth and seed yield of two competing plant species in a wide range of environments (Kiniry et al., 1992). On the other hand, the EPIC model has since evolved into a comprehensive agro-ecosystem model with a soil organic carbon (SOC) module adapted from the CENTURY model (Parton, 1996) capable of simulating SOC dynamics in a wide range of plant species, including crops, native grasses, and trees (Izaurralde et al., 2006).

Using the new 2-yr growth cycle sugarcane crop we then compiled a simulation budget (Table 1) to model sugarcane growth in the experiment from which we gathered the crop parameters (Field no. 609). We ran the model simulation using actual 2011 to 2013 weather summarized in Fig. 3 and the NRCS USDA Soil Survey Geographic (SSURGO) soils data for a Molokai soil series (Table 2). To refine the crop parameters, we systematically adjusted the new crop parameters iteratively by running the ALMANAC model, comparing the simulated LAI and aboveground dry biomass yields to actual data, and then altering crop parameter values until there was a good match between predicted and measured LAI and dry matter yield values.

Table 1. Actual sugarcane field management operations and inputs for field 609 that were simulated with the ALMANAC model.

Field operations	Irrigation	Fertilizer†	Date of operation
	mm ha^{-1}	kg N ha^{-1}	
Subsoiler, deep ripper, depth: 40 cm			1 June 2011
Harrow, finisher, depth: 8–15 cm			5 June 2011
Planting, 18 stalks m^{-2}			26 June 2011
	150	22	17 July 2011
	210	79	4 Aug. 2011
	250	55	23 Sept. 2011
	216	45	28 Oct. 2011
	128		2 Nov. 2011
	148	34	5 Dec. 2011
	128	11	4 Jan. 2012
	198	11	8 Feb. 2012
	149		7 Mar. 2012
	170	88	27 Apr. 2012
	183		9 May 2012
	287		13 June 2012
	216		4 July 2012
	126		15 Aug. 2012
	265		8 Sept. 2012
	293		3 Oct. 2012
	197		7 Nov. 2012
	207		2 Dec. 2012
Harvesting (Harvest Index = 0.90)			21 May 2013

† Fertilizer was applied as liquid urea (46–00–00) through the drip irrigation lines. Fertilizer amounts shown in table represent the elemental N equivalent.

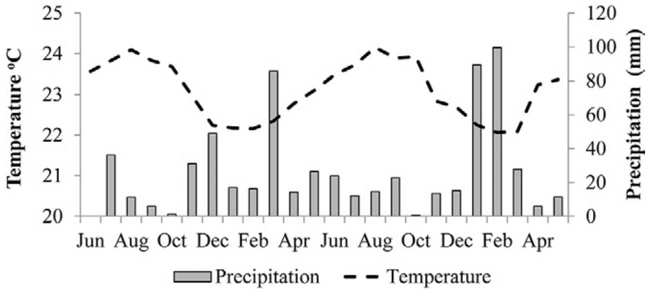

Fig. 3. Mean monthly temperature and precipitation for Field no. 609: June 2011 to May 2013.

Crop Parameter and Model Evaluation

To evaluate the developed crop parameters and test the calibrated ALMANAC model's ability to accurately simulate 2-yr cycle sugarcane management practices and yields, we applied the model to simulate historical sugarcane yields across 7 HC&S fields; F no. 202, 308, 312, 416, 601, 719, and 905 over five to six 2-yr growth cycles. These fields were chosen primarily based on different soil types and the availability of the nearest weather station data (Table 3). Before conducting the simulations, historical management information and data on field preparations, applied N and P fertilizer (N and P fertigation), and drip irrigation amounts for each of the seven fields were processed into monthly formats for input into the ALMANAC management database. The simulated crop budgets for the seven fields are summarized in Table 3. For most simulated 2-yr growth cycles we noted that the model often required supplemental P additions to attain actual measured sugarcane yields. As a result we opted to use the automatic P fertilizer trigger option in the model, instead of the actual applied P. When the plant suffers any P stress, the automatic option triggers P fertilization to achieve an optimum soil P level.

Customized weather data from the HC&S weather station nearest each field and the corresponding SSURGO soils data were used for the simulations. We applied the Penman–Monteith method option in the model as it best accounts for proper water balance and evapotranspiration rates under the windy conditions of the island and is critical for estimation of actual ET in such environments (Osorio et al., 2014).

Data Analysis

The REG procedure in SAS version 9.3 (SAS Institute, 2007) was used to conduct regression analyses to describe the relationship between FIPAR vs. LAI, aboveground dry biomass vs. accumulated intercepted PAR, crop growth rate vs. LAI, and simulated vs. measured yields. Differences between measured and simulated dry biomass yields were assessed using Fisher's Paired t test. We applied mean separation statistics–standard errors for the mean at $P \leq 0.05$ probability levels (Snedecor and Cochran, 1989) to determine any significant differences between measured variables.

RESULTS AND DISCUSSION

Recorded Meteorological Data for Field Number 609

Mean monthly temperature and precipitation for Field no. 609 showed normal trends for this site for June 2011 to May 2013 (Fig. 3). Mean annual air temperature and precipitation during the study period were 23.4°C (range 19.7–29.0°C) and 241 mm, respectively. Mean daily relative humidity was 76% (range 67–91%), while the average daily incident solar radiation was 21.5 MJ m^{-2} d^{-1} (range 10–27 MJ m^{-2} d^{-1}). Wind speed ranged from 0 to 37 km h^{-1} with a daily mean of 6.8 km h^{-1}.

Table 2. Initial soil conditions for a few selected soil variables for the simulated Molokai (MUA) silty clay loam, slope: 0 to 3% (Field no. 609). The soil properties were compiled from the USDA NRCS SSURGO database: http://sdmdataaccess.nrcs.usda.gov/ (accessed March 2014).

