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Bowen ratio and evapotranspiration dynamics of oil palm

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Abstract. *Asyura MF, June T, Salmayenti R. 2023. Bowen ratio and evapotranspiration dynamics of oil palm. Intl J Trop Drylands 7: 37-45.* To optimize its biophysical processes, plant needs water and this requirement can be quantified as Evapotranspiration (ET). There are various methods for estimating ET from a vegetated surface, and Bowen ratio is one method commonly used for agricultural purposes. We use Bowen ratio method to estimate ET from oil palm (Elaeis guineensis Jacq.) plantation in PT. Perkebunan Nusantara VI, Batang Hari, Jambi Province, Indonesia for the period 2014-2015 using observed micrometeorology data and looked at the strength of micrometeorological components in influencing the daily and diurnal patterns, which include net radiation (Rnetto), heat fluxes (latent LE and sensible H), actual vapor pressure (ea), soil moisture (SM), wind speed (WS), air temperature (Ta), ground heat fluxes (G), and LE-H. We found that the daily pattern of Bowen ratio was strongly influenced by LE-H, LE, H, SM, shown by a correlation coefficient of -0.85, -0.75, 0.84, -0.58, respectively. The diurnal pattern of Bowen ratio was affected by ea with a correlation coefficient of -0.52, while daily ET was strongly influenced by Rnetto, LE-H, H, Bowen ratio with a correlation coefficient of 0.85, 0.95, -0.63, -0.75 respectively. WS, Ta, Rnetto, G, ea, RH and LE-H affected diurnal ET with a correlation coefficient of 0.72, 0.72, 0.96, 0.89, 0.51, -0.64 and 0.9, respectively. Within this period of 2014-2015 there were 7 months where rainfall was greater than ET (wet period December 2014 to April 2015, November 2015) and 5 months where rainfall was lower than ET (dry period May 2015 to October 2015). During this long dry period of 2015, caused by strong El Nino events, oil palms became vulnerable to drought.

Keywords: Latent heat fluxes, net radiation, sensible heat fluxes, temporal analysis ET, water requirement

INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) is a plant species belonging to the subfamily Cocoideae from tropical region of South America. The first industrialization of oil palm in Indonesia was when the dutch colonial in 1848 brought these plants to Kebun Raya Bogor (Benny et al. 2015). These days oil palm has a major contribution to Indonesia's GDP because the Crude Palm Oil (CPO) product from plants is used in many industries such as food, cosmetics and pharmacy (Apriyanto et al. 2020; Darkwah et al. 2020). Indonesia has an area of oil palm plantations, approximately 11,67 million hectares, with the largest parts in North Sumatra and Riau. Total oil palm production in Indonesia could reach 33,50 million tonnes annually (Sirait 2020). Solar radiation is crucial for growth and development, especially visible light with a 400-700 nm wavelength for carbon assimilation, photosynthesis, and respiration to grow and produce the best quality fruit (Suryadi et al. 2013). According to Evizal et al. (2020), oil palm is categorized into 5 ages: ages 3 to 8 are young, ages 9 to 13 are juvenile, ages 14 to 20 are mature, ages 21 to 24 are old and more than age 25 is vulnerable. Oil palm could grow in regions where sunshine duration is about 5 to 7 hours long, which suits most tropical regions like Indonesia (Putra et al. 2017).

Abundant solar radiation throughout the year in tropical regions due to earth's relative position to the sun makes Indonesia have 2 seasons: the rainy and dry seasons, with 2 transition seasons in between. This complex and dynamic phenomenon also makes Indonesia had 3 main rainfall patterns which are monsoonal, equatorial and lokal pattern (Molle and Larasati 2020). Rainfall pattern significantly impacts growth and palm oil development because it is sensitive to water stress, especially in dry season, and requires tremendous water resources for optimum growth (Wagino et al. 2018). One of the natural factors that makes water loss in a plant is the evapotranspiration process. Evapotranspiration is a combined process between plants transpiration and surface evaporation. The evaporation process is caused by surrounding micrometeorological conditions such as air temperature, wind speed, humidity, solar radiation, actual vapor pressure and sunshine duration. Evapotranspiration is crucial for water resources management in order to make more effective and sustainable agricultural practices (Singh et al. 2018). Estimating the evapotranspiration rate could be done with various methods such as aerodynamics, Penman-Monteith, and Bowen ratio (June et al. 2018), but this research focuses on the energy balance method using Bowen ratio calculation. Bowen ratio, by definition, is between sensible and latent heat flux.

According to Xuanlan et al. (2021), research shows that the Bowen ratio value is influenced by a complex interaction between micrometeorological variables, vegetation and soil characteristics but the dominant factors are air temperature, humidity and albedo. Bowen ratio calculation needs micrometeorological data such as air temperature, net radiation, ground heat flux, and psychrometric constant, with two minimum elevations to quantify energy transfer vertically. Bowen ratios have different values for various land cover, and according to Kuang et al. (2015), urban populated, dense areas had a bigger value of Bowen ratio compared to a rural area with a high concentration of vegetation cover. Bowen ratio and evapotranspiration on various land cover need to be reviewed for temporal analysis if there's an influence of seasonal and daily cycles. These two variables could be varied within the same land cover in a certain period.

