1 Satellite-Based Crop Coefficient and Regional Water Use Estimates for Hawaiian Sugarcane

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Abstract

Water availability is a major limiting factor for sustainable production of potential biofuel crops in Maui, Hawaii, USA. It is essential to improve regional, near-real time estimates of crop water use to facilitate optimal water management. Satellite remote-sensing offers multiple methods to estimate water management, however, most approaches assume a spatially homogeneous regional meteorology, which does not apply in Hawaii due to strong orographically-induced variations in climate. Canopy ground cover (f_c) and spectral reflectance were measured over two sugarcane fields on the satellite Landsat 7 overpass dates. A strong linear relationship between satellite-based Normalized Difference Vegetation Index (NDVI) values and f_c was found ($R^2 = 0.97$). Canopy ground cover was also found to be highly correlated to crop coefficient (K_c) which was calculated from reference evapotranspiration (ET_0) and sugarcane crop evapotranspiration (ET_c) observations from the Eddy Covariance towers. Spatial ET_0 for the entire sugarcane plantation was determined from an automated weather station network previously installed by the commercial grower of the plantation. Regressions were used to convert the satellite NDVI to K_c maps, and then the satellite-based ET_c maps were created from the satellite-based K_c maps and ET_0 values computed and interpolated from the weather station network. To compare with the satellite-based crop coefficient/reference ET method, ET_c and K_c were also estimated using a satellite-based surface energy balance technique, the METRIC model. These two satellite-based methods were correlated fairly well ($R^2 = 0.84$ for K_c and 0.81 for ET_c). Compared to the METRIC model, the satellite-based crop coefficient/reference ET method may be more practicable for estimating crop water use in Maui, where ground-based ET_0 measurements are available through the on-site automated weather station network with right choice of reference ET equation.

- 65 Keywords: Crop Coefficient, Canopy Crop Cover, Evapotranspiration, METRIC, Eddy
66 Covariance, Sugarcane

1. Introduction

Sugarcane is one of the most advantageous agronomic crops for biofuels due to its high productivity, efficiency, and return on energy investment (Goldemberg et al., 2008; Waclawovsky et al., 2010). However, sugarcane has a large water demand (http://www.sugarcane crops.com/agronomic_practices/irrigation_water_management/, accessed 3/20/2015). Though multiple studies support the idea that Maui has sufficient land suitable for cultivating biofuel crops (Black&Veatch, 2010), water availability is often cited as a major potential barrier to biofuel production on Maui and elsewhere in Hawaii (Grubert et al., 2011), and around the world where sugarcane is being considered as an energy crop but where water is limiting. Therefore, it is necessary to more accurately estimate the water requirement of sugarcane.

Crop coefficient (K_c) is defined as the ratio of actual crop evapotranspiration (ET) and reference ET. Multiple studies have investigated crop coefficient (Watanabe et al., 2004) and crop water use for sugarcane (Thompson and Boyce, 1967, Omary and Izuno, 1995, Hurst et al., 2004). Inman-Bamber and McGlinchey (2003) confirmed the FAO-56 (Food and Agricultural Organization approach presented in Irrigation and Drainage Paper 56 – Allen et al., 1998) crop coefficients for sugarcane during initial and mid growth stages for a sugarcane crop in Australia based on Bowen ratio energy balance measurements. Da Silva et al. (2013) conducted field experiment to determine K_c , water requirement and water use efficiency of sugarcane ratoon crops in Brazil using field soil water balance and reference ET from the Penman-Monteith method. Sugarcane ET ranged from 2.7 to 4.2 mm day⁻¹, corresponding to a non-irrigated rain-

fed condition and a 100% ET irrigation treatment, respectively. Win et al. (2014) used a lysimeter to determine water requirement and K_c of sugarcane at different crop growth stages in Myanmar. Campbell et al. (1960) determined sugarcane ET and the relationship between crop water use and sugarcane yield using in-field lysimeters in Hawaii. Most of these studies have focused on field scale or site-specific water use parameterization in relation to crop age or growth (Anderson et al, 2015a). Relatively little work has been done in evaluating sugarcane growth and water use using remotely-sensed satellite data.

Satellite remote sensing is one of the few practical and effective methods to observe crop water use at a regional scale. Some studies have used fractional canopy ground cover (f_c) as a factor to estimate crop water use and with reasonable success (Bausch, 1995, Grattan et al., 1998).