Soil property	Soil layer number	
	1	2
Depth, m	0.00–0.32	0.32–1.58
Porosity, m m^{-1}	0.54	0.50
Field capacity, m m^{-1}	0.47	0.45
Wilting point, m m^{-1}	0.30	0.29
Saturated conductivity, mm h^{-1}	32.40	32.40
Bulk density 33kpa, T m^{-3}	1.23	1.33
Bulk density (Oven dry soil), T m^{-3}	1.29	1.29
Sand, %	6	6
Silt, %	44	44
Clay, %	50	50
pH	7.20	7.80
CEC, cmol kg^{-1}	10.50	10.50
Soil organic carbon, %	1.62	0.77

Measured and Derived Crop Parameters

The full suite of measured and derived parameters that were incorporated into the ALMANAC model crops parameter database to represent the growth and development of the 2-yr cycle sugarcane are presented in Table 4.

Leaf Area Index. Measured LAI increased from 0.40 at 2 mo after planting to a peak value of 7.5 at 13 mo (Fig. 4). This LAI value is similar to the 8.0 reported by Muchow et al. (1997) on a study conducted in Kunia, HI. The sugarcane crop maintained this LAI for 3 mo, after which it started to decline. According to Williams and Izaurralde (2013) the LAI of vegetative crops such as sugarcane and some forage crops reaches a plateau at which time the rates of senescence and growth of leaf are approximately equal. The LAI started to decline when the calculated fraction of the growing season was 0.65

The LAI and FIPAR were used to derive k (Fig. 5). The fitted exponential curve indicated a value of 0.53 and a coefficient of determination of 0.88. According to Thornley (1976), k varies with foliage characteristics, sun angle, row spacing, row direction, and latitude. A somewhat smaller value (0.40–0.60) might be appropriate for tropical areas in which average sun angle is higher and for cropping systems with wide row spacing (Begg et al., 1964; Bonhomme et al., 1982; Muchow et al., 1982). Our estimated value compares well with the value of 0.58 derived by Inman-Bamber (1994) for irrigated sugarcane.

Dry Matter Accumulation. The dry matter (DM) accumulation closely resembled the LAI evolution. As pointed out earlier, sugarcane cultivars grown in Hawaii over a 2-yr growth cycle have two distinct growth patterns (Fig. 6). During the first 5 to15 mo after planting, the cultivars exhibit a rapid and almost linear growth pattern. Thereafter, DM plateaus at the maximum measured yield of 80.20 Mg $ha^{-1}$and then starts

Table 3. Summary of historical management and cane yield data for seven Hawaii Commercial & Sugar Company (HC&S) fields used to test ALMANAC's capability to accurately simulate sugarcane yields. All lands were subsoiled with a deep ripper (40 cm) and harrowed (8–15 cm) before mechanized planting.

Field	F no. 202	F no. 308	F no. 312	F no. 416	F no. 601	F no. 719	F no. 905
HC&S Weather station	201	501	201	414	501	711	906
Latitude	20.88	20.87	20.88	20.80	20.87	20.86	20.81
Longitude	–156.35	–156.39	–156.35	–156.41	–156.39	–156.46	–156.50
Elevation, m	255	131	255	189	131	30	30
Soil series	Paia (PcC)	Keahua (KnB)	Haliimaile (HgB)	Waiakoa (Wh)	Molokai (MuA)	Jaucas (JL)	Pulehu (PrA)
Soil texture	silty clay	silty clay loam	silty clay loam	silty clay loam	silty clay loam	loamy sand	cobbly silty loam
Slope, %	7–15	3–7	3–7	3–7	0–3	0–15	0–3
Years of simulation	1998–2011	1997–2010	1999–2012	1999–2012	1998–2011	1999–2011	1998–2011
Number of 2-yr growth cycles (GC)	6	6	5†	5†	6	6	6
GC precipitation, mm							
Average	1533	925	1667	559	990	831	721
Range	1125–2173	517–1236	1316–2544	312–763	712–1314	283–1412	342–1481
GC irrigation, mm							
Average	1897	2633	2015	2895	2579	3191	2734
Range	1433–2305	1941–3272	1750–2423	1892–4177	1952–3277	2290–3849	1139–3665
GC applied N, kg ha^{-1}							
Average	375	424	358	348	344	331	351
Range	327–512	384–492	339–366	197–404	303–377	241–375	323–383
GC applied P, kg ha^{-1}							
Average	71	93	75	77	9	0	0
Range	0–308	0–205	0–256	0–212	0–55	0	0
Cane yield, Mg ha^{-1}							
Average	84	86	88	83	88	101	85
Range	55–115	57–114	64–108	62–115	61–103	86–118	68–107

† Only five 2-yr growth cycles were simulated for fields F no. 312 and F no. 416 because of errors in data records for the sixth cycle.

Table 4. Determined crop parameters for 2-yr cycle sugarcane used to calibrate the ALMANAC model. The biomass-energy ratio (WA) value includes cane mat and root dry matter. Nitrogen and P nutrient contents are from Williams et al. (1989).

Category	Crop parameter definition	Symbol	Determined value
Plant growth	Biomass-energy ratio, g MJ^{-1} m^{-2}	WA	3.37
	Max. leaf area index (LAI)	DMLA	7.50
	Fraction of season when LAI starts to decline	DLAI	0.65
	Leaf area decline rate index	RLAD	0.30
	Light extinction coefficient for Beer's Law	*k*	0.53
	First point on optimal LAI curve	DLAP1	15.10
	Second point on optimal LAI curve	DLAP2	55.99
	Maximum crop height, m	HMX	3.60
	Maximum root depth, m	RDMX	2.00
	Potential heat units, °C	PHU	9250
Yield components	Plant population (stalk number), m^{-2}	PLANTPO	18.00
	Dry matter decline rate index	RBMD	1.00
	Fraction of water in forage yield	WCY	0.75
	Harvest index	HI	0.90
Nutrient content (kg nutrient/kg of biomass)	Nitrogen content at early establishment	BN1	0.0100
	Nitrogen content at mid-season	BN2	0.0040
	Nitrogen content at maturity	BN3	0.0025
	Phosphorus content at early establishment	BP1	0.0075
	Phosphorus content at mid-season	BP2	0.0030
	Phosphorus content at maturity	BP3	0.0019