MATERIALS AND METHODS

Study area

This research is conducted on site of PT. Perkebunan Nusantara VI in Batang Hari District, Jambi Province, Indonesia. Geographically PTPN VI is located at 01° 41' 35'' S and 103° 23' 29'' E. There are five land cover types, but study site is mostly covered with tropical rainforest and plantations shown by green color. A black rectangle box marks PTPN VI in Figure 1.

Jambi Province is a central production of good quality oil palm because the location is agglomerated for the specialization of oil palm commodities due to soil characteristics that suit growth and development (Wahyudi 2022). Batang Hari District is 11,59% of the total area in Jambi Province where this district continues to develop oil palm plantation areas, indirectly caused by local farmers and the private sector because this commodity is economically profitable compared to others. Farmers and the private sector also realized that oil palm relatively has fewer pests thus, the operational cost is low and profit could be maximum (Anggreany et al. 2013).

PTPN VI has a 2025 Ha area of oil palm plantation mostly covered by ultisol soil where nutrient content is low but could hold a high water concentration, thus it suits for oil palm characteristics (Adriadi et al. 2012). The optimal vegetation density for oil palm in PTPN VI is 120 plants per hectare and each tree is approximately 9 meters apart. If oil palm is too dense, the sunlight cannot reach individual trees optimally and tree will also compete for other resources and make businesses less profitable. Compared to the rainforest, where trees compete each other, the density of oil palm is lower thus Bowen ratio value is usually higher (Kuang et al. 2015). Two patterns influence rainfall in Jambi Province: on the eastern side is dominated by monsoonal while the western side is dominated by equatorial (Pradiko et al. 2016). PTPN VI is located in Batang Hari District, which are the eastern side of Jambi Province, thus monsoonal pattern has dominated this region.

Procedures

Calculate actual vapor pressure and gradient of actual vapor pressure

Micrometeorological data from PT. Perkebunan Nusantara VI, Batang Hari, Jambi is observed by climate tower at six different heights: 22m, 16.3m, 12.3m, 8.1m, 2.3m and 0.9m. Data used to calculate actual vapor pressure and the gradient of actual pressure (Upreti and Ojha 2018; Walls et al. 2020):

$$ea = 0.6108 \left\{exp\left(\frac{17.27\,Tzi}{Tzi + 237.3}\right)\right\} * Rh/100$$

$$\frac{\partial ea}{\partial z} \approx \frac{0.6108 \left\{\exp\left(\frac{17.27\,T1}{T1 + 237.3}\right) * Rh1 - \exp\left(\frac{17.27\,T2}{T2 + 237.3}\right) * Rh2\right\}}{z1 - z2}$$

