Journal of Sustainable Energy & Environment 9 (2018) 1-9

Estimation of Evapotranspiration from Sugarcane Plantation Using Eddy Covariance Method

Sujittra Singta[1], Amnat Chidthaisong[1,*], Daisuke Komori[2], Vanisa Surapioith[3] and Wonsik Kim[4]

[1]The Joint Graduate School of Energy and Environment (JGSEE) King Mongkut's University of Technology Thonburi (KMUTT), Bangkok, Thailand and Center for Energy Technology and Environment, Ministry of Education, Thailand
[2] Department of Civil Engineering, Tohoku University, Japan
[3] Pollution Control Department, Ministry of Natural Resources and Environment, Bangkok, Thailand (Current address: International Centre for Integrated Mountain Development, Kathmandu, Nepal)
[4] National Institute for Agro-Environmental Sciences, Tsukuba, Japan
[*]Corresponding author: amnat_c@jgsee.kmutt.ac.th

Abstract: This study reports the estimate of evapotranspiration (ET) over a rainfed sugarcane field in Takfa, Nakornsawan province during May 2011 to Feb 2014. The ET was measured by eddy covariance method. The annual ET ranged from 685 to 800 mm year^{-1}. The total ET was 851.17 mm for plant cane while it was 655.20 mm for first ratoon cane. In both plant cane and ratoon cane, total ET in germination phase was less than other growth phases, mainly due to less precipitation and low plant growth activity. The daily ET varied from 1 mm day^{-1} in the dry season to 7 mm day^{-1} in the wet season. Net radiation and soil moisture were found to be the main drivers of variations in ET. Water use efficiency (WUE) of plant cane was less than of the ratoon cane due to higher ET and precipitation in plant cane.

Keywords: Evapotranspiration, Eddy covariance, Sugarcane plantation, Water use efficiency.

1. Introduction

Evapotranspiration (ET) is an important process in the agricultural water cycle and surface energy balance, resulting from an interaction between soil, vegetation, and the atmosphere [1]. ET is separated into two processes whereby water is vaporized from soil surface by evaporation and water is lost by transpiration of leaf [2]. ET varies depending on environmental variables such as air temperature, air humidity, wind speed, vapor pressure deficit, soil water content, direct solar radiation and characteristics of plant and crop management [3-5]. As water shortage especially in the dry season is common in Thailand, available water for crop field irrigation is becoming limited. In addition, extreme climatic events, such as drought and shift in rainfall distribution pattern, have been widespread in recent decades and imposed a significant threat to water resources management, especially for agriculture use. As a result, quantifying ET is crucial for water resource and agricultural management.

Thailand is one of the main exporters of sugar and sugar products, in 2016 its sugar exported value was ranked 2nd after Brazil [6]. For this reason, sugar cane production is one of the major economic sectors in Thailand. The current planting area is 1.7 million ha covering higher fraction of the country's arable land than cassava and palm plantation in Thailand [7]. Besides it is utilized in food and food products, sugarcane is one of the important feed stocks for biofuel production in Thailand [8]. Effective water management and maximizing sugarcane yield therefore are crucial for sustainable sugarcane field management.

ET is the crucial parameter to assist in water management in sugarcane cultivation. There have been various studies that estimated the amount of ET and showed the variations of ET according to location and mode of cultivation practices. Thompson et al. [9] determined water requirements of sugarcane using lysimeter technique in Natal, Brazil. They reported the ranges of ET values of 2.3 to 6.1 mm day^{-1}. Omary and Izuno [10] evaluated sugarcane actual ET from water table data. They found a clear diurnal trend of ET with a maximum in the afternoon (2:00 and 3:00 pm) and a minimum close to zero around midnight. Seasonally, the minimum ET rates occurred during December through February (0.7-1.5 mm day^{-1}) and maximum ET rates (4.5-4.6 mm day^{-1}) occurred during June through September. Total ET was 106.2 cm year^{-1}. Watanabe et al. [11] used Hargreaves equation to estimate the seasonal change of ET rate of sugarcane over Northeast Thailand. They found that the ET rate was between 2 and 6 mm day^{-1} during wet season and remained around 1 mm day^{-1} in dry season. Da Silva et al. [12], using Penman–Monteith method, found that ET in sugarcane field in Brazil was about 2.7 to 4.2 mm day^{-1}. On the other hand, maximum ET in the sugarcane field in Brazil and Australia was reported to be as high as 7 mm day^{-1} [13, 14]. The varying rates of ET mentioned above indicate its dependence on local factors. Thus, site specific measurements of ET are desirable to support water management at field scale.

The objective of this study is to estimate ET of sugarcane plantation by eddy covariance technique and to identify the environmental controls of evapotranspiration. The results of this study are expected to improve our understanding on water use, water use efficiency and its temporal and spatial variations among sugarcane plantation. In addition, it would also help manage effectively irrigation design parameters and scheduling.

2. Materials and methods

2.1 Experiment site

Field measurements were carried out during May 2011 to February 2014 in a farmer's sugarcane field located in Takfa District, Nakornsawan province (latitude 15°20.926'N and longitude 100°25.344'E). The measurement location was surrounded by sugarcane fields in all directions within a distance of approximately 550 m. The sugarcane (*Saccharum officinarum L.*, variety Khon Kaen 3 and LK-92-11) was planted under rainfed conditions, and has been routinely replanted approximately every two to three years. The canopy height was about 3 meter at its maturity. Chemical fertilizers were applied three times for each planting cycle; at the planting time (with 16-20-0), two months after planting (with 15-7-7) and 3-4 months after planting (with 46-0-0). The application for each time was 187.5 kg ha^{-1}. During 2011-2013, the mean annual rainfalls and air temperature were 1352.5 mm 27.9°C [15]. The wet season generally starts in May and ends in August. However, in this study the season is identified by precipitation distribution and the wet season is during May to October. The soil type at this site was clay loam, classified as a Takhil soil series according to the classification of the Land Development Department [16].

Table 1. Detailed information of the eddy covariance instrument used in the current study.