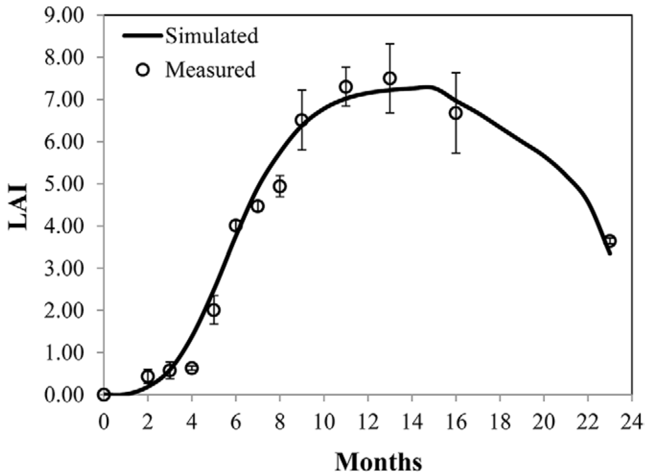

Fig. 4. Measured and ALMANAC model simulated leaf area index (LAI) evolution of 2-yr cycle sugarcane at Hawaii Commercial & Sugar Company (HC&S) plantation, Maui Island, Hawaii. The crop growth and simulation period started on June 2011 to May 2013. Each data point is the average of three replicates. Vertical bars represent the standard error of the means of the measured data.

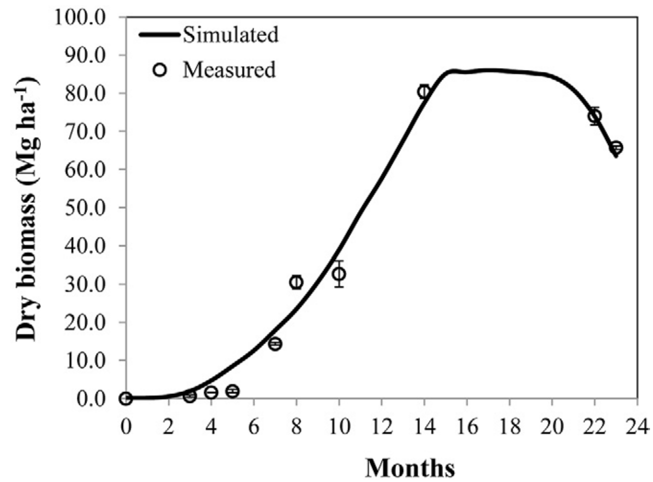

Fig. 6. Measured and ALMANAC model simulated 2-yr cycle sugarcane dry matter accumulation at the Hawaii Commercial & Sugar Company (HC&S) plantation, Maui Island, Hawaii. The crop growth and simulation period started from June 2011 to May 2013. Each data point is the average of three replicates. Vertical bars represent the standard error of the means of the measured data.

to decline at about 21 mo. At HC&S no fertilizer is applied in the last 12 mo before harvesting of the commercial crop, while irrigation is progressively withdrawn during the last 6 mo. The induced water and nutrient stresses decrease vegetative growth, thus pushing photosynthates toward sucrose storage (Humbert, 1968; Gascho, 1985). Furthermore, the induced dry weather conditions also help concentrate the sucrose through increased evaporation from the leaf surface. The high sucrose concentration is attractive to both growers and millers because of reduced costs for harvesting, hauling, and milling.

According to Rostron (1972), as DM increases with crop age, the proportion of respiring to photosynthesizing tissue increases, causing a gradual decline in net productivity. Muchow et al. (1997) also attribute the reduced DM to stalk death. The estimated harvest index (HI) for total harvested biomass yield and cane moisture content at the last biomass harvest sample (23 mo) were 0.90 and 75%, respectively. Commercial harvesting of sugarcane occurs between 20 and 24 mo.

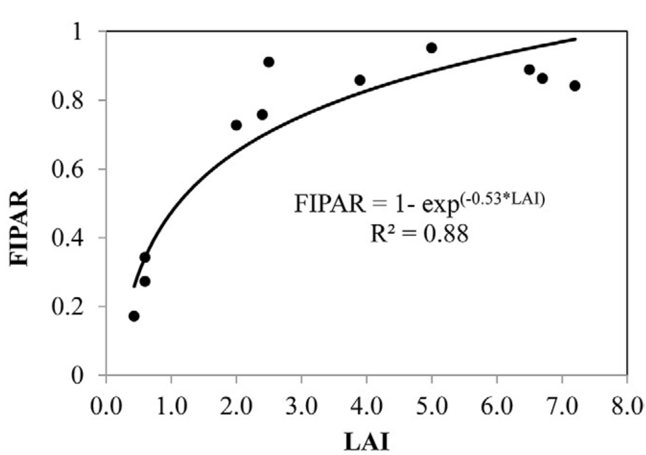

Fig. 5. Relationship between the fraction of intercepted photosynthetically active radiation (FIPAR) and leaf area index (LAI). Each data point is the average of three replicates. The light extinction coefficient (*k*) derived from the fitted exponential curve indicates a value of 0.53 and a coefficient of determination of 0.88.

Compared to sugarcane grown in other regions of the world, the high DM accumulation in 2-yr cycle sugarcane is a result of the longer growing season, higher LAI, light interception, and RUE. Sugarcane growth rate is a function of the LAI (Fig. 7). For the 2-yr growth cycle sugarcane in this study, the relationship is linear. According to Evans (1993), LAI is a key driving variable for biomass accumulation in most crops, especially before full crop canopy closure when light interception by individual leaves is at its maximum. The tillering plant population was estimated at 18 stalks m^{-2} (Table 4). Sugarcane has the capacity to tiller rapidly. Under favorable conditions, stalk numbers increase exponentially with time until a maximum of 20 to 30 stalks m^{-2} is reached at 4 to 6 mo (Bull and Glasziou, 1975). Over time many younger tillers begin to die due to shading by older tillers, and tiller number normally stabilizes at 10 to 20 stalks m^{-2}. In crops such as sugarcane which produce a high number of yielding tillers compared to the number of seeds or shoots planted, the modeled plant population is estimated based on the final yield producing tiller number. The crop grew to a maximum height (HMX) of 3.6 m. Root studies by Youkhana et al. (2013) showed sugarcane roots reaching to more than 2.0 m.