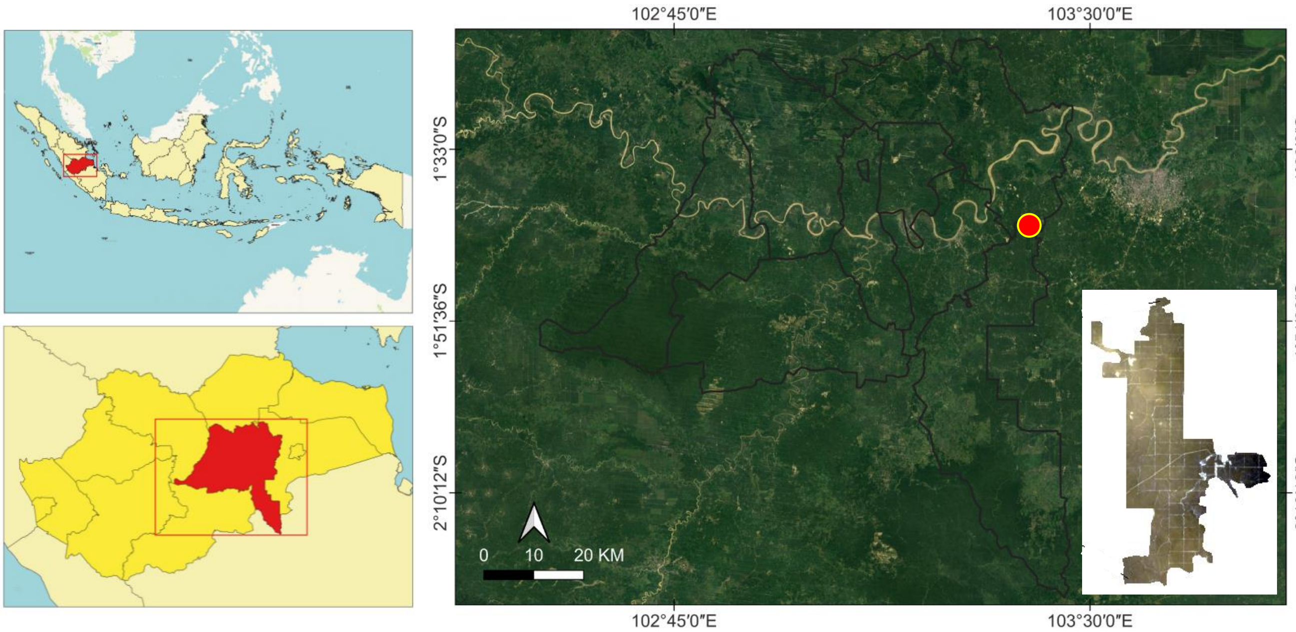

Figure 1. Location of PT. Perkebunan Nusantara VI, Batang Hari District, Province of Jambi, Indonesia

Calculate gradient of air temperature

Calculation of air temperature gradient could be done directly from observational micrometeorological data (Schilperoort et al. 2018):

$$\frac{\partial T}{\partial z} \approx \frac{T1 - T2}{z1 - z2}$$

Calculate latent heat vaporization (λ) and psychrometric constant (γ)

Latent heat of vaporization and psychrometric constant also could be done directly from observational data, using equations (4) and (5) (Allen et al. 1998):

$$\lambda = 2.501 - (2.361 \; x \; 10^{-3})Tmean$$

$$\gamma = \frac{Cp \; P}{\varepsilon \; \lambda} = 0.665 \; X \; 10^{-3} \; P$$

Calculate Bowen ratio

Bowen ratio (β) value is calculated after we obtained psychromentric constant (γ), gradient of air temperature and gradient of actual vapor pressure.

$$\beta = \frac{H}{LE} = \gamma \left(\frac{\partial T / \partial z}{\partial ea / \partial z} \right) = \gamma \left(\frac{\partial T}{\partial ea}\right)$$

Calculate latent heat flux (LE) and sensible heat flux (H)

$$LE = \frac{Rn - G}{1 + \beta}$$

$$H = \frac{Rn - G}{1 + (\frac{1}{\beta})}$$

Calculate Evapotranspiration (ET)

Evapotranspiration calculation could be done after we obtained latent heat flux (LE) divided by air densities times psychrometric constant.

$$ET = \frac{LE}{\rho \lambda}$$

Calculate micrometeorological correlation coefficient

In order to see the relationships between evapotranspiration, Bowen ratio to other micrometeorological variables, we used Pearson's correlation equation (Bruce et al. 2020).

$$r = \frac{\sum_{i=1}^{n}(xi - x)(yi - y)}{\sqrt{\sum_{i=1}^{n}(xi - x)^2} - \sqrt{\sum_{i=1}^{n}(yi - y)^2}}$$

Data analysis

The tools used in this research are Microsoft Excel for data calculation process and Python 3.9 using Jupyter Notebook IDE (Integrated Development Environment) for data visualization and exploratory data analysis. The materials used in this research are micrometeorological data measured at the climate tower in PTPN VI, Batang Hari, Jambi, from December 2014 to November 2015. We split the data based on 4 season, which is wet season (DJF), transition season I (MAM), dry season (JJA), and transition season II (SON).

RESULTS AND DISCUSSION

Daily micrometeorological correlation matrix

Figure 2 shows the matrix correlation between micrometeorological variables daily from December 2014 until November 2015 in PTPN VI, Batang Hari District. This research focuses on Bowen ratio (β) and evapotranspiration (ET), the last two lines in Figure 1. Micrometeorological components consist of rainfall (CH), air pressure (P), wind speed (Ws), relative humidity (Rh), air temperature (Ta), soil temperature (Tsoil), soil moisture (SM), net radiation (Rnetto), ground heat flux (G), actual vapor pressure (ea), sensible heat flux (H), latent heat flux (LE), LE-H, Bowen ratio (β) and evapotranspiration (ET). These data were obtained from measurements in study site using various instruments such as sap flow sensors, soil chamber, and automatic weather stations every thirty minutes. Pearson's correlation coefficient estimates each relationship between variables.

Figure 2 shows the correlation matrix of micrometeorological variables daily, where the yellow color represents the highest possible value of 1. As the color starts to get darker, the correlation value becomes smaller. The axis of x and y both represent the micrometeorological variables, where the main diagonal in yellow shows a perfect correlation because it's the same variable. Rnetto strongly influenced ET and LE-H by positive correlation coefficients of 0.85 and 0.95, while H and β influenced ET negatively, shown by a correlation coefficient of -0.63 and -0.75, respectively. LE has a perfect relationship with ET, shown by one correlation coefficient, this is caused by LE divided by water density (ρ) and latent heat vaporization (λ) that has a constant value. β is strongly influenced by H shown by the positive correlation coefficient, which is 0.84, while SM, LE-H and ET have a negative influence on β shown by a correlation coefficient of -0.58, -0.85, and -0.75, respectively. A high positive correlation between β and H shows that biophysically if the Rnetto is allocated more to H, it will decrease ET processes since H is used for heating up surrounding air temperature, while LE biophysically used by the ecosystem to transform water that is available into vapor, that is why LE – H had strong positive correlation coefficient with ET. The correlation coefficient also shows that net radiation is allocated more to LE rather than H, this indicates that in PTPN VI, the energy available is prioritized to transform water into vapor rather than heating up surface air temperature, thus water availability in the region is sufficient.