Observed item	Sensor type
CO_2 and H_2O density	EC 150 (Campbell Sci., Inc., USA)
Three-dimensional wind velocity	3D sonic anemometer (CSAT3, Campbell Sci., Inc., USA)
Air temperature	Sonic temperature (CSAT3, Campbell Sci., Inc., USA)
Radiation	(CNR1, Kipp and Zonen)
Soil temperature Three depth (cm): 2.5, 15, 60	Thermocouple
Soil moisture Three depth (cm): 2.5, 15, 60	Water content reflectometer (CS616, Campbell Sci., Inc., USA)

Table 2. Growth stages and duration of sugarcane in the current study

Type of sugarcane	Growth stage			
	Germination	Tillering	Stalk elongation	Maturity
2nd Ratoon	-	-	1 Jun-30 Sep 2011	1 Oct-31 Dec 2011
Plant cane	1-29 Feb 2012	1 Mar-30 Apr 2012	1 May-31Oct 2012	1 Nov 2012-28 Feb 2013
1st Ratoon	1-31 Mar 2013	1 Apr-31 May 2013	1 Jun-30 Nov 2013	1 De c2013-28 Feb 2014

2.2 Estimation of ET

In this study ET over sugarcane field was estimated from the fluxes of latent heat (LE) as indicated in Eq. 1 [17];

$$ET = 0.035 \times LE \qquad (1)$$

where LE is latent heat (J m^{-2} s^{-1}), ET is evapotranspiration rate (mm day^{-1}), and 0.035 is constant value (m^3 J^{-1}) and is equal to conversion factor (86400 s day^{-1} x 1000 mm m^{-1}) divided by latent heat of vaporization (2.45×10^6 J kg^{-1}) and water density (1×10^3 kg m^{-3}). LE is directly calculated from eddy covariance measurement of energy and water fluxes. The EC system was consisted of an 3D sonic anemometer (CSAT3, Campbell Scientific Inc., USA) and an open path CO_2/H_2O gas analyzer (EC150, Campbell Scientific Inc., USA) mounted at a tower height of 7 m. Net radiation (R_n) was measured by a net radiometer (Kipp & Zonen CNR1). Soil-heat flux was measured by thermocouple and reflectometer (CS616). The data were stored in a CR1000 logger (Campbell Scientific Inc., USA) at a sampling frequency of 10 Hz. The EC data were processed with an averaging time of 30 min. The micrometeorological parameters as described in Table 1 were also measured. The fluxes of LE were calculated as indicated in Eq. 2 [18],

$$LE = \lambda\, \overline{w'\rho_v'} \qquad (2)$$

where λ is latent heat of vaporization (J g^{-1}), ρ_v' is instantaneous deviation from mean of water vapor density (g m^{-3})**.** ET rate can be estimated from the vertical wind speed and water vapor concentration which is component of latent heat flux.

2.3 Data processing

EddyPro 6.1.0 software (Li-COR Corp., U.S.A.) was used to process real time or instantaneous data. These data were converted into half-hourly average by using this software including despiking and other basic corrections. Afterward, these half-hourly averaged data were applied through quality filtering process. Firstly, the data were inspected based on the knowledge of some basic characteristics. For instance, negative fluxes of H_2O vapor during daytime were removed. Secondly, the upper and lower limits of effective H_2O flux, latent heat, and sensible heat data were determined according to Wolf et al. [19] such that only the data within ±3 SD range of a 14 day running mean were included. Thirdly, low turbulence conditions were excluded based on friction velocity (u*). We evaluated annual u^*-thresholds from the relationship between the nighttime NEE and u*, which yielded $u^* < 0.1$ m s^{-1}. After quality filtering, 74.0 % of good to excellent quality data was remained for 2011 (60.6% daytime, 39.4% nighttime data), 42.6% (72.2% daytime, 27.8% nighttime data) for 2012, and 37.0% (83.2% daytime, 16.8% nighttime data) for 2013. The gap-filling based on mean diurnal variations (MDV) was used to fill gaps in the flux data [20]. Data windows of 7 and 14 days were chosen for averaging in the daytime and nighttime data, respectively.

Raw weather data were collected at 10 min interval, and averaged into half-hourly data set. Afterward, quality filtering was applied to remove unrealistic measurements and outliers. For periods of instrument failure of the rain gauge, the data from nearby station (about 12 km to the Northeast) of Takfa meteorological station were used instead.

2.4 Determination of sugarcane growth stage

Since the exact growth stage was not determined in the field, for supporting the interpretation of the measured flux data the growth stage of sugarcane was determined according to a standard growth stage described by previous studies [6, 21]. The four phases using growth duration according to these literatures are germination phase, tillering (formative) phase, grand growth phase and maturity & ripening phase (Table 2). These were confirmed by comparing with *in situ* photographs taken at the sites (infrared sensor) to monitor sugarcane growth (picture not shown).

2.6 Water use efficiency of sugarcane

Water use efficiency (WUE) in this study is defined as the ratio of total biomass or grain yield to water supply or evapotranspiration on a period time basis as shown in Eq. 3 [22].

$$WUE\ \left(\frac{kgCane}{kgH_2O}\right) = \frac{yield\ (kgCane\ ha^{-1})}{Total\ ET\ (mm)} \qquad (3)$$

where total ET (mm) is total evapotranspiration for each crop cycle and yield (kg ha^{-1}) is total biomass measured at harvest.

3. Results and Discussion

3.1 Micrometeorological variables

The changes of environmental variables including net radiation (R_n), air temperature (T_a), precipitation (P), soil water content (SWC) and soil temperature (T_{soil}) are shown in Fig. 1. The weekly mean R_n ranged from 70 to 170 J m^{-2} s^{-1} with high variations in the wet season (Fig. 1a). Such large variations have been suggested to attribute to changes in cloud cover [23]. The maximum R_n was observed during wet season (May to October).

Relatively higher albedo during the dry season is one of the reasons of high net radiation during the wet season [24].

Air (T_a) and soil (T_{soil}) temperature patterns are shown in Fig. 1b. The wet season T_a was fairly constant whereas the peak T_a occurred during the dry seasons (32.7±0.5 °C) and the lowest T_a occurs in December (21.4±0.6 °C). T_{soil} was varied in the range between 18.0±0.5 °C and 37.5±1.3 °C. During the summer time (March-May) T_a was usually lower than T_{soil}, but during the winter (i.e. in December) T_a was higher than T_{soil}. Thus, variations in T_{soil} were larger than T_a. Generally, soil temperatures are also controlled by solar radiation, soil water content, presence or absence of canopy leaves and wind speed [25]. Seasonal trends of soil temperatures are therefore driven by one or combinations of these factors. The lower soil temperature than air temperatures during the dry months may be due to combination effects of high solar radiance and low soil moisture as shown in Fig. 1a and 1b. However, from Fig. 1b it is clear that large difference between air and soil temperature was found in 2012 but not in 2013 (in April). This difference seems to be modulated by rainfall such that rainfall removes heat from the air but adds heat to soil due to higher heat capacity of water. Therefore, rainfall during dry months could reduce the temperature difference between air and soil as observed in 2013 when there were more rain events when compared to 2012.