Radiation Use Efficiency. The relationship between DM and accumulated intercepted PAR from early establishment to final harvest is sigmoid due to DM leveling off at between 15 and 21 mo after planting (Fig. 6 and 8a). This leveling off of DM is commonly referred to as the reduced growth phenomena (van Heerden et al., 2010) and is widely reported in the literature (Donaldson et al., 2008; Muchow et al., 1994; Park et al., 2005; Robertson et al., 1996; Rostron, 1972; Wood et al., 1996). The leveling off of DM resulted in an overall crop cycle RUE of 2.06 g MJ^{-1}. This RUE value is close to values reported for sugarcane elsewhere in the literature; 1.70 g MJ^{-1} (Robertson et al., 1996), 1.75 and 2.00 g MJ^{-1} (Muchow et al., 1994; 1997) for irrigated sugarcane under tropical conditions.

The relationship between DM and accumulated intercepted PAR during the rapid growth phase can however be viewed as being linear (Fig. 8b). Sugarcane growth is generally characterized by a period of rapid biomass accumulation which corresponds to the near-linear portion of a sigmoidal growth curve (Coale et al., 1993). According to Muchow et al. (1994), the linear relationship is more useful as an estimation of RUE for crop modeling purposes. The RUE during this rapid growth phase hereby referred to in the model as the Biomass-energy ratio (WA-Table 4) is approximately 3.37 g MJ^{-1}. This relatively high RUE value is most certainly due to the inclusion of trash cane mat. Failure to account for trash biomass results in an underestimation of aboveground biomass (Muchow et al., 1997). Several studies showed that trash cane mat can contribute as much as 10 to 34 Mg ha^{-1} yr^{-1} of total sugarcane DM (Evensen et al., 1997; Trivelin et al., 1995; Vitti et al., 2011; Fortes et al., 2012). The computation of RUE can vary with the experimental assumptions and methodologies which can result in a wide range of RUEs for the same crop (Gallo et al., 1993; Sinclair and Muchow, 1999). Demetriades-Shah et al. (1992) stressed that comparisons of RUE should only be made when measurements are made under similar conditions.

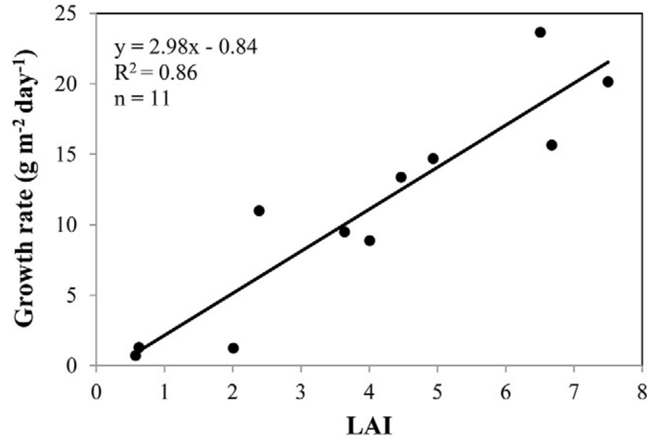

Fig. 7. Sugarcane growth rate is a function of the leaf area index (LAI). Each data point is the average of three replicates. For the 2-yr growth cycle sugarcane in this study, the relationship is linear.

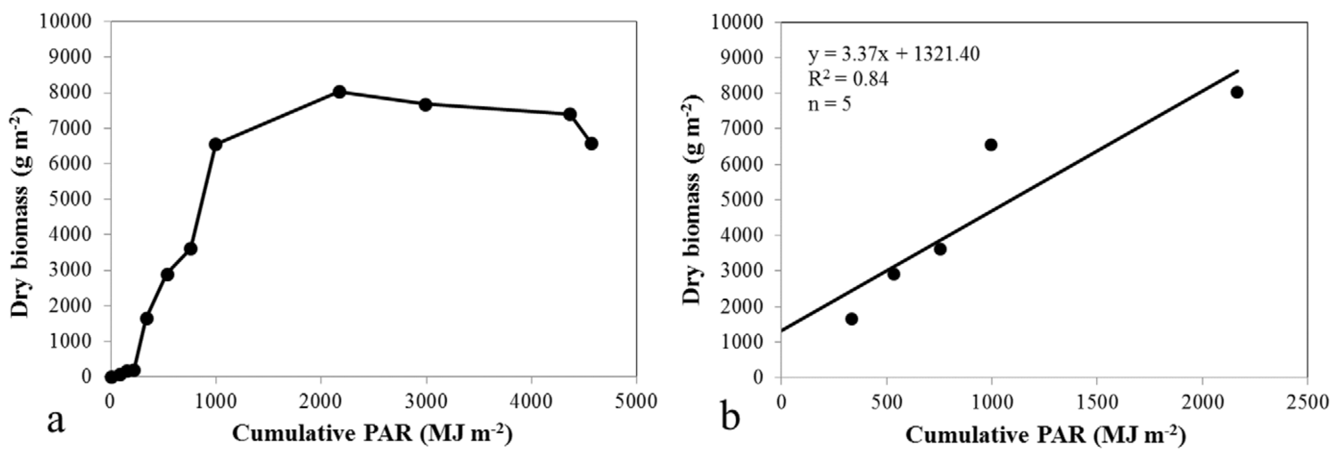

Fig. 8. (a) Relationship between aboveground (AB) dry matter accumulation and cumulative intercepted photosynthetically active radiation (PAR) during the 2-yr growth cycle, and (b) The linear relationship between dry matter accumulation and cumulative intercepted PAR during the period of rapid growth. Each data point is the average of three replicates.

Table 5. Measured and ALMANAC simulated sugarcane yields of seven HC&S plantation fields, Maui, Hawaii. The Mean Error % = [(Measured – Simulated)/Mean Measured] × 100.