Scatterplot of evapotranspiration and Bowen ratio

Figure 3 shows a scatterplot between evapotranspiration (ET) and Bowen ratio (β) from December 2014 to November 2015 at PTPN VI, Batang Hari, Jambi. The correlation coefficient between these two variables based on Figure 1 is -0.75, where green dots represent the wet season (December, January, February), orange dots represent transition season I (March, April, May), purple dots represent dry season (June, July, August) and pink dots represent transition season II (September, October, November).

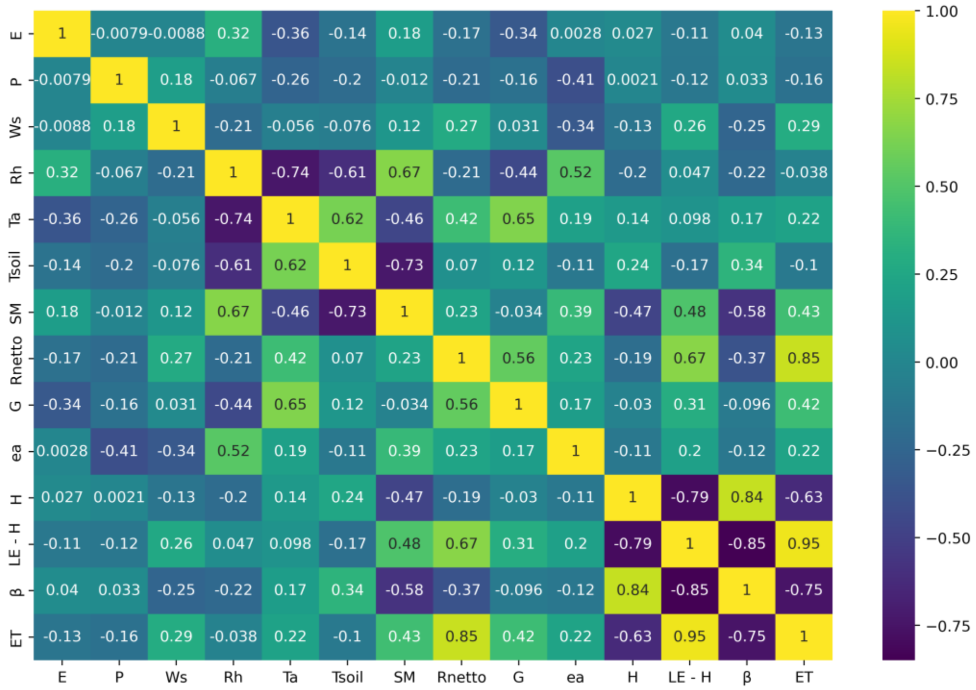

Figure 2. Daily micrometeorological variables correlation matrix in PTPN VI, Batang Hari, Jambi Province, Indonesia for December 2014 – November 2015 period

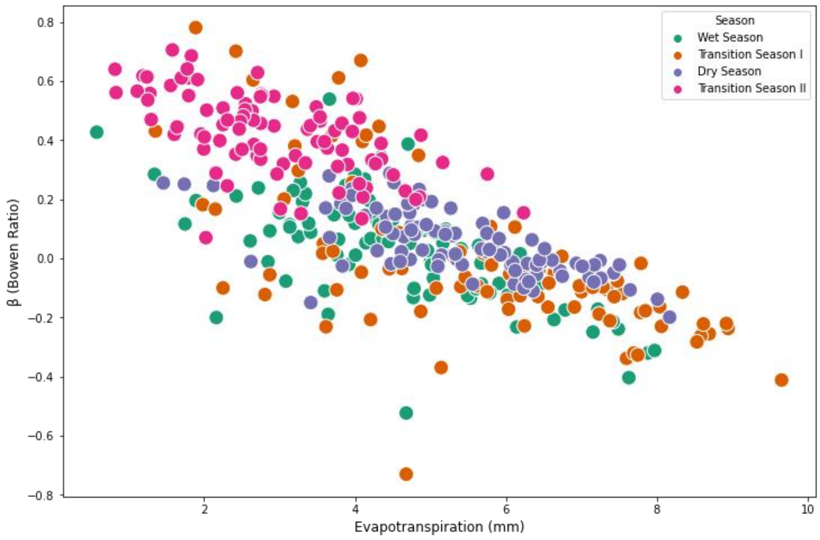

Figure 3. Scatterplot of daily evapotranspiration and Bowen ratio in PTPN VI, Batang Hari, Jambi Province, Indonesia for December 2014 – November 2015 period