The weekly precipitation and soil moisture change are depicted in Fig.1c. The pattern of soil water content at 2.5 cm was similar to that of precipitation. The total precipitation at this site was 1208.7 mm in 2012 and 1148.3 mm in 2013 (Fig. 1c). More than 80% of total rainfall occurred during the monsoon or wet season (late April - end of October). During this period, the monthly rainfall was more than 50 mm. On the other hand, the daily average volumetric soil water content ranged from 19% to 45% (Fig. 1c).

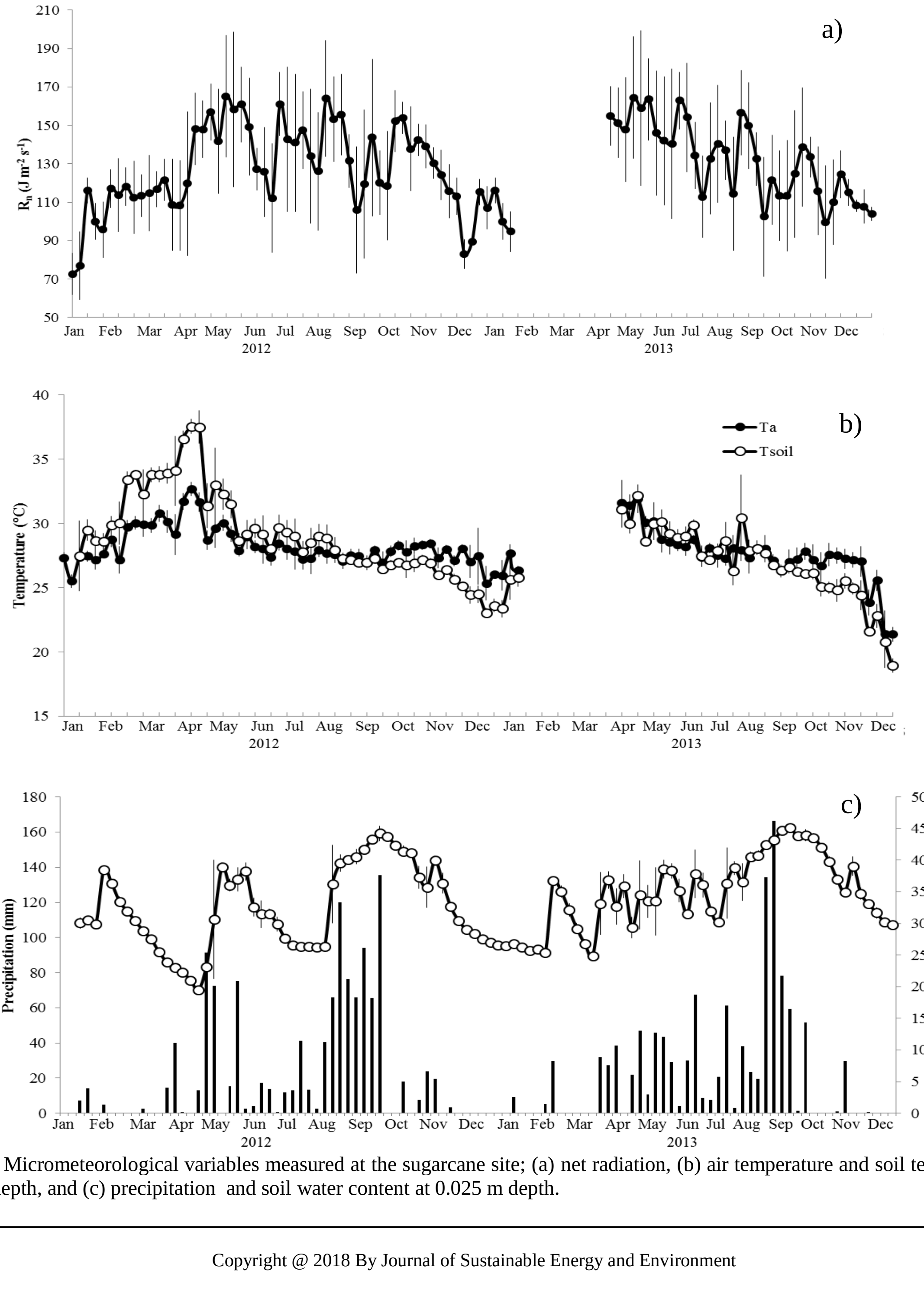

Figure 1. Micrometeorological variables measured at the sugarcane site; (a) net radiation, (b) air temperature and soil temperature at 0.025 m depth, and (c) precipitation and soil water content at 0.025 m depth.

3.2 Variation of energy balance components

Energy balance closure was evaluated to examine the overall reliability of EC measurements [26]. Principally, surface energy balance closure can be evaluated through a relationship between available energy (R_n – G_s) and the dependent flux variables or sum of latent heat and sensible heat (H+LE) [27]. The intercept and slope of regression should be close to zero and 1, respectively. In most cases, it is difficult to obtain a perfect energy balance and such imbalance closure problem was reported by several scientists. The common ranges of this imbalance by EC method range from 10 to 30%. In many case, this is related to underestimation of turbulent fluxes (H+LE) [28, 29]. Moreover, the cause of energy imbalance generally occurs from the selection and installation of the measurement site, i.e. the surface topography (flat vs. slope surface), homogeneous surfaces alignment, and the interference from tower [30]. At this study site, the linear regression between the turbulent heat flux (H+LE) and the available energy (R_n-G) during year 2013 was established (Fig. 2). Other storage terms were not measured and then assumed to be negligible on a half hourly basis. When all data flux was investigated by linear regression, a slope of 0.60 and an intercept of 8.76 W m^{-2} were obtained (Fig. 2a). It means that the energy balance closure was about 60% of available energy and the underestimation of turbulent fluxes affected low energy closure. The degree of closure in this study is lower than other reports for other field eddy covariance systems [26, 31]. However, it is still within the normal range found in the literatures (the ranges of slope, intercept and R^2 are 0.53 to 0.99, -32.9 to 36.9, and 0.64 to 0.96, respectively) [32]. When considered short-term variation in energy (for example in May), the slope was increased 5% and the intercept was decreased to 0.6 W m^{-2} (Table 3). The energy closure balance varied from month to month and within the range of 59±4%.

The energy balance closure was on the lower end of normal range closures and possible reasons are discussed as follows. The energy storage may have a significant influence on energy balance closure, especially energy in the ground is the largest storage term according to Oncley et al. [31] and Meyers et al. [33]. Since the heat storage (G_s) was not directly measured but calculated from temperature measurements, accurate soil heat flux would help improve the energy balance closure at this site. In addition, the surface heterogeneity is also connected with imbalance of energy closure. The large eddies on heterogeneous surface affected to advection and fluxes and the forest sites are more homogeneous than agricultural site [34]. Thus, the closure in forest is also better than the low vegetation sites.