Field	Yield	Two-year growth cycle number							Mean error
		1	2	3	4	5	6	Mean	
no.	Mg ha^{-1}								%
202	Measured	111.1	114.6	68.4	73.8	55.4	78.8	83.7	
	Simulated	110.2	101.3	69.1	78.9	53.2	80.6	82.2	1.8
308	Measured	114.5	89.8	92.7	71.4	56.7	90.2	85.9	
	Simulated	105.6	88.5	92.8	71.3	58.4	91.5	84.7	1.4
312	Measured	89.0	108.0	96.1	63.7	84.8	†	88.3	
	Simulated	88.3	106.8	94.1	92.8	70.0	†	90.4	–2.4
416	Measured	90.6	114.6	77.4	61.6	76.9	†	84.2	
	Simulated	91.2	115.3	102.5	61.8	77.1	†	89.6	–6.4
601	Measured	92.4	103.3	79.2	89.6	61.4	102.2	88.0	
	Simulated	113.1	105.6	79.2	96.2	60.4	100.8	92.6	–5.2
719	Measured	118.2	110.8	95.2	93.4	86.2	103.4	101.2	
	Simulated	112.7	109.6	115.3	100.1	85.7	103.4	104.5	–3.2
905	Measured	93.4	107.1	91.3	68.0	75.6	73.9	84.9	
	Simulated	93.1	106.8	91.0	74.6	77.0	75.4	86.3	–1.7

† Only five 2-yr growth cycles were simulated for fields Fno.312 and Fno.416 because of errors in data records for the sixth cycle.

Supplementary Parameters. The fraction of the growing season when the LAI starts to decline (DLAI) was derived from data in Fig. 4, while the LAI decline rate index (RLAD) defines the shape of the LAI curve after DLAI (Fig. 4). We used the data presented in Fig. 4 in conjunction with the ALMANAC LAI simulation data to estimate DLAP1 and DLAP2, which are two points on the optimal (non-stress) leaf area development curve. In both DLAP1 and DLAP2 (Table 4), numbers before the decimal are percent of growing season, while numbers after the decimal are fractions of maximum potential LAI (DMLA). The DM decline rate index (RBMD) functions like the RLAD for LAI and reduces the efficiency of conversion of intercepted PAR to biomass toward the end of the growing season. As with RLAD the RBMD decline rate index was determined by adjusting pre-set values (range 1–10) until the simulated decline rate approximates that of measured DM data values. The model estimated PHUs for the 2-yr cycle sugarcane at approximately 9250°C.

Even though root studies by Youkhana et al. (2013) showed sugarcane roots exceeding 2 m, we applied the model maximum default rooting depth of 2.00 m. This depth is adequate for simulating water and nutrient uptake with the ALMANAC model in most cases. The N and P nutrient contents decline from early seedling emergence (BN1; BP1), midseason (BN2; BP2) and at maturity (BN3; BP3) (Table 4) (Williams et al., 1989). These crop parameters represent the optimal N and P concentrations at key growth stages and decline with increasing growth (Jones, 1983).

Except for the plateauing of DM accumulation in the second year of growth, the 2-yr cycle sugarcane's growth pattern is similar to that of 12 to 18 mo sugarcane systems on the U.S. mainland and other regions of the world. Modelers applying the crop parameters determined in this study in these regions should however be aware of the need to pay attention to specific parameters whose values are dependent on local conditions, such as climate, soil type, and rooting depth, crop management practice etc. For example, the growth cycle PHUs will have to be adjusted for local climatic conditions, while as pointed out earlier, *k* varies with foliage characteristics, sun angle, row spacing, row direction, and latitude.

Overall, our results on DM accumulation and RUE confirm the recent findings of Anderson et al. (2015) which showed that 2-yr cycle sugarcane has higher overall biomass and net productivity compared to sugarcane systems in other regions of the world.

Table 6. Paired *t* test statistics to assess differences between measured and simulated sugarcane yields.

Data variable	Measured yield	Simulated yield
Mean	88.12	90.03
Variance	303.31	289.44
Observations	40	40
Pearson Correlation	0.88	
Degrees of freedom	39	
t Statistic	1.41	
P (T $\leq t$) two-tail	0.17	
t Critical two-tail	2.02	

ALMANAC Model Evaluation

The calibrated model satisfactorily simulated historical sugarcane yields harvested from seven HC&S fields; F no. 202, 308, 312, 416, 601, 719, and 905, over five to six 2-yr growth cycles (Tables 5 and 6 and Fig. 9). The mean simulation percent (%) errors ranged from −6.4 to 1.8%. The small negative mean simulation percent errors indicate that the model slightly overpredicted sugarcane yields (fields 312, 416, 601, 719, and 905), while the positive errors indicated that sugarcane yields were slightly underpredicted (fields 202 and 308). The slope and intercept of the regression line shown in Fig. 9 were not significantly different from 1 and zero, respectively. In addition, the calculated Paired *t* test of 1.41 with 39 degrees of freedom, and the Pearson correlation coefficient of 0.88 (Table 6) show that there were no significant differences ($P \geq 0.05$) between measured and simulated yields. The coefficients of variation of the measured and simulated yields were 3.05 and 2.99%, respectively.

Although the model managed to capture various sugarcane production stresses on water, nutrient (N and P), and temperature across the fields and over years, the model simulated N and irrigation water inputs were in general adequate to meet historical yields, though additional P fertilizer was required across fields and growth cycles (Table 3). Field-applied irrigation water and N averaged 2563 mm (1433–4177 mm), and 362 kg N ha^{-1} (197–512 kg N ha^{-1}), respectively. ALMANAC additional auto P fertilizer applications averaged 80 kg P ha^{-1} (0–168 kg P ha^{-1}). The higher P additions by the model could be attributable to either low P levels in the NRCS SSURGO soils database used in the model or the ALMANAC model's incapability to accurately model P dynamics of various soils. There was no sufficient soil P analysis data for the modeled fields that could be used to update the soil available P for each soil type (field) as impacted by various management practices over time. As the soil survey for NRSC SSURGO soils characterization was conducted several years before the simulated years, this discrepancy in soil P and modeled P inputs could somewhat be expected. While P fixation is predominant in