The x-axis of Figure 3 represents the evapotranspiration (ET) value in millimeters, while the y-axis represents Bowen ratio value (β) and the dots represent those two variables values on daily scale. The colors represent different season, the green one represents wet season (December, January, February), the orange one represents transition season I (March, April, May) which is between wet and dry season, the purple one represent dry season (June, July, August) and the pink one represent transition season II (September, October, November) which is between dry and wet season. ET value at the lowest with average 2.95 mm showed by transition season II and the β value is relatively bigger than others. Transition season II indicates that the amount of net radiation received in PTPN VI is mostly allocated to sensible heat flux (H) compared to another season, thus ET is low due to latent heat flux (LE) deficiency. Dry season showed β value mostly within the range of -0.2 to 0.2 with an average ET of 5.33 mm. Wet season and transition season I had relatively wider ranges of ET and β values compared to dry season and transition season II, which had more clusters and narrower interval values. Wet season and transition season I have an average ET 4.56 mm and 5.63 mm, respectively.

A negative value of β indicates that LE and H move in an opposite direction vertically, this usually happens during the night when atmospheric condition is stable, thus H moving towards surface while ET process still happens. A negative value of β also could happen in midday caused by vertical advection due to stable atmospheric conditions (Neog et al. 2005). LE and H are crucial components for local hydrological cycles that could estimate vapor transfer from surface into the atmosphere (June et al. 2018).

A higher β value indicates that more net radiation energy is allocated to H where this component is used by ecosystem to heat up surrounding surface air temperature, thus the higher β, the higher air temperature, which can lead to drought stress (Göckede et al. 2017). Transition season II is transition from dry to wet season, but in 2015 there was an enormous wildfire triggered by a strong El Nino event where the amount of hotspots increased from 1,152 in 2014 to 1,654 in 2015 mostly from July to October (Saharjo and Velicia 2018). The phenomenon of this wildfire causes longer drought, thus obstructing natural precipitation and hydrological cycle and affecting plant's water availability.

Diurnal micrometeorological variables correlation matrix

Figure 4 shows diurnal Pearson's correlation value between micrometeorological variables for 24 hours cycle from December 2014 to November 2015 at PT. Perkebunan Nusantara VI, Batang Hari, Jambi. This research focuses on evapotranspiration (ET) and Bowen ratio (β) correlation with other diurnal micrometeorological variables shown by the last two lines in Figure 4.

Figure 4 shows the correlation matrix of micrometeorological variables on a diurnal basis, where the dark green color represents the highest possible value of 1. As the color gets brighter, the correlation value becomes smaller and eventually becomes negative as the color turns red. The axis of x and y both represent the micrometeorological variables, where the main diagonal in dark green shows a perfect correlation because it's the same variable. WS, Ta, Rnetto, G, and LE-H have a strong positive influence on ET diurnal pattern shown by correlation coefficients 0.72, 0.72, 0.96, 0.89 and 0.9, while RH and ea have a moderate negative influence, with correlation coefficients -0.64 and -0.51. Variables like CH, P, Tsoil, sm, H and β have a minor influence on ET. Micrometeorological variables like CH, P, WS, RH, Ta, Tsoil, Rnetto, G, and LE also have a minor influence on diurnal pattern of β shown by a correlation coefficient less than 0.4. Variables like sm, ea and LE-H have a moderate negative correlation coefficient of -0.4, -0.52, and -0.43, while H has a moderate positive correlation coefficient of 0.44 with β. Evapotranspiration processes are generally limited by four factors: energy availability that mostly comes from incoming solar radiation, water availability, plant physiology and surface vapor lifting. It is crucial to understand that these four limiting factors interact with each other formed by surface-atmospheric heat and water exchange.