Table 3. Parameters and coefficient of the linear regression between the turbulent flux (H+LE) and the available energy for the entire original dataset in 2013.

Month	Slope	intercept	R^2
Jan	0.52	-2.45	0.93
May	0.63	8.17	0.95
Jun	0.60	11.87	0.92
July	0.61	5.94	0.90
Aug	0.62	0.46	0.90
Sep	0.57	13.82	0.75
All data	**0.60**	**8.76**	**0.91**

3.3 Variations in energy fluxes

As shown in Fig. 3, there was a clear diurnal pattern of net radiation (R_n), latent heat flux (LE), sensible heat flux (H), and soil heat flux (G_s). The R_n accounted for a large proportion of turbulent fluxes. The maximum R_n ranged from 460 to 580 J m^{-2} s^{-1} at midday in each month. The variation of LE and H were similar

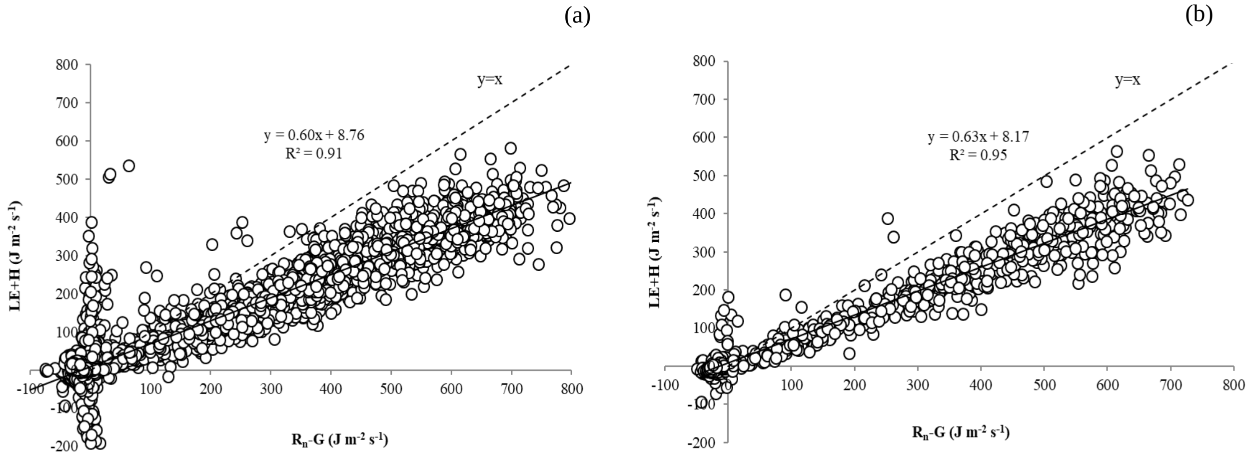

Figure 2. Energy balance closure (a) for all data of 2013 (b) for only May 2013.

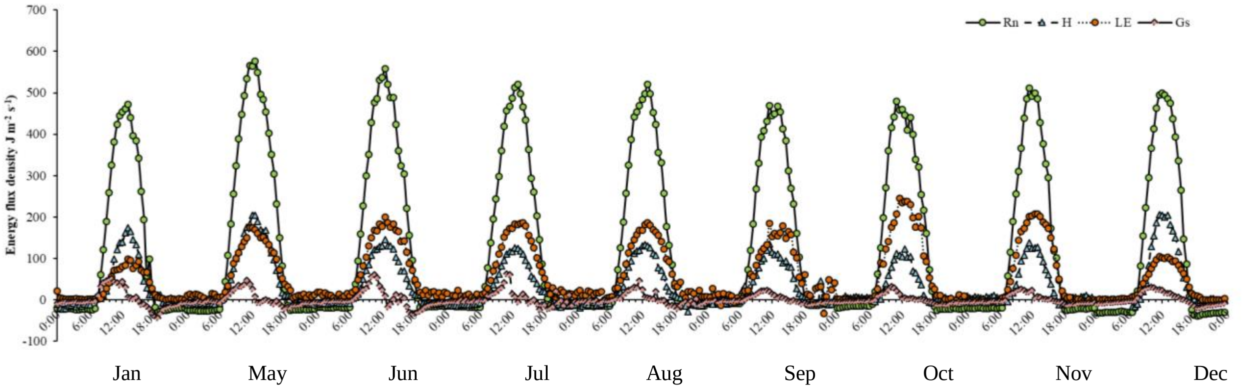

Figure 3. Diurnal variation in net radiation (R_n), sensible (H), latent heat (LE), and ground heat flux (G_s) for each month during 2013.

to those observed for R_n, indicating that they are driven by solar radiation. During the wet months (June to November), the LE was about two times greater than H. On the other hand, the H was greater than LE during the dry months (January and December). The G_s in generally contributed only small fraction of total energy fluxes, especially during stalk elongation stage. The peak of G_s reached about 60 J m^{-2} s^{-1} at 10.30 a.m. This behavior was probably resulted from rainfall event in evening and nighttime. Precipitation could increase SWC and lead to increased thermal conductivity and is then linked to G_s in the morning [35]. Therefore, G_s in early morning was higher than during afternoon and after that declined due to soil evaporation. It was observed that the maximum G_s (61.82 J m^{-2} s^{-1}) occurred during the months when heavy rainfall was concentrated (114.5 mm), similar to those reported by Huizhi and Jianwu [36].

Throughout the growing season, the latent heat was a dominant component with maximum value about 250 J m^{-2} s^{-1}. This could be explained by a dense and green vegetation whereas the sensible heat was gradually increased and became the main turbulent energy fluxes when the sugarcane was in germination and ripening stage.

3.4 Seasonal and diurnal variations of ET

ET rates were characterized by large seasonality (Fig. 4). Maximum ET rate were between 2 and 7 mm day^{-1} during wet season. However, ET rate decreased to approximately 1 mm day^{-1} in dry season. During months with more rainfall, namely, June 2011, July 2011, August 2011, September 2011, August 2012, September 2012, May 2013, and September 2013, the daily ET ranged were between 2 and 7 mm day^{-1}. The seasonal variations of ET were strongly correlated with the distribution of precipitation. In the tropical climate where excessive solar energy and high temperature are present all year round, the limited factor for ET is therefore the amount of available water. These results of ET in the current study are consistent with those reported previously by others. For example, seasonal ranges of ET rate in sugarcane, maize, and cassava fields during wet season were between 2 and 6 mm day^{-1} and remained around 1 mm day^{-1} during dry season [11].