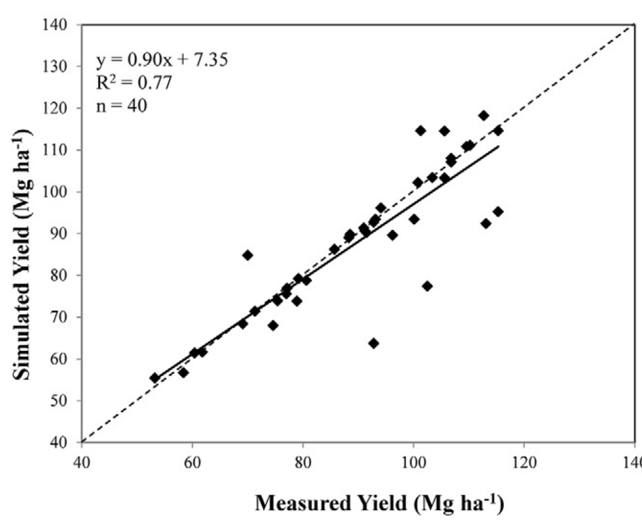

Fig. 9. Measured and ALMANAC model simulated historical sugarcane yields for fields 202, 308, 312, 416, 601, 719, and 905 over five to six growth cycles (see Table 3 for the actual years that were simulated for each field). The dashed line is the 1:1 line through the origin.

oxidic tropical soils and P deficiency is a major limitation to crop production (Grierson et al., 2004), measuring plant-available P in these soils is challenging (Gama-Rodrigues et al., 2014). According to FAO (2013), sugarcane requires 20 to 90 kg P ha^{-1} with the actual amounts varying depending on several factors such as soil type, management history etc.

CONCLUSIONS

When compared to sugarcane grown in other regions of the world, the results of this study indicate that the high biomass yield of 2-yr cycle sugarcane is due to multiple factors that include the long growing season, high LAI, light interception, and RUE. When the crop parameters were incorporated into the ALMANAC biophysical model, the model was able to accurately simulate sugarcane yields across five to six 2-yr growth cycles, different soil types and multiple management scenarios of applied irrigation water, N fertilizer inputs, and various planting and harvest dates. Not only did the model give a good representation of final biomass yields, but also a good simulation of crop growth and development throughout the growth cycle. It is apparent that when fully calibrated and tested, the model can be used by researchers to evaluate growers' management alternatives that can potentially maximize biomass yields while optimizing water, N and P nutrient inputs. Furthermore, the crop parameters developed in this study can also be used in watershed scale models such as the Agricultural Policy/Environmental eXtender (APEX) and Soil and Water Assessment Tool (SWAT) (both of which share the same crop growth model with ALMANAC) for simulating crop growth at a much larger scale.

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REFERENCES

Anderson, G.R., R. Tirado-Corbala, D. Wang, and J.E. Ayars. 2015. Long-rotation sugarcane in Hawaii sustains higher carbon accumulation and radiation use efficiency in 2nd year of growth. Agric. Ecosyst. Environ. 199:216–224. doi:10.1016/j.agee.2014.09.012

Begg, J.E., J.F. Bierhuizen, E.R. Lemon, D.K. Misra, R.O. Slatyer, and W.R. Stern. 1964. Diurnal energy and water exchanges in bulrush millet. Agric. Meteorol. 1:294–312. doi:10.1016/0002-1571(64)90037-8

Behrman, K.D., J.R. Kiniry, M. Winchell, T.E. Juenger, and T.H. Keitt. 2013. Spatial forecasting of switchgrass yield under current and future climate change scenarios. Ecol. Appl. 23:73–85. doi:10.1890/12-0436.1

Bonhomme, R., F. Ruget, M. Derieux, and P. Vincourt. 1982. Relationship between aerial dry matter production and intercepted solar radiation for various maize genotypes. Comptes Rendus Hebdomadaires Séances Acad. Sci. III 294:393–398.

Bull, T.A., and K.T. Glasziou. 1975. Sugarcane. In: L.T. Evans, editor, Crop physiology. Some case histories. Cambridge Univ. Press, Cambridge, UK. p. 51–72.

Bull, T.A., and D.A. Tovey. 1974. Aspects of modeling sugarcane growth by computer simulation. Proc. Int. Soc. Sugar Cane Technol. 15:1021–1032.

Coale, F.J., C.S. Sanchez, F.T. Izuno, and A.B. Bottcher. 1993. Nutrient accumulation and removal by sugarcane grown on Everglades histosols. Agron. J. 85:310–315. doi:10.2134/agronj1993.00021962008500020028x

Demetriades-Shah, T.H., M. Fuchs, E.T. Kanemasu, and I. Flitcroft. 1992. A note of caution concerning the relationship between cumulated intercepted radiation and crop growth. Agric. For. Meteorol. 58:193–207. doi:10.1016/0168-1923(92)90061-8

Donaldson, R.A., K.A. Redshaw, R. Rhodes, and R. van Antwerpen. 2008. Season effects on productivity of some commercial South African sugarcane cultivars, I: Biomass and radiation use efficiency. Proc. SASTA. 81:517–527.

Engel, B., I. Chaubey, M. Thomas, D. Saraswat, P. Murphy, and B. Bhaduri. 2010. Biofuels and water quality: Challenges and opportunities for simulation modeling. Biofuels 1:463–477. doi:10.4155/bfs.10.17

Evans, L.T. 1993. Crop evolution, adaptation and yield. Cambridge Univ. Press, Cambridge, UK.

Evensen, C.I., R.C. Muchow, S.A. El-Swaify, and R.V. Osgood. 1997. Yield accumulation in irrigated sugarcane: I. Effect of crop age and cultivar. Agron. J. 89:638–646.

FAO (Food and Agricultural Organization). United Nations. 2013. Water. Natural Resources Management and Environment Department. http://www.fao.org/nr/water/index.html (accessed March 2014) .