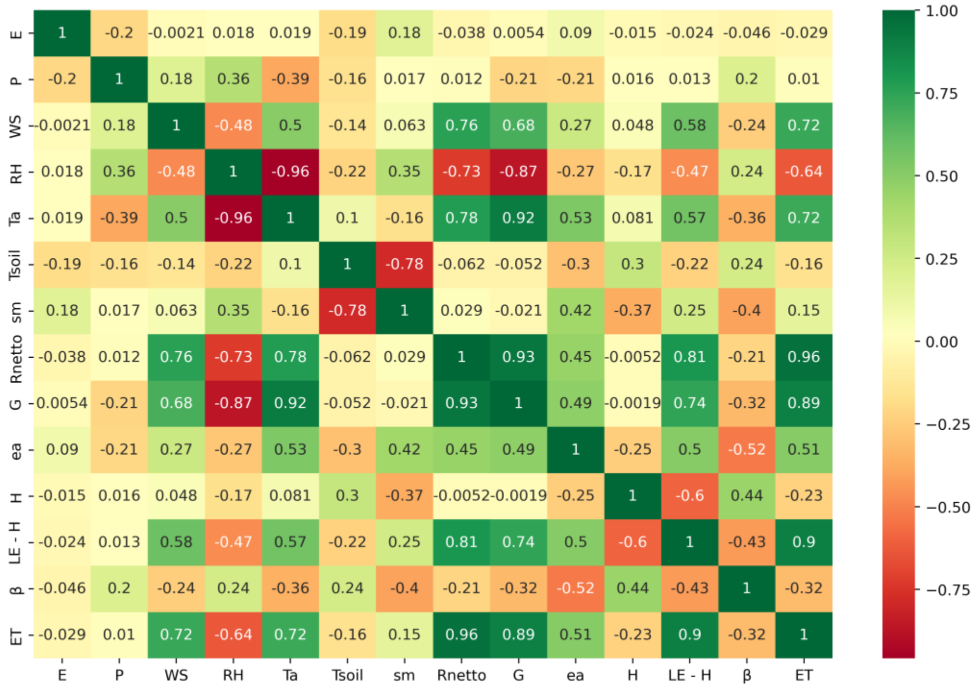

Figure 4. Diurnal micrometeorological variables correlation matrix in PTPN VI, Batang Hari, Jambi Province, Indonesia for December 2014 – November 2015 period

Diurnal Rnetto directly influenced ET, shown by a strong correlation of 0.96. variation of diurnal Rnetto pattern causing an imbalance in surface energy budget and heat exchange between day and night (Kleidon and Renner 2017). Heat exchange between surface and lower atmosphere affects surface air temperature, vapor pressure, and wind speed, which are driving factors of diurnal ET process (Van Heerwaarden et al. 2010), which is why these variables strongly correlate with ET. Rnetto is a dominant factor of LE and H partition, which is influenced by factors like vapor pressure deficit, air temperature, actual vapor pressure and soil moisture that affect vapor transport from terrestrial ecosystem into the atmosphere (Chen et al. 2020). LE allocation has a major role in the amount of carbon plants absorb. The optimal ET process will lead to good regulation between CO_2 and H_2O through plant's stomata (June 2002).

Diurnal evapotranspiration pattern

Figure 5 shows a diurnal pattern of ET in each season from December 2014 until November 2015. Dynamics of diurnal ET are relatively stable throughout the season at night until dawn before sunrise. The maximum ET for all seasons mostly occurred midday, around 12 o'clock.

The diurnal ET pattern differs for each season, especially during midday. ET in wet season starts to vary around 10 o'clock and has a different maximum ET at its peak. December, January and February have maximum ET of 18 mm, 20 mm and 16 mm, respectively, with an average ET of 5.08 mm in wet season. Transition season I relatively have a higher maximum ET than other seasons, especially in April, where ET could reach 30 mm while March and May are 25 mm and 22 mm, respectively. Diurnal average of ET in transition season I is 6.55 mm. Dry season especially June, has a bigger maximum ET of 25 mm, while July and August had 17 mm and 14 mm, respectively. The diurnal average of ET in dry season is 4.84 mm.

Transition season II relatively had a low maximum ET compared to other seasons, with an average 3 mm. November had a maximum ET of around 17 mm, while September and October had a maximum ET of 10 mm and 8 mm, respectively. ET at night until dawn shows a negative value for all seasons, indicating the reversed process of ET, condensation. The condensation process occurs when plants capture moisture and vapor in atmosphere and turn it into liquid water. Low ET on transition season II caused by a strong El Nino event in 2015 led to increasing hotspots. Figure 3 implicitly explains the low value of daily ET in transition season II, caused by El Nino events.