Remote sensing technology can provide an effective tool for estimating of canopy ground cover. Spectral indices, such as the Normalized Different Vegetation Index (NDVI), are highly related to canopy ground cover of many crops (Trout and Gartung, 2006, Trout et al., 2008). Basal crop coefficient (the ratio of the crop evapotranspiration over the reference evapotranspiration when the soil surface is dry but transpiration is occurring at a potential rate) can be more accurately estimated by the fraction of ground cover by vegetation (Allen et al., 1998, Allen and Pereira, 2009). With NDVI: f_c and f_c : K_c relationships, Johnson and Trout (2012) used a time series of satellite NDVI to monitor vegetative crop ET in California. Their results suggest that satellite based algorithms applied in regions with available reference ET networks can provide timely estimation of crop water use for irrigation scheduling or water resource management.

A relatively more direct satellite-based approach to estimate crop ET is using an energy balance technique (Moran et al, 1989, Kustus and Norman, 1996, Bastiaanssen et al., 1998a, Anderson et al., 2012). These approaches calculate available energy using earth surface temperature (T_s), derived from thermal band of satellite imagery, to constrain the sensible heat flux for one or more canopy and soil layers, and then computing latent heat as a residual to the surface energy balance. With visible, NIR, and thermal bands of satellite imagery and ground meteorological data, the METRIC model (Mapping Evapotranspiration at High Resolution using Internalized Calibration, Allen et al., 2007b) has been applied for ET estimation under various agro-climatic conditions in several countries worldwide, however, not in Hawai'i. Tasumi et al. (2005) found that SEBAL (the Surface Energy Balance Algorithm for Land)/METRIC (early version) models agreed well with lysimeter-based ET observations in the semi-arid United States. Santos et al. (2008) combined ET derived from the METRIC model with a water balance model to significantly improve irrigation scheduling in southwest Spain. Gonzalez-Dugo et al. (2009) compared the performance of ET estimation from the METRIC model, a two-source energy balance model (Kustas and Norman, 1997), and vegetation index derived crop coefficient in rain-fed crop production in Iowa and found that the satellite-based ET methods all gave satisfactory results.

Most of the development and validation of these satellite-based energy-balance models have taken place in semi-arid to arid interior regions with surrounding non-irrigated land and mountains (Allen et al., 2007a; Bastiaanssen et al., 1998b; Su, 2002). These models generally assume near constant local and mesoscale meteorology. Relatively little validation of ET derived from satellite thermal imagery has been done in regions with significant coastal advection, higher

relative humidity, and locally varying meteorology, such as Maui, Hawaii. This study compared the performance of two satellite-based crop coefficient and evapotranspiration approaches: (1) a crop coefficient/reference ET method using remotely sensed canopy ground cover (canopy cover-based), and (2) the METRIC model. Successful application of satellite imagery could significantly advance effective crop water management in semi-arid tropical regions with increasing water demands.

2. Materials and Methods

2.1. Study fields

There is a wide variation in the climate across the central valley of Maui, especially with respect to precipitation (Giambelluca et al., 2013) and wind. Two sugarcane fields with contrasting climate conditions were selected on the sugarcane plantation in Maui (Fig. 1). Field #905, hereafter designated as Windy, (20.824633°N, 156.491278°W) has an elevation of 44 m and area of 63 ha. Field #415, hereafter designated as Lee, (20.784664°N, 156.403869°W) has an elevation of 203 m and area of 99 ha. The soil textures of Lee and Windy fields are clay and sandy clay loam, respectively. Field campaigns were conducted from 2011 to 2013. Both fields were planted in the same sugarcane cultivar (H65-7052 – Heinz et al., 1981), which is used majority of the plantation. Sugarcane was planted on March 28, 2011 and May 11, 2011, and harvested on December 2012 and May 2013 for Lee field and Windy field, respectively. Cropping period was about 21 months for Lee field and 24 months for Windy field. A drip irrigation system was used to deliver water to the crops. The system consists of drip tape spaced at 2.7 m intervals with sugarcane lines planted on both sides of the drip tape at 45 cm distance

away from the tape. The drip tapes were slightly buried at a shallow depth so that the tapes were stayed in place before the plants get bigger. The irrigation was scheduled by the farm agronomist and irrigation manager two or three times a week using reference ET calculated from local meteorological data.

Figure 1. Eddy covariance towers (red dots) were installed at sugarcane field #905(Windy), #917, and #415 (Lee) in Maui Island. Image is true color Landsat 7 (30 m resolution – image date: February 5, 2000).

