

# The influence of surface roughness and turbulence on heat fluxes from an oil palm plantation in Jambi, Indonesia

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**Abstract.** Oil palm plantations are expanding vastly in Jambi, resulted in altered surface roughness and turbulence characteristics, which may influence exchange of heat and mass. Micrometeorological measurements above oil palm canopy were conducted for the period 2013–2015. The oil palms were 12.5 years old, canopy height 13 meters and 1.5 years old canopy height 2.5 m. We analyzed the influence of surface roughness and turbulence strength on heat (sensible and latent) fluxes by investigating the profiles and gradient of wind speed, and temperature, surface roughness (roughness length,  $z_0$ , and zero plane displacement,  $d$ ), and friction velocity  $u^*$ . Fluxes of heat were calculated using profile similarity methods taking into account atmospheric stability calculated using Richardson number  $Ri$  and the generalized stability factor  $\zeta$ . We found that roughness parameters ( $z_0$ ,  $d$ , and  $u^*$ ) directly affect turbulence in oil palm canopy and hence heat fluxes; they are affected by canopy height, wind speed and atmospheric stability. There is a negative trend of  $d$  towards air temperature above the oil palm canopy, indicating the effect of plant volume and height in lowering air temperature. We propose studying the relation between zero plane displacement  $d$  with a remote sensing vegetation index for scaling up this point based analysis.

## 1. Introduction

Current land transformation in Jambi resulted in a rapid expansion of oil palm plantations. Oil palm (*Elaeis guineensis*) is one of the crops which has high economic value as global market demands for its products are very high. Currently, along with Malaysia, Indonesia produces more than 80% of palm oil to meet global market demands [1,2]. With increasing global need and price, the demand for oil palm is projected to increase sharply, leading to further land use changes towards oil palm plantations.

Transformation from forest to oil palm plantation will result in changing surface biophysical parameters. Biophysical surface characteristics determine microclimate variability which influences many ecological processes at the land surface as well as results in feedback to the atmosphere [3]. In other words, there is an interrelationship between atmosphere and the vegetation covering the ground surface [4]. Interest in



understanding this vegetation-atmosphere feedbacks increases continuously, however, direct measurements of micrometeorological parameters in oil palm plantations are still scarce.

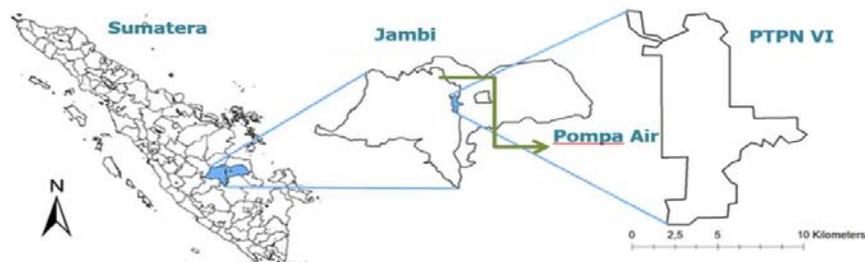
Biophysical parameters of the land surface include surface roughness (roughness length,  $z_0$ , zero plane displacement,  $d$ ), friction velocity  $u^*$  (indicating strength of turbulence), sensible and latent heat (water) fluxes and  $\text{CO}_2$  fluxes. By analysing wind speed profiles together with air temperature above the related surface, we can obtain the three parameters  $z_0$ ,  $d$ , and  $u^*$  [5-7]. These roughness parameters are useful for describing surface-atmosphere exchange of heat, water vapor, and greenhouse gases such as  $\text{CO}_2$ . The sink strength of the land surface for momentum [8] determines the dynamics of the boundary layer, especially for characterizing the surface boundary layer. Surface roughness determines the vertical wind speed and air temperature profile, mesoscale and global momentum exchange [9], land-atmosphere energy exchange [10], and turbulent air mixing beneath, within, and above its roughness elements.

In this paper we focus on the relationship of surface roughness with air temperature and sensible heat flux. Our objectives are (a) to estimate key surface biophysical parameters such as surface roughness (roughness length,  $z_0$ , zero plane displacement,  $d$ ), friction velocity  $u^*$  (indicating strength of turbulence), (b) to calculate sensible and latent heat fluxes, and (c) to investigate their interactions.