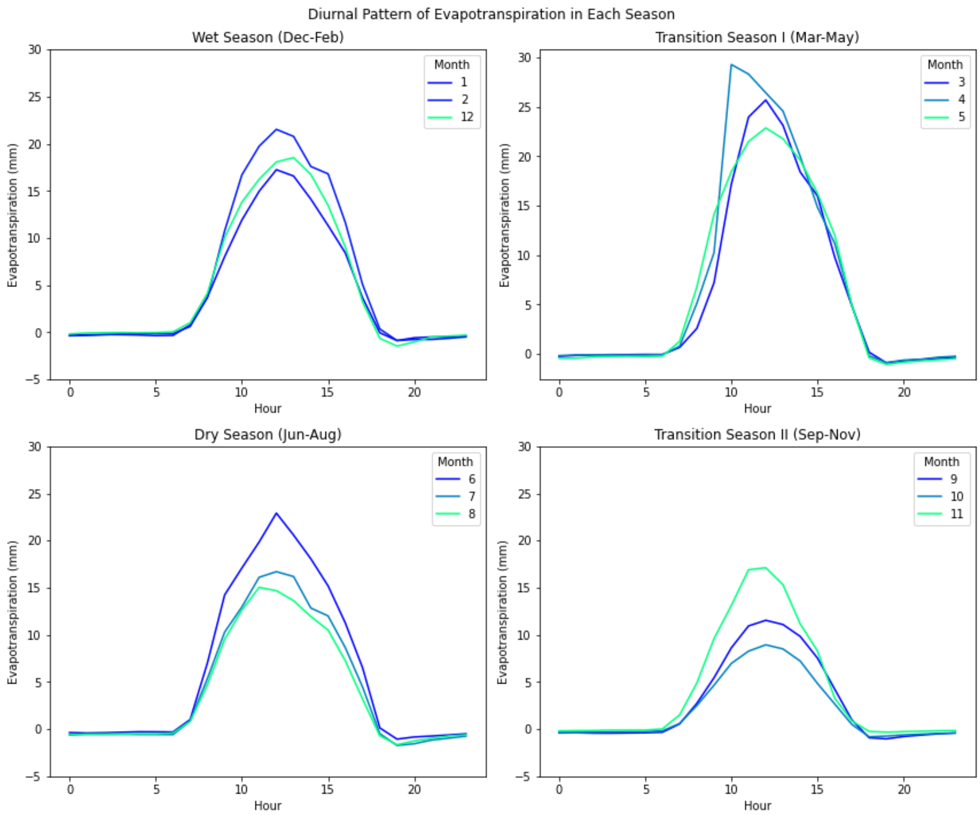

Figure 5. Diurnal evapotranspiration (ET) pattern for each season in PTPN VI, Batang Hari, Jambi Province, Indonesia for December 2014 – November 2015 period

Diurnal Bowen ratio pattern

Figure 6 shows a diurnal pattern of β in each season from December 2014 until November 2015. Dynamics of diurnal Bowen ratio is high throughout the season in 24 hours cycle. A positive β value shows the movement of LE and H within the same direction, while a negative β value indicates that LE and H are moving in opposite directions vertically. The diurnal β value in wet season has a similar pattern for December and February, while January has a relatively stable pattern. There is a gradual increase of β value from midnight until 06.00 and a decrease after sunrise until 10:00. After 10:00, the β value is relatively stable for December and February. The maximum and minimum values of β in wet season are 0.83 and -0.47. During transition season, I have a uniform pattern each month. Still, more fluctuation compared to other seasons where from midnight to morning around 07:00, β gradually increases. There is a sudden decrease until 09:00. The sudden decline indicates that within this time interval, atmospheric condition is stable thus, the H is moving towards surface while LE is still moving upward. β value remains stable until 20:00, and the Bowen ratio gradually increases until midnight. The maximum and minimum values of β in transition season I are 0.91 and -0.7.

Dry season also had a uniform diurnal pattern of β for each month but not fluctuating as much as transition season I. There are 2 peaks and 2 valleys, where β value increases at midnight until 06:00, then decreases until 10:00. Then, β value increases again after 10:00 until 15:00 and gradually decreases until 20:00. Maximum and minimum values of β in dry season are 0.44 and -0.41. Transition season II had a relatively higher value of β with a uniform pattern for September and October, while November's pattern is slightly different. The sudden decline of β value happened at 07:00. The Bowen ratio pattern for September and October is relatively stable with gradual changes. The maximum and minimum values of β in transition season II are 0.74 and 0.05. Gradual decline in β value mostly during sunrise throughout the season, which indicates that net radiation allocated more to LE to transform water into vapor in PTPN VI while on night until dawn β value is relatively high in most of the season where this indicates that the leftover of net radiation is used to heating up surface air temperature.

Monthly rainfall and evapotranspiration

Figure 7 shows a histogram between monthly observational rainfall (blue bar) and estimated evapotranspiration (orange bar) using the Bowen ratio calculation method from December 2014 to November 2015 at PT. Perkebunan Nusantara VI, Batang Hari, Jambi. Table 1 show statistic between rainfall and estimated evapotranspiration using the Bowen ratio method.