Fig. 5 shows averaged diurnal variation of ET during 2011-2013. During day time, the ET gradually increased and reached a maximum value about 6 to 9 mm day^{-1} and remained around these values until 7 p.m. After that the ET was quickly decreased to almost zero. The peaks of ET were during 1.00–2.00 p.m. which is the period of maximum R_n (about 530 J m^{-2} s^{-1}). Nassif et al. [13] used Bowen ratio method to evaluate the mass and energy exchanges over the sugarcane field in Brazil. They found similar results that ET peaks (7 mm day^{-1}) were strongly related with high net radiation values. The annual ET is summarized in Table 4, which shows the monthly totals and averages. Total annual ET ranged from 685 to 800 mm in 2012 and 2013, respectively.

Table 4. Summary of the monthly and annual evapotranspiration (ET**)** in sugarcane field

Month	2011		2012		2013		2014	
	Average daily ET (mm day^{-1})	Total ET (mm)	Average daily ET (mm day^{-1})	Total ET (mm)	Average daily ET (mm day^{-1})	Total ET (mm)	Average daily ET (mm day^{-1})	Total ET (mm)
Jan	-	-	0.59	18.29	0.96	29.78	0.76	23.56
Feb	-	-	0.53	15.34	1.39	38.95	0.52	14.98
Mar	-	-	0.43	13.24	1.54	47.89	-	-
Apr	-	-	2.17	65.19	1.89	56.82	-	-
May	-	-	3.93	121.69	2.07	64.29	-	-
Jun	3.96	118.95	1.85	55.60	2.47	74.15	-	-
Jul	3.67	125.45	2.43	75.32	2.29	70.91	-	-
Aug	3.29	102.11	3.13	97.11	2.26	70.17	-	-
Sep	3.27	98.14	3.71	111.40	2.19	65.63	-	-
Oct	2.39	74.05	3.72	115.22	2.37	73.61	-	-
Nov	2.17	65.15	2.29	68.70	2.05	61.43	-	-
Dec	1.17	36.35	1.46	43.72	1.02	31.76	-	-
Total	**-**	**-**	**-**	**800.81**	**-**	**685.39**	**-**	**-**

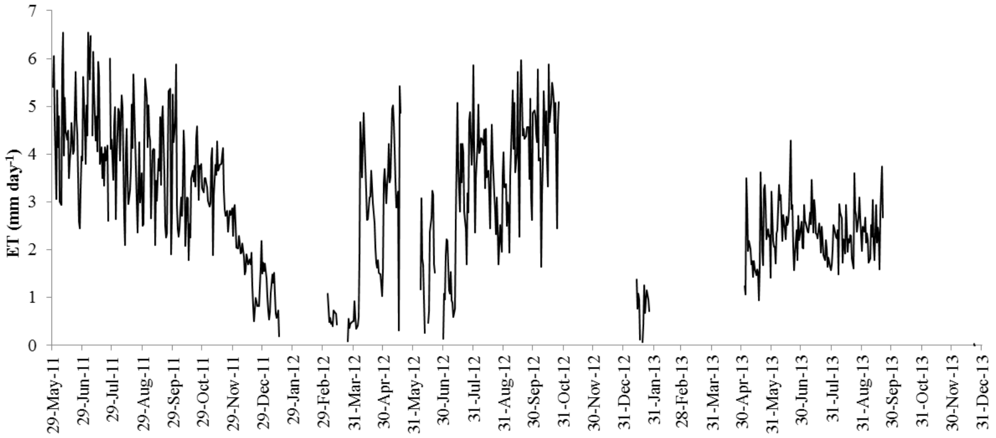

Figure 4. Seasonal variations of daily ET during 2011-2013.

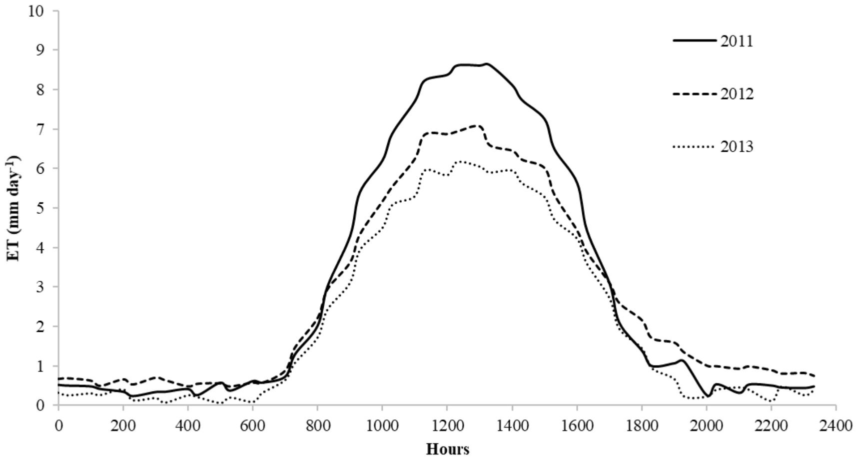

Figure 5. Diurnal variation in ET during 2011-2013.

Table 5. Summary of total ET for each growth stages

Stage	Plant cane			1st ratoon		
	Rainfall (P) (mm)	Total ET (mm)	ET/P Ratio	Rainfall (P) (mm)	Total ET (mm)	ET/P Ratio
Germination	4.81	15.34	3.19	29.70	47.89	1.61
Tillering	68.61	78.43	1.14	177.48	121.11	0.68
Stalk elongation	1059.45	576.33	0.54	925.67	415.90	0.45
Maturity	69.06	181.07	2.62	29.26	70.30	2.40
Total	**1201.93**	**851.17**	**0.71**	**1162.11**	**655.20**	**0.56**