2.2. Landsat 7 imagery preparation

A series of Landsat 7 ETM+ imagery for path 63 row 46 was acquired from the U. S. Geological Survey Earth Explorer site (<http://earthexplorer.usgs.gov/>). The image dates are given in Table 1. The imagery was atmospherically corrected to surface reflectance images using the Landsat Ecosystem Disturbance Adaptive Processing System (Masek et al., 2006). NDVI imagery was calculated based on red and near-infrared band reflectance data in commercial software (ERDAS Imagine 2011, Intergraph, Inc., Madison, AL, USA)². Mean Landsat NDVI was calculated for each study field on clear sky satellite overpass dates.

Table 1. Satellite NDVI, ground measured NDVI, canopy ground cover (f_c) and crop coefficient (K_c) on satellite overpass days in Windy and Lee fields.

	Sampling Date / Image Date*	DAP [†]	Satellite NDVI	Ground NDVI	f_c	K_c
Windy	08/30/2011	111	0.3415		0.1762	0.513
	10/01/2011*	143		0.5985	0.5958	0.601
	11/02/2011*	175		0.6829	0.6791	0.783
	11/17/2011*	190		0.7308	0.7720	0.779
	12/05/2011*	208		0.7725	0.8235	0.864
Lee	08/17/2011	142	0.4763		0.415	
	08/30/2011	155	0.5846		0.5918	0.704

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

	09/15/2011	171	0.61		0.7055	0.838
	10/01/2011*	189		0.7132	0.7436	0.787
	11/02/2011*	219		0.7842	0.8211	0.976
	11/16/2011*	233		0.7795	0.8085	0.905
	04/13/2013	65	0.802		0.065	0.292

*DAP=Day after planting

*Satellite NDVI was not available due to cloud cover.

2.3. Field measurements

During the satellite overpass dates, canopy ground cover was measured with a multispectral camera (Tetracam Inc., Chatsworth, CA, USA). The camera contains a single precision 3.2 megapixel image sensor optimized for capturing green (520-600 nm), red (630-690 nm), and near-infrared (760-900 nm) wavebands of reflected light at bandwidths approximating Landsat bands 2, 3, and 4. A handheld CropScan multispectral radiometer MRS5 (CROPSCAN Inc., Rochester, MN, USA) was used to measure spectral reflectance from sugarcane plants. The sensor wavebands of the radiometer are similar to Landsat TM. NDVI was also calculated from the reflectance measurements from the red and near-infrared wavebands of the radiometer. Due to the cloud coverage of some satellite images, we were not able to get satellite NDVI data for one or both fields. Therefore, NDVI measured using the radiometer on the ground during satellite overpass periods could be used when satellite data are not available. A telescoping pole tripod system (GeoData Systems Management Inc., Berea, OH, USA) was used to suspend the camera and radiometer directly above the plant and aim vertically downward at nadir view. The camera and radiometer were suspended 2.7 m above the canopy. Each field was measured every

16±2 days coincident with Landsat 7's overpass of Maui. During each measurement day ten Tetracam images and CropScan reflectance readings were taken at pre-selected sampling locations around the EC tower in each field around solar noon; sampling locations were identical throughout the study. Each Tetracam image was preprocessed in image processing software (LView Pro 2006 - CoolMoom Corp., Hallandale, FL, USA) to paint out the pixels of soil, grass, shadow and other background. The preprocessed image was then analyzed using PixelWrench software (Tetracam Inc., Chatsworth, CA, USA) to classify fractional crop cover, and the crop cover readings from the ten locations were averaged to determine mean and standard error of field crop cover. Crop canopy cover and NDVI readings from the ten locations were averaged for each field for each measurement day. The relationship between NDVI and crop canopy cover was established using regression analysis.

2.4. Crop evapotranspiration (ET_c)

An eddy covariance (EC) tower was established in each field; full details are found in Anderson and Wang (2014) and Anderson et al. (2015a) with a summary provided here. Tower instrumentation consisted of an integrated Eddy Covariance system (EC150 - Campbell Scientific, Logan, Utah, USA) with an infrared gas analyzer, aspirated temperature probe, attached 3-D sonic anemometer head (CSAT3A - Campbell Scientific), and enhanced barometer (PTB110 – Vaisala, Vantaa, Finland). Relative humidity and air temperature were measured by a combined temperature and relative humidity probe (HMP45C – Vaisala). Net radiation was measured with a single component net radiometer (NR-Lite2 – Kipp and Zonen, Delft, Netherlands). Ground heat flux was measured as the average of four self-calibrating heat flux plates (HFP01SC – Huskeflux, Delft, Netherlands). The plates were installed at 5 cm depth at