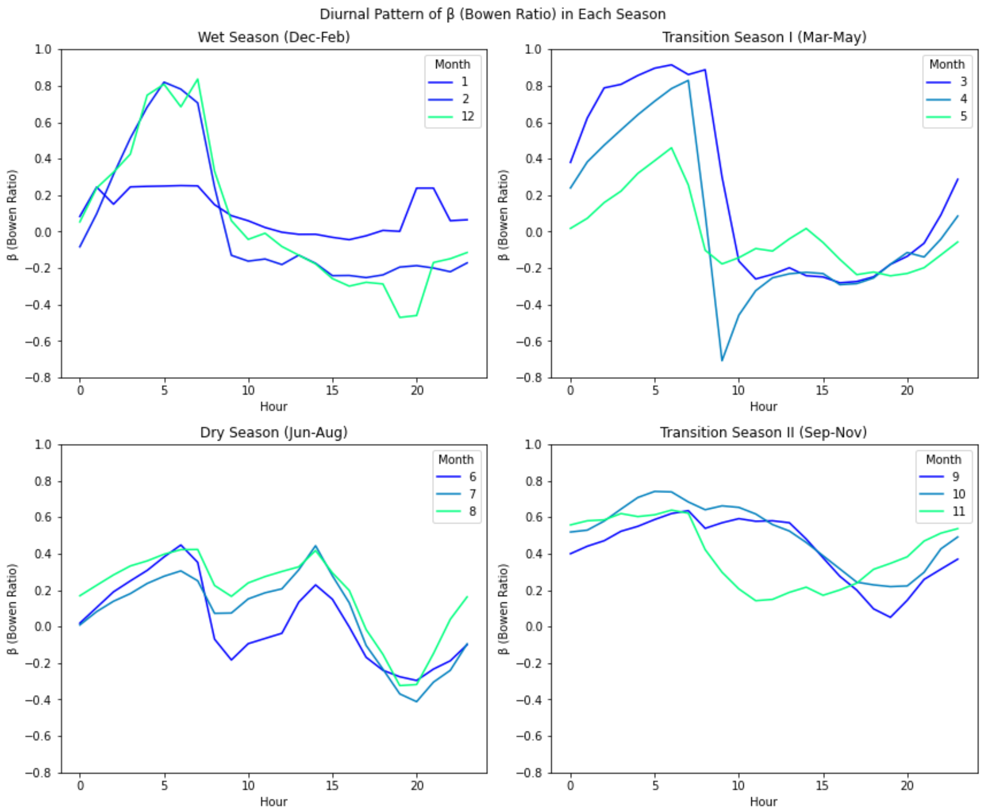

Figure 6. Diurnal Bowen ratio (β) pattern for each season in PTPN VI, Batang Hari, Jambi Province, Indonesia for December 2014 – November 2015 period

Table 1. Statistic between rainfall and evapotranspiration in PTPN VI, Batang Hari District, Province of Jambi, Indonesia

	Mean	Std	Min	25%	50%	75%	Max	Total
Rainfall	161.05	115.73	23.95	61.51	145.63	260.73	352.1	1932.6
Evapotranspiration	140.68	37.69	68.81	123.6	145.33	164.06	197.02	1688.17

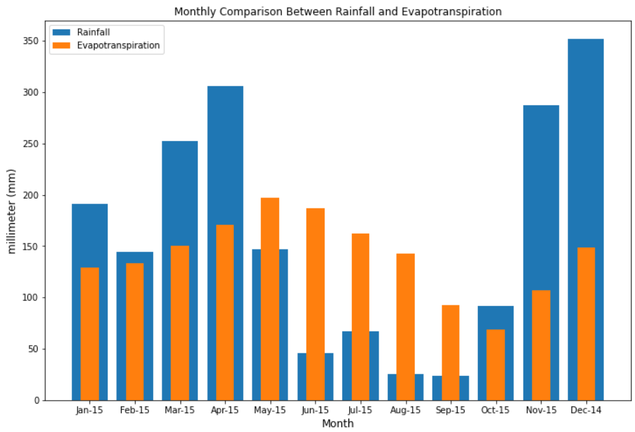

Figure 7. Histogram of monthly rainfall and evapotranspiration in PTPN VI, Batang Hari, Jambi Province, Indonesia for December 2014 – November 2015 period

Monthly ET in the wet season has a lower value than rainfall, whereas, in December, January, and February, it has a surplus of rainfall of 203 mm, 62 mm and 11 mm, respectively. Monthly rainfall in transition season I show a surplus of 101 mm and 135 mm in March and April, while in May, there is a deficiency of 49 mm rainfall shown by higher ET due to the El Nino phenomenon that started to occur. On the other hand, dry season shows low monthly rainfall compared to ET; in June, July, and August, the water supply deficiency is 141 mm, 94 mm, and 116 mm, respectively. Transition season II also has a deficit of 68 mm of rainfall in September, while in October and November, the rainfall exceeds ET by 22 mm and 179 mm, respectively. The monsoonal rainfall pattern is due to Intertropical Convergence Zone (ITCZ) caused by earth's relative position to the sun, thus the amount of radiation received varies at higher altitudes compared to lower ones (Ilfan and Arwin 2019). High variation of radiation received caused high gradient of air pressure between northern and southern hemispheres, causing air mass moving from high pressure to low pressure. Two air masses with different characteristics then converge in the equator in December, January, and February causing a wet season in Indonesia.

Strong El Nino events in 2015 obstructed Indonesia's natural monsoonal rainfall patterns, causing longer drought and significantly reducing monthly rainfall known by declining SOI index (Pradiko et al. 2016). A long drought, water supply deficiency, and dry spells of more than 20 days in terms of oil palm could cause the malformation of fruits, obstruct CO2 assimilation processes and interfere with nutrient absorption, could decrease productivity significantly on economic scale (Syarovy et al. 2015). The average value of rainfall in Figure 6 is 161,1 mm, while for ET is 140,7 mm which indicates water surplus on an annual scale but distributed unequally per month where this phenomenon precisely could make oil palm and topsoil more vulnerable due to extreme rainfall conditions from the dry period to wet period transition.

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