## 2. Material and method

### 2.1. Research Sites

The research sites are a young oil palm plantation at Pompa Air Village and a mature oil palm plantation at PTPN VI Jambi, Indonesia (Figure 1), where micrometeorological towers were installed. The age of the oil palms plantations were 1 and 12 years, with canopy height of 2.5 m and 13 m respectively. The tower in Pompa Air is located at S 01°50' 7.6", E 103°17' 44.2" altitude 75 m a.s.l (-1.83545 °S, 103.29562 °E) and the tower in PTPN VI is located at S01°41'35.052", E 103°23'29.040", altitude 76 m a.s.l. (-1.69307 °S 103.3914 °E) (Figure 2 and 3). Soil types around both towers are mineral. The plantation at PTPN VI has an area of 2025 ha.



**Figure 1.** Research sites, Pompa Air Village and PTPN VI oil palm plantation, Jambi.



**Figure 2.** Research site in Pompa Air Village with micrometeorology tower installed on a 2.5 years old oil palm. **Figure 3.** Research in PTPN VI with micrometeorology tower installed within 13 years old oil palm.

## 2.2. Instrumentation and Data Analysis

Micrometeorological instruments were installed on a tower at several heights which include air temperature sensors above canopies; atmospheric pressure sensors, humidity sensors, wind direction and wind speed sensors. Above the 1 years-aged plantation, four cup anemometers were installed at 2.4 m, 3.15 m, 4.14 m, and 5.08 m above the ground, whereas in the mature 12 years old plantation, cup anemometers were installed at 13, 15.4 and 18.5 m above the ground. The sensors for temperature and relative humidity were installed at the same height as the anemometers. Data analysis were conducted for the period 2013-2015. The data were recorded every 10 minutes. The meteorological tower is part of the CRC 990 EForTS project, a collaboration between the University of Göttingen, Bogor Agricultural University, University of Jambi and the University of Tadulako. Details on the tower instrumentation are found in [11].

### 2.2.1 Roughness characteristics

Three roughness parameters *i.e.* zero-plane displacement ( $d$ ), friction velocity ( $u^*$ ), and roughness length ( $z_0$ ) were derived from the logarithmic wind profile equation under neutral conditions [12,13]:

$$n(z - d) = \frac{k}{u^*} u(z) + \ln z_0 \quad (1)$$

where  $k$  is von Karman's constant (0.40) and  $z$  denotes measurement height (m). Zero-plane displacement were estimated based on [14].

### 2.2.2 Sensible and latent heat flux

Under neutral condition, sensible heat flux  $Q_H$  ( $W\ m^{-2}$ ) was approximated by equation:

$$Q_H = \rho c_p K_H \frac{dT}{dz} \quad (2)$$

where  $c_p$  is specific heat at constant pressure ( $1004.2\ J\ kg^{-1}\ K^{-1}$ ),  $K_H$  is eddy diffusivity of heat, and  $dT/dz$  is vertical gradient of air temperature. The equation of  $Q_H$  under non-neutral condition was corrected as followed:

$$Q_H = \rho c_p k^2 \frac{(u_2 - u_1)(\theta_2 - \theta_1)}{\left[\ln\left(\frac{z_2 - d}{z_1 - d}\right)\right]^2 \varphi_m \varphi_s} \quad (3)$$

where  $\varphi_s$  (the dimensionless gradient of  $\theta$ ) and  $\varphi_m$  (the dimensionless wind shear) were calculated using the following equations:

$$\varphi_s = (1 - 15 \zeta)^{-1/2}, \text{ and } \varphi_m = (1 - 15 \zeta)^{-1/4} \quad \text{if } \zeta < 0 \quad (4)$$

$$\varphi_s = 1 + 5 \zeta, \text{ and } \varphi_m = 1 + 5 \zeta \quad \text{if } \zeta \geq 0 \quad (5)$$

$\zeta$  denoting Monin-Obukhov stability parameter, and is related to Richardson Number, Ri [15,7]:

$$\zeta = Ri \quad \text{if } Ri < 0 \quad (5)$$

$$\zeta = Ri / (1 - 5 Ri) \quad \text{if } 0 \leq Ri \leq 0.1 \quad (6)$$

$$\zeta = 0.2 \quad \text{if } Ri > 0.1 \quad (7)$$

$$Ri = \frac{g \left(\frac{\partial \theta}{\partial z}\right)}{\theta_a \left(\frac{\partial u}{\partial z}\right)^2} \quad (8)$$

$Ri < -0.01$  refers to unstable condition,  $-0.01 < Ri < 0.01$  neutral condition, and  $Ri > 0.01$  stable condition. Equation (8) shows that Ri is classified based on the ratio of gradient of potential air temperature ( $\theta$ ) and gradient of horizontal wind velocity,  $g$  is acceleration due to gravity, and  $\theta_a$  denotes average potential air temperature (K).