four lateral locations perpendicular to the irrigation drip line: 0 cm (drip line), 45 cm (sugarcane row), 75 cm, and 135 cm (mid-point between drip lines). All data were recorded and processed on solid state dataloggers (CR3000, Campbell Scientific, Logan, UT, USA). The EC150 system measured CO₂, H₂O, wind velocity, and sonic temperature at 10 Hz. Other variables were averaged to 30 minute fluxes. After installation, tower heights were raised periodically to keep meteorological instrumentation ~3.0-3.3 m above the zero plane displacement height, which was assumed to be 67% of crop canopy height. ET was corrected for energy balance closure at daily time scale (Anderson and Wang, 2014; Anderson et al., 2015a). The eddy covariance tower in the Lee field was installed back to the field after planting for the second crop cycle in 2013. A third eddy covariance tower was established in another commercial sugarcane field #917 (20.798659°N, 156.453065°W, an elevation of 22 m) in April 2013 (Fig. 1). These data were used to check the results from the first crop cycle.

2.5. Reference ET_0

There is a network of 17 automated full weather stations throughout the 15,000 hectares plantation (http://www.westernwx.com/hcs/data/HourlyData_css.htm). These stations are equipped with anemometer (Wind Monitor Jr., R.M. Young, Traverse City, MI, USA), rain gauge (TE525, Texas Electronics, Dallas, TX, USA), down welling (incoming) pyranometer (LI200X, LI-COR, Inc.), and air temperature and relative humidity probe (HMP35C or 45C, Vaisala). Most stations are mounted at ~10 m above ground elevation on wooden poles near sugarcane fields. Operation, maintenance, annual instrument calibration, and data processing for the network are contracted to a commercial company (Western Weather Group, Chico, CA, USA). Reference ET_0 was calculated using modified Pan Equation presented by Doorenbos and

Pruitt (1977) in FAO Irrigation and Drainage paper #24 with the correction factors developed by Frevert et al. (1983). The farm irrigation manager uses the data from these weather stations for irrigation scheduling. An ET_0 map of the entire plantation was developed by interpolating the data from the weather station network for each overpass date using Spline tool in Arc GIS 9.3 (ESRI Inc., Redlands, CA).

For both Lee and Windy fields, there is no farm weather station co-located with the EC towers. Therefore, daily and hourly reference ET values were calculated from EC tower measurements using the ASCE (American Society of Civil Engineers) standardized (ET_0) equation for these two fields, as follows:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (1)$$

where ET_o is in mm/day or mm/hour depending on time step, R_n and G are net radiation and ground heat flux ($\text{MJ m}^{-2} \text{ day}^{-1}$ or $\text{MJ m}^{-2} \text{ hour}^{-1}$), γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), T is mean daily or hourly air temperature ($^\circ\text{C}$), u_2 is mean daily or hourly wind speed measured at or scaled to 2 m height, e_s and e_a are mean saturation and actual vapor pressure (kPa), respectively, and C_n and C_d are empirical numerator and denominator constants that change with reference surface and time step (see Table 1 in Allen et al., 2005). All meteorological variables were scaled from 3 m above the zero plane displacement to 2 m height following the ASCE procedure for adjusting meteorological measurements at non-standard height. Following ASCE, the mean daily meteorological values were calculated as an average of daily minimum and maximum values.

2.6. METRIC

METRIC was developed to quantify spatial ET over large area using satellite-based surface energy fluxes (Allen et al., 2007b). The model calculates latent heat flux (ET) as a residual of the surface energy balance

$$LE = R_n - G - H \quad (2)$$

where LE = latent energy ($W m^{-2}$); R_n = net radiation ($W m^{-2}$); G = soil heat flux ($W m^{-2}$); and H = sensible heat flux ($W m^{-2}$). R_n is the difference between all outgoing and incoming radiant fluxes, which is expressed as

$$R_n = R_{s\downarrow} - \alpha R_{s\downarrow} + R_{L\downarrow} - R_{L\uparrow} - (1 - \varepsilon_o) R_{L\downarrow} \quad (3)$$

where $R_{s\downarrow}$ = incoming short-wave radiation ($W m^{-2}$); α = surface albedo (dimensionless); $R_{L\downarrow}$ = incoming long-wave radiation ($W m^{-2}$); $R_{L\uparrow}$ = outgoing long-wave radiation ($W m^{-2}$); and ε_o = broadband surface thermal emissivity (dimensionless). Soil heat flux G was estimated as a ratio G/R_n using an empirical equation by Bastiaanssen (2000)

$$\frac{G}{R_n} = (T_s - 273.15) (0.0038 + 0.0074\alpha) (1 - 0.98 NDVI^4) \quad (4)$$

where T_s = surface temperature (K), and α = surface albedo. G is then calculated by multiplying G/R_n by R_n . Sensible heat flux was estimated from the following function

$$H = \rho_{air} C_p \frac{dT}{r_{ah}} \quad (5)$$

where ρ_{air} = air density (kg m^{-3}); C_p = specific heat of air at constant pressure ($\text{J kg}^{-1} \text{K}^{-1}$); and r_{ah} = aerodynamic resistance to heat transfer (s m^{-1}).