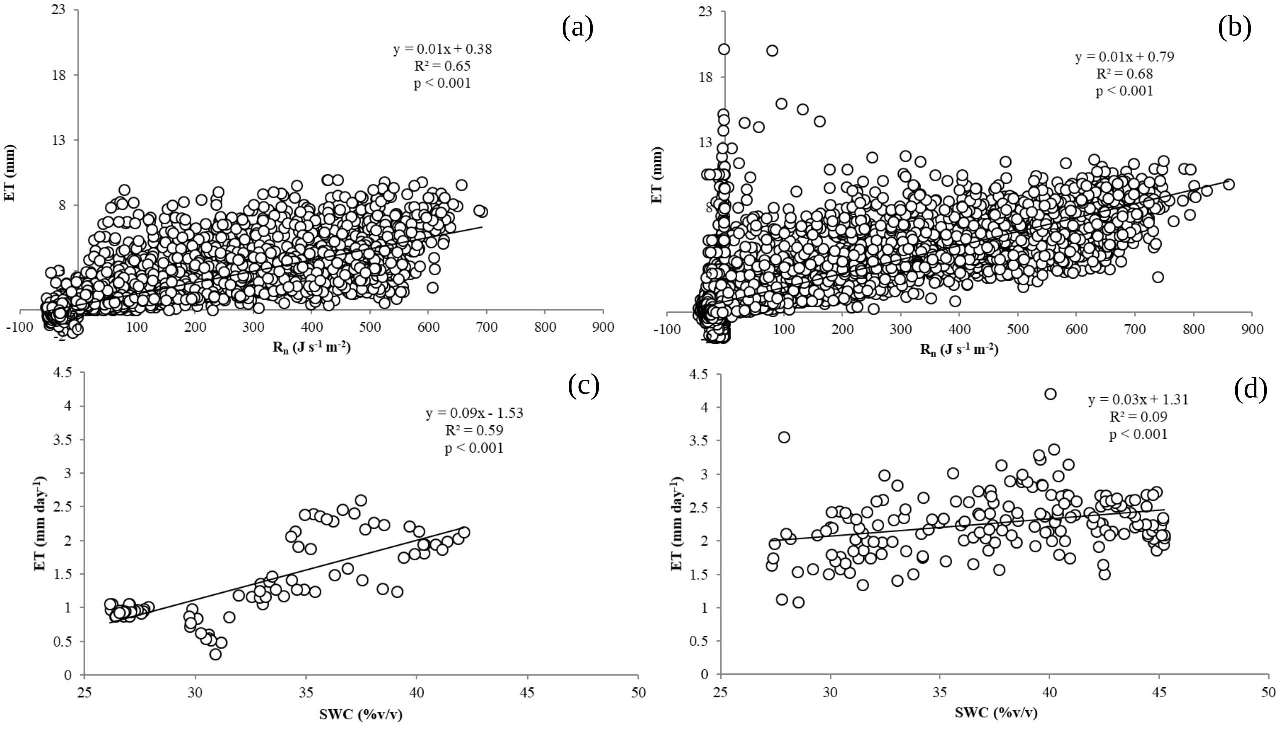

Figure 6. Linear regression between environmental variation and ET during 2013; a) net radiation and ET in dry season, b) net radiation and ET in wet season, c) soil water content in dry season, and d) soil water content in wet season.

3.5 ET and growth stage of sugarcane

Total ET in each growth stage is shown in Table 5. Both plant cane and first ratoon cane have maximum total ET as 576.33 and 415.90 mm during stalk elongation stage. The actual cane formation and maximum growth and thus yield build up takes place in this stage [37]. Hence, sufficient water supply is crucial during this growth stage [38]. The lowest ET was found during germination phase, which was 15.34 and 47.89 mm in plant cane and first ratoon cane, respectively. Because of less water loss and the lowest amount of rainfall in germination stages, ET rate was much lower than other stages [39]. In plant cane, lower rainfall (4.81 mm) during this growth stage resulted in lower ET than during other phases. Similarly, the lower rainfall (29.70 mm) during germination also led to low ET for first ratoon cane. The total ET for plant cane of 851.17 mm was much higher than the ET of first ratoon cane (655.20 mm). Chaichana et al. [39] studied water use for first ratoon cane (2010/2011) using eddy covariance in Kanchanaburi, Thailand. They reported the total water use per crop of 682.1 mm. In other studies, plant cane also consumed more water (540 mm) than first ratoon cane (410 mm) [39]. In addition to the plant type of sugarcane, the difference in the amount of ET among these studies seems to depend on the amount of rainfall during crop cycle (about 1200 mm for first ratoon cane in the current study compared to 1000 mm in the study of Acreche [40].

The ratio of ET to rainfall is an important index to determine water budget in plant community [41]. This index indicates whether the amount of rainfall is met with water requirement of sugarcane. Ideally, it should be equal or less than one. For plant cane, the ET account for 71% of rainfall (1201.93mm). Meanwhile, ET in the first ratoon cane was about 56% compared to rainfall (1162.11 mm). Due to more bare soil in beginning stage and longer period for planting of plant cane, the ET/P was greater than ratoon cane. During first and last stage in both plant cane and ratoon cane, this ratio was higher than one thus the field need additional irrigation. However, this ratio was less than one in other stages, indicating water required for growth could be sufficiently supplied through rainfall.

3.6 Water use efficiency (WUE) of sugarcane plantation

Plant cane was cultivated between February 2012 and February 2013 and after harvesting, first ratoon cane had developed until February 2014. In the year 2012/2013, average sugarcane yields and the amount of water required for sugarcane are 72.19 ton ha^{-1} and 851.17 mm, respectively [7]. In the year 2013/ 2014, these were 69.44 ton ha^{-1} and 655.20 mm, respectively. In this study, WUE of plant cane thus lower than that of the ratoon cane. The WUE for this sugarcane field thus ranged from 84.81 kg cane (mmH$_2$O)$^{-1}$ in plant cane to 105.98 kg cane (mmH$_2$O)$^{-1}$ in first ratoon cane. The factor affecting difference WUE between plant cane and first ratoon cane is that the amount of rainfall was higher during plant cane period (1201.9 mm) than during first ratoon cane period (1157.8 mm), causing higher ET in plant cane crop than in ratoon crop. Due to changes of rainfall, WUE was affected directly by plant transpiration and soil evaporation [42]. Another factor is that the number of stalk was higher for ratoon cane than plant cane, causing higher dry stalk weight in ratoon cane than in plant cane [42-43].

3.7 Relationship between ET and environmental factors

Effect of environmental factors on ET was determined by Pearson correlation coefficient (r) at confidence level at 95% (Table 6) and linear regression is shown in Fig. 6. Because of variations in environment variables in different seasons, we also separated the data into two seasons; wet and dry. In this study, ET was significantly related with most of micrometeorological variables at 95% confidence level. However, ET was not significantly related with air temperature and humidity in the wet season because of small variation in air temperature and humidity during this period. Among variables, soil moisture in the dry season and net radiations in both wet and dry season strongly affect ($p<0.05$) ET variations (Fig 6). Alfieri et al. [43] also reported that soil water content is key factor to control ET because of surface resistance to water transfer. Yin et al. [44] estimated ET from Faber Fir Forest in China and studied the control environmental factors to ET. The result showed the net radiation is the most impact on ET and air temperature is secondary whereas there is no distinct correlation between soil water content and ET. During wet season, there are weaker correlation than dry season because of cloud cover, low temperature, and distribution.

Table 6. Pearson's correlation coefficient (r) between environmental variables and evapotranspiration for dry and wet seasons.

Variable	Correlation coefficient (r)	
	Dry season	Wet season
Net radiation	0.80*	0.82*
Air temperature	0.57*	0.15*
Relative humidity	0.45*	0.09
Wind speed	0.51*	0.18*
Soil water content	0.77*	0.30*

Note: *significant at 0.05 levels.