Fortes, C., P.C.O. Trivelin, and A.C. Vitti. 2012. Long-term decomposition of sugarcane harvest residues in São Paulo state, Brazil. Biomass Bioenergy 42:189–198. doi:10.1016/j.biombioe.2012.03.011

Gallo, K.P., C.S.T. Daughtry, and C.L. Wiegand. 1993. Errors in measuring absorbed radiation and computing crop radiation use efficiency. Agron. J. 85:1222–1228. doi:10.2134/agronj1993.00021962008500060024x

Gama-Rodrigues, A.C., M.V.S. Sales, P.S.D. Silva, N.B. Comerford, W.P. Cropper, and E.F. Gama-Rodrigues. 2014. An exploratory analysis of phosphorous transformations in tropical soils using structural equation modeling. Biogeochemistry 118:453–469. doi:10.1007/s10533-013-9946-x

Gascho, G.J. 1985. Water-sugarcane relationships. Sugar J. 48:11–17.

Goldemberg, J. 2008. The Brazilian biofuels industry. Biotechnol. Biofuels 1:6 (1–7). doi:10.1186/1754-6834-1-6.

Grantz, D.A., and H.B. Vu. 2009. Sensitivity in a potential C_4 bioenergy crop: Sugarcane in California. Crop Sci. 49:643–650. doi:10.2135/cropsci2008.04.0210

Grierson, P.F., P. Smithson, G. Nziguheba, G.S. Radersma, and B. Comerford. 2004. Phosphorus dynamics and mobilization by plants. In: M. van Noordwisk, G. Cadisch, and C.K. Ong, editors, Below-ground interactions in tropical agroecosystems: Concepts and models with multiple plant components. CABI Int., Wallingford, UK. p. 127–142.

HC&S. 2011. Hawaiian Commercial & Sugar Co., Maui. http://www.hcsugar.com/hcs_qa.shtml#about (accessed March 2014).

Heinz, D.J., T.L. Tew, H.K. Meyer, and K.K. Wu. 1981. Registration of H65-7052 Sugarcane reg. no. 51. Crop Sci. 21:634–635. doi:10.2135/cropsci1981.0011183X002100040050x

Humbert, R.P. 1968. The growing of sugarcane. Elsevier Publishing Co. Ltd, Amsterdam.

Inman-Bamber, N.G. 1994. Temperature and seasonal effects on canopy development and light interception of sugarcane. Field Crops Res. 36:41–51. doi:10.1016/0378-4290(94)90051-5

Izaurralde, R.C., J.R. Williams, W.B. McGill, N.J. Rosenberg, and M.C. Jakas. 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecol. Modell. 192:362–384. doi:10.1016/j.ecolmodel.2005.07.010

Jones, C.A. 1983. A survey of the variability in tissue nitrogen and phosphorus concentrations in maize and grain sorghum. Field Crops Res. 6:133–147. doi:10.1016/0378-4290(83)90053-9

Jones, C.A. 1985. C-4 Grasses and Cereals. John Wiley & Sons, New York.

Kemanian, A.R., C.O. Stöckle, and D.R. Huggins. 2004. Variability of barley radiation-use efficiency. Crop Sci. 44:1662–1672. doi:10.2135/cropsci2004.1662

King, J.E., J.M. Hannifan, and R. Nelson. 1998. An assessment of the feasibility of electric power derived from biomass and waste feedstocks. Rep. KRD-9513. Kansas Electric Utilities Research Program and Kansas Corp. Commission, Topeka. p. 1–266.

Kiniry, J.R., K.A. Cassida, M.A. Hussey, J.P. Muird, W.R. Ocumpaugh, J.C. Read et al. 2005. Switchgrass simulation by the ALMANAC model at diverse sites in the southern US. Biomass Bioenergy 29:419–425. doi:10.1016/j.biombioe.2005.06.003

Kiniry, J.R., M.V. Johnson, S.B. Bruckerhoff, J.U. Kaiser, R.L. Cordsiemon, and R.D. Harmel. 2012. Clash of the Titans: Comparing productivity via radiation use efficiency for two grass giants of the biofuel field. BioEnergy Res. 5:41–48. doi:10.1007/s12155-011-9116-8

Kiniry, J.R., M.A. Sanderson, J.R. Williams, C.R. Tischler, M.A. Hussey, W.R. Ocumpaugh et al. 1996. Simulating Alamo switchgrass with the ALMANAC model. Agron. J. 88:602–606. doi:10.2134/agronj1996.00021962008800040018x

Kiniry, J.R., M.R. Schmer, K.P. Vogel, and R.B. Mitchell. 2008. Switchgrass biomass simulation at diverse sites in the northern Great Plains of the US. BioEnergy Res. 1:259–264. doi:10.1007/s12155-008-9024-8

Kiniry, J.R., J.R. Williams, P.W. Gassman, and P. Debaeke. 1992. A general process oriented model for two competing plant species. Trans. ASABE 35:801–810. doi:10.13031/2013.28665

Kinoshita, C., and J. Zhou. 1999. Siting evaluation for biomass-ethanol production in Hawaii. Natl. Renewable Energy Lab., Oak Ridge, TN.

Laclau, P.B., and J.P. Laclau. 2009. Growth of the whole root system for a plant crop of sugarcane under rainfed and irrigated environments in Brazil. Field Crops Res. 114:351–360. doi:10.1016/j.fcr.2009.09.004

Meek, D.W., J.L. Hatfield, T.A. Howell, S.B. Idso, and R.J. Reginato. 1984. A generalized relationship between photosynthetically active radiation and solar radiation. Agron. J. 76:939–945. doi:10.2134/agronj1984.00021962007600060018x

Meki, N.M., J.L. Snider, J.R. Kiniry, R.L. Raper, and A.C. Rocateli. 2013. Energy sorghum biomass harvest thresholds and tillage effects on soil organic carbon and bulk density. Ind. Crops Prod. 43:172–182. doi:10.1016/j.indcrop.2012.07.033

Monsi, M., and T. Saeki. 1953. Uber den Lichtfaktor in den Pflanzengesellschaften und sein Bedeutung für die Stoffproduktion. J. Jpn. Bot. 14:22–52.