The output of the METRIC model is a 30 m resolution map of actual ET or K_c (designated or parameterized as ET_{rf} in the model, calculated using equations (1-5). A detailed description of the METRIC methodology is discussed in Allen et al. (2007b). We ran the model for the images on Sept. 15, 2011, Jan 5, 2012, Jan 21, 2012, and May 12, 2012 to obtain the spatial distribution of ET_c and K_c . The results of METRIC were compared with the ET_c and K_c values from satellite derived crop coefficient using canopy ground cover measurements for each study field.

3. Results and Discussion

3.1. Meteorological observation

Figure 2(a) shows the monthly maximum and minimum temperature and mean daily wind speed in the Lee field from July 2011 to November 2012 and in the Windy field from July 2011 to April 2013, respectively. The maximum temperatures in both fields were very close, while the minimum temperatures in Windy field were higher than those in the Lee field. The highest temperature was in August and lowest in February. Wind speed in the Lee field was relatively constant with an average value of 2 m s^{-1} during the experimental period. Wind speed in the Windy field was much higher than those in the Lee field with the highest mean monthly of 6.4 m s^{-1} and daily mean wind speed up to 10.4 m s^{-1} occurring in July 2011. Daily and cumulative precipitation from weather stations was shown in Figure 3 for both fields. The total

amount of rainfall during the study periods were 74 mm and 148 mm for Lee and Windy, respectively (Fig. 3). Daily relative humidity for both fields was approximately the same for both fields at 62-65 % (Anderson et al., 2015a, Table 1).

Figure 2. The monthly maximum and minimum temperatures, and mean monthly wind speed at Windy and Lee field, respectively.

Figure 3. (a) Daily and (b) cumulative precipitation at Windy and Lee field during the study period, respectively.

3.2. Fractional canopy ground cover (f_c) and NDVI

Four stages of crop growth were defined based on f_c . The initial stage was from emergence to approximately 10% crop cover; the crop development stage was from 10% ground cover to full effective coverage (around 80%) (Allen et al., 1998); from complete crop cover to the start of ripening and maturation was mid-season; and the rest of period was called late-season. Ground measurements of f_c were made at ten locations across these two fields over our observation period (Fig. 4). Because of logistic limitations, we were not able to acquire crop cover readings for the initial stage in 2011. The first measurement was made at DAP (Days After Planting) 111 from Windy field and at DAP 142 from Lee field. The first crop cover reading was 18% for Windy field and 42% for Lee field. In addition, some samplings were also missing at the crop development stage due to initial technical difficulties in using the tri-pod system, especially in the Windy field where the average wind speed was 3 to 6 m s⁻¹. The fraction of canopy ground cover increases in an approximately linear pattern during the rapid crop development stage. Although the asymptotes are 0.88 and 0.89 for the Lee and Windy field, respectively after fitting 3-parameter logistic curve to these two data sets, we would say crop reached full coverage (about 80%) at DAP 201 for Windy field and DAP 228 for Lee field, which indicated the beginning of the mid-season (Fig. 4). Both fields developed at a slower rate than FAO-56 guidelines (which indicate a fixed 180 days to reach mid-season based on early Hawaiian sugarcane research). Due to the unexpected failure of the drip irrigation system in the Lee field at the late season and due to overall drought in Maui, Lee was harvested about three months earlier than scheduled. The second cropping cycle of sugarcane in the Lee began when the field was replanted on Feb. 7, 2013. Ground cover measurements were taken during this cycle from March to June in 2013 to

fill the observational gap at the early growth stage. The data points taken in year 2013 were indicated within an oval in Fig. 4. At DAP 65 in 2013, f_c was about 0.065.

Figure 4. Mean canopy ground cover measurements in Windy and Lee fields during the study period. The three points in the oval were from replanted sugarcane in the Lee field.