4. Conclusions

The main findings in this study can be summarized as follows;

1. Large variations over growth duration of sugarcane were found, consistent with variations of environmental factors including R_n, precipitation and soil water content, T_a, T_{soil}. The maximum ET occurred during stalk elongation stage which correlated with actual cane formation and maximum growth and amount of rainfall. On the other hand, the minimum ET was found in germination stage which led to low water availability in this period.

2. The annual ranges of ET in this sugarcane field were 685 to 800 mm in 2012 and 2013, respectively. The results indicate that the maximum ET occurred during March through May (when temperature and rainfall were relatively high at the beginning of wet season) whereas minimum ET occurred during August through December (dry season). Total ET for plant cane was 851.17 mm while first ratoon cane was 655.20 mm which consistent with precipitation change. The ET was 71% of total precipitation in plant cane and 56% in ratoon cane.

3. Water use efficiency (WUE) of plant cane is less than the ratoon cane due to higher ET in plant cane while yield in plant cane was similar for ratoon cane

4. During dry season, the main factor affecting ET was net radiation and soil moisture content, while net radiation was only key factor to control ET during wet season.

Acknowledgements

This study was supported by the Science and Technology Research Partnership for Sustainable Development, JST-JICA, Japan, and the Ministry of Education, Science, Sports and Culture, Japan, Grant-in-Aid for Scientific Research (S), 23226012, 2011, in parts by The Thailand Research Fund (RMU5080051) and the National Research University Project of Thailand's Office of the Higher Education Commission (CHE).

References

[1] Liu SM, Xu ZW, Zhu ZL, Jia ZZ, Zhu MJ, Measurements of evapotranspiration from eddy-covariance systems and large aperture scintillometers in the Hai River Basin, China, *Journal of H ,ydrology* 487 (2013) 24-38.

[2] Food and Agriculture Organization of the United States, *Introduction to evapotranspiration* (2016) Available online: http://www.fao.org/docrep/x0490e/x0490e04.htm#evapotranspirationconcepts [accessed March 23, 2016]

[3] Scott RL, Huxman TE, Cable WL, Emmerich WE, Partitioning of evapotranspiration and its relation to carbon dioxide exchange in a Chihuahuan Desert shrubland, *Hydrological Processes* 20/15 (2006) 3227-3243.

[4] Stoy PC, Katul GG, Siqueira M, Juang JY, Novick KA, Mccarthy HR, Oishi AC, Uebelher JM, Kim H, Oren RAM, Separating the effects of climate and vegetation on evapotranspiration along a successional chronosequence in

the southeastern US, *Global Change Biology* 12/11 (2006) 2115-2135.

[5] Sauer TJ, Singer JW, Prueger JH, DeSutter TM, Hatfield JL, Radiation balance and evaporation partitioning in a narrow-row soybean canopy, *Agricultural and Forest Meteorology* 145/3 (2007) 206-214.

[6] Food and Agriculture Organization of the United Nations, *Crop Water Information: Sugarcane* (2015) Available online: http://www.fao.org/nr/water/cropinfo_sugarcane.html [accessed November 2016]

[7] Office of the cane and sugar board, *Ministry of industry, Report of sugarcane plantation area in year 2012/2013* (in Thai) (2013) Available online: http://www.ocsb.go.th/upload/journal/fileupload/923-2469.pdf [accessed March 2016]

[8] Woiciechowski AL, Medeiros ABP, Rodrigues C, de Souza Vandenberghe LP, de Andrade Tanobe VO, Dall'Agnol A, Gazzoni DL, Soccol CR, Feedstocks for Biofuels, *Green Fuels Technology* (2016) 15-39, Springer International Publishing.

[9] Thompson GD, Pearson CHO, Cleasby TG, The estimation of the water requirements of sugarcane in Natal, *Proceedings of the South African Sugar Technologists Association* 37 (1963) 134-141.

[10] Omary M, Izuno FT, Evaluation of sugarcane evapotranspiration from water table data in the everglades agricultural area, *Agricultural Water Management* 27/3 (1995) 309-319.

[11] Watanabe K, Yamamoto T, Yamada T, Sakuratani T, Nawata E, Noichana C, Higuchi H, Changes in seasonal evapotranspiration, soil water content, and crop coefficients in sugarcane, cassava, and maize fields in Northeast Thailand, *Agricultural Water Management* 67/2 (2004) 133-143.

[12] Da Silva VDP, da Silva BB, Albuquerque WG, Borges CJ, de Sousa IF, Neto JD, Crop coefficient, water requirements, yield and water use efficiency of sugarcane growth in Brazil, *Agricultural Water Management* 128 (2013) 102-109.

[13] Nassif DS, Marin FR, Costa LG, Evapotranspiration and transpiration coupling to the atmosphere of sugarcane in southern Brazil: scaling up from leaf to field, *Sugar Tech* 16/3 (2014) 250-254.

[14] Australian Bureau of Meteorology, *Average Annual & Monthly Evapotranspiration* (2017) Available online: http://www.bom.gov.au/watl/eto/ [accessed January 2017].

[15] TMD-Thai Meteorological Department, *3-hourly data report* (2016) Available online: https://www.tmd.go.th/cis/main.php [accessed November 2016].

[16] Sornpoon W, *Greenhouse Gas Balance under Burned and Unburned Sugarcane Plantation in Thailand, Doctoral dissertation* (2013) Ph. D. Thesis, King Mongut's University of Technology Thonburi, Bangkok, Thailand.

[17] Tang X, Li H, Desai AR, Nagy Z, Luo J, Kolb TE, Olioso A, Xu X, Yao L, Kutsch W, Pilegaard K, Kostner B, Ammann C, How is water-use efficiency of terrestrial ecosystems distributed and changing on Earth?, *Scientific reports* 4 (2014) 7483.

[18] Johnson MJ, *Summer Evapotranspiration Rates, by Bowen-ratio and Eddy-correlation Methods, in Boulder Flat and in Maggie Creek Area, Eureka County, Nevada, 1991—91* (1995) US Geological Survey.

[19] Wolf S, Eugster W, Potvin C, Buchmann N, Strong seasonal variations in net ecosystem CO_2 exchange of a tropical pasture and afforestation in Panama, *Agricultural and Forest Meteorology* 151/8 (2011) 1139-1151.