Monteith, J.L. 1965. Radiation and crops. Exp. Agric. 1:241–251. doi:10.1017/S0014479700021529

Muchow, R.C., D.B. Coates, G.L. Wilson, and M.A. Foale. 1982. Growth and productivity of irrigated Sorghum bicolor L. Moench. In: Northern Australia. I. Plant density and arrangement effects on light interception and distribution, and grain yield, in the 128 hybrid Texas 610SR in low and medium latitudes. Aust. J. Agric. Res. 33:773–784. doi:10.1071/AR9820773

Muchow, R.C., C.I. Evensen, R.V. Osgood, and M.J. Robertson. 1997. Yield accumulation in irrigated sugarcane: II. Utilization of intercepted radiation. Agron. J. 89:646–652. doi:10.2134/agronj1997.00021962008900040017x

Muchow, R.C., M.F. Spillman, A.W. Wood, and M.R. Thomas. 1994. Radiation interception and biomass accumulation in a sugarcane crop grown under irrigated tropical conditions. Aust. Agric. Res. 45:37–49. doi:10.1071/AR9940037

NASS. 2013. National statistics for sugarcane. USDA. http://www.nass.usda.gov (accessed June 2014).

Osorio, J., J. Jeong, K. Bieger, and J. Arnold. 2014. Influence of potential evapotranspiration on the water balance of sugarcane fields in Maui, Hawaii. J. Water Resour. Protection 6:852–868. doi:10.4236/jwarp.2014.69080

Park, S.E., M. Robertson, and N.G. Inman-Bamber. 2005. Decline in the growth of a sugarcane crop with age under high input conditions. Field Crops Res. 92:305–320. doi:10.1016/j.fcr.2005.01.025

Parton, W.J. 1996. The CENTURY model. In: D.S. Powlson, P. Smith, and J.U. Smith, editors, Evaluation of soil organic matter models using existing long-term datasets. Springer-Verlag, Berlin, Germany.

Persson, T., B. Ortiz, B.I. Bransby, W. Wu, and G.T. Hoogenboom. 2011. Determining the impact of climate and soil variability on switchgrass (*Panicum virgatum* L.) production in the south-eastern USA; a simulation study. Biofuels Bioprod. Biorefin. 5:505–518. doi:10.1002/bbb.288

Robertson, M.J., A.W. Wood, and R.C. Muchow. 1996. Growth of sugarcane under high input conditions in tropical Australia. I. Radiation use, biomass accumulation and partitioning. Field Crops Res. 48:11–25. doi:10.1016/0378-4290(96)00041-X

Rostron, H. 1972. The effects of age and time of harvest on the productivity of irrigated sugarcane. Proc. SASTA 46:142–150.

SAS Institute. 2007. SAS system version 9.3. SAS Inst. Cary, NC.

Sinclair, T.R., and R.C. Muchow. 1999. Radiation use efficiency. Adv. Agron. 65:215–265. doi:10.1016/S0065-2113(08)60914-1

Snedecor, G.W., and W.G. Cochran. 1989. Statistical methods. 8th ed. Iowa State Univ. Press, Ames.

Stöckle, C.O., and J.R. Kiniry. 1990. Variability in crop radiation use efficiency associated with vapor-pressure deficit. Field Crops Res. 25:171–181. doi:10.1016/0378-4290(90)90001-R

Thornley, J.H.M. 1976. Photosynthesis. In: J.H.M. Thornley, editor, Mathematical models in plant physiology. Academic Press, London, UK. p. 92–110.

Trivelin, P.C.O., R.L. Victoria, and J.C.S. Rodrigues. 1995. Utilization by late harvest sugar cane ratoon of nitrogen from 15N-aqua ammonia and 15N-urea applied to the soil as vinasse N-complement. Pesqi. Agropecu. Bras. 30:1375–1385.

USDA NRCS. Soil Survey Staff. 2011. Spatial and tabular data of the Soil Survey for Maui, Hawaii. USDA. http://soildatamartnrcs.usda.gov/ (accessed July 2014).

van Heerden, P.D.R., R.A. Donaldson, D.A. Watt, and A. Singels. 2010. Biomass accumulation in sugarcane: Unravelling the factors underpinning reduced growth phenomena. J. Exp. Bot. 61:2877–2887. doi:10.1093/jxb/erq144

Vitti, A.C., H.C.J. Franco, P.C.O. Trivelin, D.A. Ferreira, R. Otto, C. Fortes, and C.E. Faroni. 2011. Nitrogen derived from fertilization and straw for plant cane nutrition. Pesqi. Agropecu. Bras. 46:287–293. doi:10.1590/S0100-204X2011000300009

Wang, M., J. Han, H. Dunn, H. Cai, and A. Elgowainy. 2012. Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. Environ. Res. Lett. 7:045905. doi:10.1088/1748-9326/7/4/045905

Williams, J.R. 1995. The EPIC model. In: V.P. Singh, editor, Computer models of watershed hydrology. Water Resources Publ., Highlands Ranch, CO. p. 909–1000.

Williams, J.R., and C. Izaurralde. 2013. APEX Theoretical Documentation. Texas A&M AgriLife Res., Blackland Res. & Ext. Ctr., Temple. http://epicapex.tamu.edu/files/2013/02/the-apex-theoretical-documentation.pdf (accessed March 2014).

Williams, J.R., C.A. Jones, J.R. Kiniry, and D.A. Spanel. 1989. The EPIC crop growth model. Trans. ASAE 32:497–511. doi:10.13031/2013.31032

Wood, A.W., R.C. Muchow, and M.J. Robertson. 1996. Growth of sugarcane under high input conditions in tropical Australia. III. Accumulation, partitioning and use of nitrogen. Field Crops Res. 48:223–233. doi:10.1016/S0378-4290(96)00043-3

Youkhana, A., S. Crow, M. Meki, J. Kiniry, R. Ogoshi, and M. Nakahata. 2013. Belowground biomass and C dynamics in sugarcane and ratooning energycane cultivated for biofuel production in Hawaii. Abstract. ASA-CSSA-SSSA Annual International Tri-Society Meeting, Tampa, FL. 3-6 Nov. 2013. ASA, CSSA, and SSSA, Madison, WI.