NDVI tracked crop phenology well (Fig. 5). Radiometer NDVI and satellite NDVI values were also tracked very closely with each other. Therefore, when satellite imagery was not available for the day, the radiometer NDVI was used for regression analysis (Table 1). A linear relationship between fraction of canopy ground cover (f_c) and NDVI values over seven satellite overpass dates from two fields was developed for crop initial and development growth stages (Fig. 6). When f_c is about 0.8, NDVI begins to lose sensitivity and water use does not increase for canopy

cover above that (Doorenbos and Pruitt, 1977). Canopy ground cover in the Lee and Windy field exceeded 80% on Dec 5, 2011 (82%) and Nov 16, 2011(81%), respectively (Table 1). The relation between measured NDVI and f_c was found as the following linear equation:

$$f_c = 1.312NDVI - 0.1921 \quad (6)$$

The coefficient of determination (R^2) is 0.97 and the Root Mean Squared Error (RMSE) value is 0.043, which indicate that NDVI is a robust indicator of crop canopy ground cover (Fig. 6). Bare ground NDVI value was about 0.15. The relationship obtained over two fields was in good agreement with the results reported in Johnson and Trout (2012), where they found a strong linear relationship for NDVI and f_c over 18 different crops in California ($r^2=0.96$). The linear relationship presented here is not valid for crop canopy cover greater than 80% or for senescing crops.

Figure 5. Ground-based CropScan NDVI measurements (CS_NDVI) and Satellite Landsat 7 NDVI (LS_NDVI) for both study fields during the study period (DAP = Day after planting).

Figure 6. The relationship between NDVI and ground measurements of canopy ground cover, f_c using the data in Table 1.

3.2. Crop coefficient (K_c) and canopy crop cover (f_c)

Daily K_c for the Lee and Windy fields was calculated by ET_c/ET_0 , where ET_c was measured by the eddy covariance towers and ET_0 was calculated by Eq. (1). High variation in K_c

values was observed in the Windy field (Fig. 7b) than Lee field (Fig. 7a). Although Windy and Lee fields had slightly different in planting dates, available soil capacity and fetch (Anderson et al, 2015b), the main factor contributing to higher variation in ET_0 in the Windy field is higher and more variable wind speed. The black lines in the figure represent the average K_c for different growth stages and the red lines indicate crop coefficient values from FAO-56 guidelines for comparison. The tower in the Lee field was reinstalled after planting the second cropping cycle in 2013 and started to collect data on April 10, 2013. The data at the early growth stage of 2013 was also shown in the figure as green triangles (Fig. 7a) to compliment the missing early period data from the 2011 cycle. For Lee field, the initial K_c value was 0.33 and lower than the FAO value of 0.4 for sugarcane crop water requirement. K_c at the development stage followed the FAO-56 guidelines fairly closely. The average K_c value was 0.82 at the mid-season. The average K_c at the late growth stage after DAP 510 was about 0.63. The irrigation in the Lee field was stopped before the earlier harvest so the K_c value dropped even before the end of mid-season. The present K_c values in the Lee field was 16%, 34% and 16% lower than FAO K_c values at initial, mid, and late growth stages, respectively. For Windy field, K_c value at the initial stage was the same as FAO value of 0.4. K_c value increased until 0.76 at mid-stage which was 39% lower than FAO value of 1.25. After DAP 510, we did not observe a decline of the K_c value values in the Windy field at the late stage. Inman-Bamber and McGlinchery (2003) reported the K_c for sugarcane in Australia and Swaziland using Bowen Ratio Energy Balance method. They found similar K_c as FAO for the initial and mid periods of crop development. Win and Zamora (2013) also reported similar K_c ; however, both these studies found higher K_c values for the final growth stage than FAO-56. Overall, the present K_c values were lower than what were found in other studies. One possible explanation for the apparently low K_c values maybe the

inappropriateness of the ASCE reference ET equation for tropical windy conditions. In an evaluation of the measured ET, soil moisture, and meteorological data of the same field sites, Anderson et al. (2015a) found significant and sustained divergence between the ASCE reference ET equations and measured ET, even during full canopy, non-water stressed periods where soil moisture was at or above field capacity in the Windy field. The amount of divergence was strongly correlated with wind speed. Anderson et al. (2015a) also found that alternate reference ET equations, including the Priestley-Taylor equation (Priestley and Taylor, 1972) and a custom version of the ASCE equation with higher bulk canopy resistance ($r_s=165 \text{ s m}^{-1}$) were less sensitive to advection and much better predictors of actual crop water demand, and showed far less day to day variation due to wind than the original ASCE short and tall reference ET equations. Some of the discrepancies were attributed to possible lower effective Leaf Area Index, increased leaf-level resistance under non-water stressed conditions, as well as suppressed nighttime evaporation due to the wet soil surface and drip irrigation system being insulated from the atmosphere by an extensive layer of sugarcane leaves and lodged cane (Anderson et al., 2015a). We also note that the increased leaf-level resistance is consistent with the both the lack of need for Hawaiian sugarcane to have low leaf resistance in order to evaporatively cool to maintain optimal leaf temperatures for photosynthesis (e.g Crafts-Brandner and Salvucci, 2002) . This reduced need for high stomatal conductance is due to the relatively mild maximum air temperatures ($< 30^\circ\text{C}$) , extensive ability to cool via sensible heat flux under high wind conditions (Rolim et al., 2008), and the ability for sugarcane leaves to absorb sufficient amounts of carbon dioxide to maintain extremely high photosynthetic rates (Anderson et al., 2015b). Thus the lower K_c values than FAO-56 K_c are likely caused by local impacts of a combination of