[20] Falge E, Baldocchi D, Olson R, Anthoni P, Aubinet M, Bernhofer C, Granier A, Burba G, Ceulemans R, Clement R, Dolman H, Granierj A, Grossj P, Grünwald T, Hollinger D, Jensen N, Katul G, Keronen P, Kowalski A, Ta Laz C, Law EB, Meyers T, Moncrieff J, Moorsi E, Munger JW, Pilegaard K, Rannik U, Rebmann C, Suykerf A, Tenhunen J, Tu K, Verma S, Vesala T, Wilson K, Wofsy S, Gap filling strategies for defensible annual sums of net ecosystem exchange, *Agricultural and Forest Meteorology* 107/1 (2001) 43-69.

[21] Wiedenfeld RP, Water stress during different sugarcane growth periods on yield and response to N fertilization, *Agricultural Water Management* 43/2 (2000) 173-182.

[22] Sinclair TR, Tanner CB, Bennnet JM, *Water use efficiency in crop production* (1984).

[23] Machado LAT, Laurent H, Dessay N, Miranda I, Seasonal and diurnal variability of convection over the Amazonia: A comparison of different vegetation types and large scale forcing, *Theor. Appl. Climatol.* 78/1–3 (2004) 61-77, doi:10.1007/s00704-004-0044-9.

[24] Rodrigues TR, de Paulo SR, Novais JWZ, Curado LFA, Nogueira JS, de Oliveira RG, Lobo FA, Vourlitis GL, Temporal patterns of energy balance for a Brazilian tropical savanna under contrasting seasonal conditions, *Int. J. Atmos. Sci.* 2013 (2013) 9 pp., doi:10.1155/2013/326010.

[25] Awe GO, Reichert JM, Wendroth OO, Temporal variability and covariance structures of soil temperature in a sugarcane field under different management practices in southern Brazil, *Soil and Tillage Research* 150 (2015) 93-106.

[26] Aubinet M, Grelle A, Ibrom A, Rannik U, Moncrieff J, Foken T, Kowalski AS, Martin PH, Berbigier P, Bernhofer C, Clement R, Elbers J, Granier A, Grünwald T, Morgenstern K, Pilegaard K, Rebmann C, Snijders W, Valentini R, Vesala T, Estimates of the annual net carbon and water exchange of European forests: the EUROFLUX methodology, *Adv. Ecol. Res.* 30 (2000) 113-175.

[27] Bagayoko F, Yonkeu S, Van de Giesen NC, Energy balance closure and footprint analysis using Eddy Covariance measurements in Eastern Burkina Faso, West Africa, *Hydrology and Earth System Sciences Discussions* 3/5 (2006) 2789-2812.

[28] Twine TE, Frustas WP, Norman JM, Cook DR, Houser PR, Meyers TP, Prueger JH, Starks PJ, Wesely ML, Correcting eddy-covariance flux underestimates over grassland, *Agricultural and Forest Meteorology* 103 (2000) 279-300.

[29] Lee X, Massman W, Law B, *Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis* (2004) Atmospheric and oceanographic sciences library vol. 29 Kluwer Academic Publishers, Netherlands, p. 250.

[30] Cava D, Contini D, Donateo A, Martano P, Analysis of short-term closure of the surface energy balance above short vegetation, *Agricultural and Forest Meteorology* 148/1 (2008) 82-93.

[31] Oncley SP, Foken T, Vogt R, Kohsiek W, DeBruin HA, Bernhofer C, Christen A, van Gorsel E, Grantz D, Feigenwinter C, Lehner I, Liebethal C, Liu H, Mauder M, Pitacco A, Ribeiro L, Weidinger T, The energy balance experiment EBEX-2000. Part I: overview and energy balance, *Boundary-Layer Meteorology* 123/1 (2007) 1-28.

[32] Wilson K, Goldstein A, Falge E, Aubinet M, Baldocchi D, Berbigier P, Bernhofer C, Ceulemans R, Dolman H, Field C, Grelle A, Ibrom A, Law BE, Kowalski A, Meyers T, Moncrieff J, Monson R, Oechel W, Tenhunen J, Valentini R, Verma S, Energy balance closure at FLUXNET sites, *Agricultural and Forest Meteorology* 113/1 (2002) 223-243.

[33] Meyers TP, Hollinger SE, An assessment of storage terms in the surface energy of maize and soybean, *Agricultural and Forest Meteorology* 125 (2004) 105-115.

[34] Gentine P, Entekhabi D, Heusinkveld BG, Systematic errors in ground heat flux estimation and their correction, *Water Resources Research* 48/9 (2012) Available online: https://doi.org/10.1029/2010WR010203.

[35] Abu-Hamdeh NH, Reeder RC, Soil thermal conductivity effects of density, moisture, salt concentration, and organic matter, *Soil science society of America Journal* 64/4 (2000) 1285-1290.

[36] Huizhi L, Jianwu F, Seasonal and interannual variations of evapotranspiration and energy exchange over different land surfaces in a semiarid area of China, *Journal of Applied Meteorology and Climatology* 51/10 (2012) 1875-1888.

[37] Burry RK, Bonnett GD, Holtum JAM, Reassessing water logging: novel method to compare the germination and early growth responses of sugarcane genotypes, *Proc. Aust. Soc. Sugar Cane Technol.* (2004) (CD-ROM) 26.

[38] Inman-Bamber NG, Smith DM, Water relations in sugarcane and response to water deficits, *Field crops research* 92/2 (2005) 185-202.

[39] Chaichana N, Pakoktom T, Phattaralerphong J, Sathornkich J, Evaluation of water use of the first ratoon cane by Eddy Covariance technique, *Proceedings of the 51st Kasetsart University Annual Conference* (2013) Bangkok, Thailand, 5-7 February 2013, Kasetsart University.

[40] Acreche MM, Nitrogen-, water-and radiation-use efficiencies affected by sugarcane breeding in Argentina, *Plant Breeding* 136 2017) 174-181.

[41] Glenn EP, Scott RL, Nguyen U, Nagler PL, Wide-area ratios of evapotranspiration to precipitation in monsoon-dependent semiarid vegetation communities, *Journal of Arid Environments* 117 (2015) 84-95.

[42] Milligan SB, Gravois KA, Bischoff KP, Martin FA, Crop effects on broad-sense heritabilities and genetic variances of sugar cane yield components, *Crop Sci.* 30 (1990) 344-349.

[43] Alfieri JG, Blanken PD, Yates DN, Steffen K, Variability in the environmental factors driving evapotranspiration from a grazed rangeland during severe drought conditions, *Journal of Hydrometeorology* 8/2 (2007) 207-220.

[44] Yin Z, Ouyang H, Xu X, Zhou C, Zhang F, Shao B, Estimation of evapotranspiration from faber fir forest ecosystem in the Eastern Tibetan Plateau of China using SHAW Model, *Journal of Water Resource and Protection* 2/2 (2010) 143-153.