factors including the standard parameterization of ASCE reference ET equation, windy tropical weather conditions, and drip irrigation systems under lodged sugarcane plants.

Figure 7. Comparison of FAO crop coefficient (K_c) for sugarcane with the eddy covariance tower measured K_c for (a) Lee and (b) Windy fields (DAP = Day after planting).

(a)

(b)

Table 1 lists canopy ground cover and crop coefficient values for crop development stages. The earliest data available is on Aug 30, 2011. The last column is the median values of K_c within 5 days (± 2 days within satellite overpass day).

Crop coefficient was linearly correlated to fraction of canopy ground cover (f_c) during the crop development stage (Table 1). The regression equation was

$$K_c = 0.7489f_c + 0.2776 \quad (7)$$

where K_c was the ratio of tower measured ET and ASCE standardized ET_0 , with $R^2 = 0.89$ and $RMSE = 0.07$.

NDVI images were converted to canopy ground cover maps using the linear Eq. (6). Then using the linear Eq. (7), these NDVI derived canopy ground cover maps were developed to K_c maps for the entire plantation. From which, ET_c maps could be developed using the K_c maps and daily ET_0 maps derived from the weather station network. Figure 8 presents the spatial daily K_c and ET_c maps of the plantation for satellite overpass dates of September 15, 2011 and January 5, 2012. The K_c or ET_c value is low in blue and high in red. The daily K_c was scaled to 0.28 ~1.1. The daily ET_c over the entire plantation ranged between 1.1~4.8 mm/day. Since there are hundreds of fields and different fields were planted at different times, the variation in the spatial and temporal K_c and ET emanates from the variation.

Figure 8. Daily crop coefficient (K_c) and ET_c maps of the plantation derived from the satellite images on September 15, 2011 and January 5, 2012 using the crop coefficient/reference ET method.

3.3. METRIC Models

Quality weather data are needed to process METRIC. We investigated the choice of EC tower (Windy vs. Lee) for providing the baseline meteorological data. Most METRIC K_c values using the EC tower in the Lee field were greater than those using the EC tower in the Windy field (Fig. 9a). METRIC predicted ET_c using the EC tower in the Lee field was lower than those using the EC tower in the Windy field (Fig. 9b). The data points that most deviate from the 1:1 relationship line represent satellite overpass dates on Sept. 15, 2011 and May 12, 2012. METRIC used Eq. (2) to calculate ET_c . To examine the discrepancy between the two data sources, we compared R_n , G , and H from METRIC for both sites. The calculated R_n and G from both fields were very close to each other and insensitive to the specific tower meteorological data we used. The average difference of R_n between the tower data in the Lee and Windy fields was about 2% and the average difference of G between the tower data in the Lee and Windy fields was about 3%. We also compared the calculated METRIC R_n to the tower measured R_n for these four overpass dates. There is no significant difference between the EC tower measured R_n and the calculated METRIC R_n . The differences between the METRIC R_n and the EC tower measured R_n

ranged from 2% to 12% for the METRIC using the tower in the Lee field and ranged from 0% to
 13% for the METRIC using the tower in the Windy field. However, H from two data sources
 was significantly different. When using the EC tower in the Lee field to process the METRIC,
 the difference of H between the METRIC parameterization and EC observations in the Lee and
 Windy field was 7% and 1% for the image on Jan 5, and Jan 21, 2012, but 77% and 41% for the
 images on September 15, 2011 and May 12, 2012, respectively. In September 2011 and May
 2012, the wind speed in the Windy field was more than twice of the wind speed in the Lee field
 (Fig. 2). As a result, Windy field had much higher H values than Lee field. In January 2012, the
 difference of the wind speed was smaller, which could explain the difference between using the
 tower data in the Lee field and in the Windy field. These examples demonstrate how sensitive
 METRIC-parameterized H is to wind speed. Figure 10 presents an example of spatial K_c and ET_c
 maps processed by the METRIC model for the images on September 15, 2011 and January 5,
 2012 using the EC tower in the Windy field. The daily K_c was scaled to 0~1.4 and the daily ET_c
 over the entire plantation ranged 0-6.9 mm/day. Although the range in maximum K_c varied from
 1.1~ 1.4, most of the K_c values are less than 1.1 cross the entire plantation for both image dates.
 The K_c values in the Lee field on the image dates September 15, 2011 and January 5, 2012
 ranged from 0.61~0.82 and 0.72~ 0.9, respectively, with some lower values along the south-east
 edge of the field.

Figure 9. Comparison of predicted sugarcane (a) K_c and (b) evapotranspiration, ET_c , between the
 Lee and Windy fields using the METRIC model. The x-axis presents the METRIC predicted
 values using the EC tower at Lee field; the y-axis presents the METRIC predicted value using
 the EC tower at Windy field.

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Figure 10. Daily crop coefficient (K_c) and ET_c maps of the sugarcane plantation derived from the METRIC processed satellite images on September 15, 2011 and January 5, 2012 using the EC tower data in the Windy field.

3.4. K_c and ET_c predicted by crop coefficient/reference ET vs. METRIC model

Figure 11 (a) shows the comparison of K_c calculated by METRIC and K_c by satellite-based canopy cover method. We also compared the METRIC results against the EC towers in the Lee and Windy fields. The figure shows that canopy cover-based K_c tended to be lower than METRIC K_c when we used the reference ET from the EC tower in the Windy field. When the reference ET was used from the EC tower in the Lee field, the canopy cover-based K_c was more correlated to METRIC K_c than using the EC tower in the Windy field. The ET_c by the canopy cover-based method was greater than METRIC ET_c when ET_c was lower than 4.0 mm day^{-1} and it was less than METRIC ET_c when ET_c exceeded 4.0 mm day^{-1} (Fig. 9 b). The root mean square error (RMSE) for using EC in the Lee field was 0.17 mm day^{-1} , while RMSE for using the EC in the Windy field was 0.19 mm day^{-1} . The EC towers in the Lee field (2nd cycle) and field #917 started to collect data on April 10 and April 27, 2013, respectively. K_c maps were derived from Landsat 7 imagery on April 13, 2013 and May 16, 2013 and Landsat 8 imagery on May 23, 2013 and June 24, 2013 using Eqs. (6-7). Although most of the K_c values derived from satellite-based canopy ground cover tend to be greater than the tower measured K_c , the result has shown that the linear model could be used to estimate crop coefficient over the entire plantation (Fig. 12). We were not able to process the METRIC on the Landsat 8 images due to the lack of updated model coefficients and technical algorithms to derive equation parameters from image digital numbers. The comparison of K_c calculated by the METRIC and K_c developed by satellite-based canopy cover method will be done in the future when the model is updated for Landsat 8.

Figure 11. Comparison of (a) K_c and (b) ET_c between the satellite-based K_c /reference ET method and the METRIC model. The x-axis presents the predicted values by K_c /reference ET method; the y-axis presents the METRIC predicted value using the EC towers at Lee and Windy fields.

Figure 12. The eddy covariance tower measured K_c and satellite derived K_c from the satellite images on April 13, May 16, and May 23, 2014 for Lee and field #917.

4. Conclusions

This study presented a satellite based approach for mapping spatial crop coefficient K_c and ET for sugarcane in Maui, Hawaii, USA. Two satellite-based approaches were investigated to estimate K_c and ET. Although METRIC is less dependent on ground based measurement, the selection of ground weather station data will affect the K_c and ET estimates, especially in Maui due to its wide variation in micro-climate. Satellite NDVI was closely correlated to fraction of crop canopy ground cover (f_c). Crop coefficient can be reliably estimated by the satellite-based crop cover. The linear relationships were fairly robust. To use the satellite-based crop coefficient/reference ET method, f_c should not exceed full crop cover and crop should not be in senescence. Compared to METRIC model, the satellite-based crop coefficient/reference ET

method may be more practicable for estimating crop growth and crop water use in Maui, where ground-based reference ET_0 measurements are available through a high density automated weather station network and where there is significant meteorological variation across a satellite imagery scene used to derive thermal-based ET estimates. K_c values measured by the eddy covariance tower were lower than values found in FAO-56, especially for mid-season growth stage. One main reason may be the inappropriate use of the standard ASCE reference ET equation that was developed for arid regions.

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