### 2.2.3 Turbulence and Turbulent Kinetic Energy (TKE)

TKE were calculated for conditions of unstable atmospheric stratification during day-time as TKE production is less important during night-time conditions due to predominantly stable atmospheric stratification [16,7] as followed:

$$TKE = 0.5[\sigma_u^2 + \sigma_v^2 + \sigma_w^2] \quad (9)$$

where  $\sigma_u^2$ ,  $\sigma_v^2$ , and  $\sigma_w^2$  are the variances of the longitudinal, lateral, and vertical wind velocity components. These three variances are defined as the square of standard deviations of wind velocities given by equations 10,11 and 12 [16]:

$$\sigma_u = 0.11 w_B (z/z_i)^{1/3} [1 - 0.7(z/z_i)] \quad (10)$$

$$\sigma_v = 0.08 w_B [0.5 + 0.4(1 - z/z_i)^2] \quad (11)$$

$$\sigma_w = 0.11 w_B (z/z_i)^{1/3} [1 - 0.8(z/z_i)] \quad (12)$$

Those equations are functions of buoyancy velocity scale ( $w_B$ ) and mixing layer depth ( $z_i$ ).  $w_B$  can be determined by using equation 13 and 14:

$$w_B = \left(\frac{1}{0.08}\right) w^* \quad (13)$$

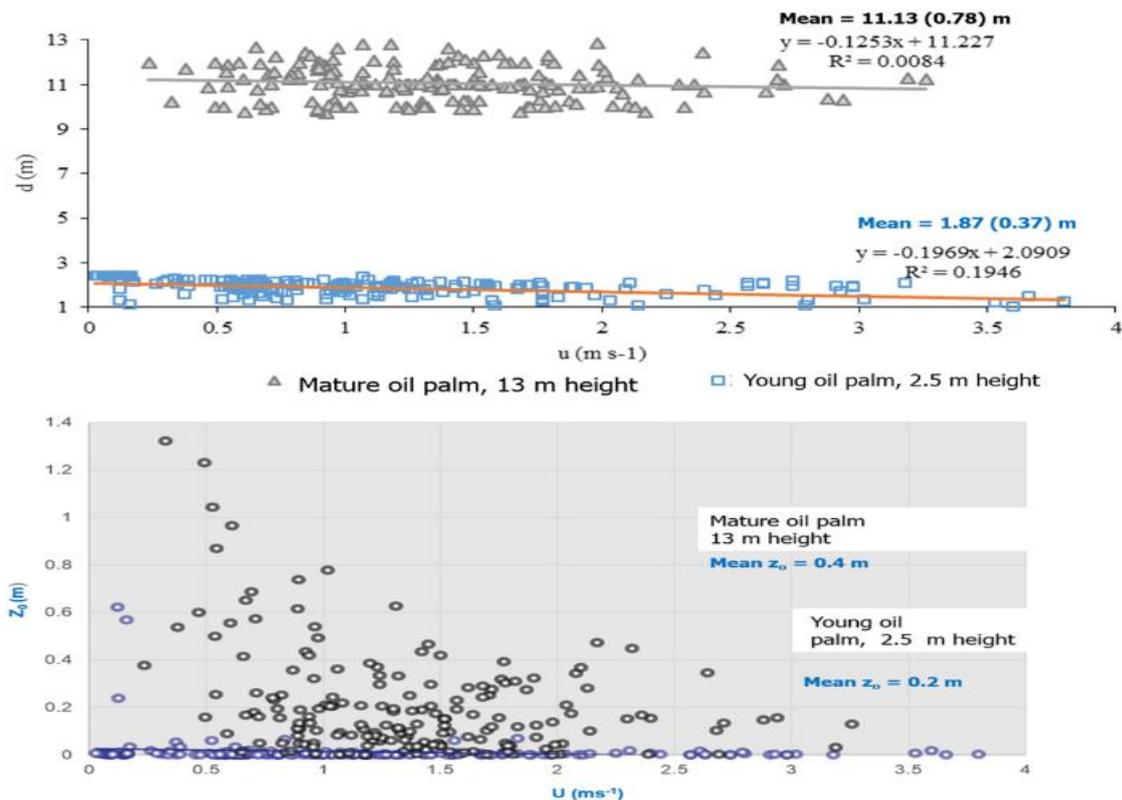
$$w^* = \left[\frac{|g| z_i \left(\frac{Q_H}{c_p \rho}\right)}{T_v}\right] \quad (14)$$

where  $w^*$  is the Deardorff velocity,  $T_v$  is virtual air temperature (K), and  $Q_H$  denotes sensible heat flux ( $\text{Wm}^{-2}$ ).

### 3. Results and discussion

#### 3.1. Roughness characteristics

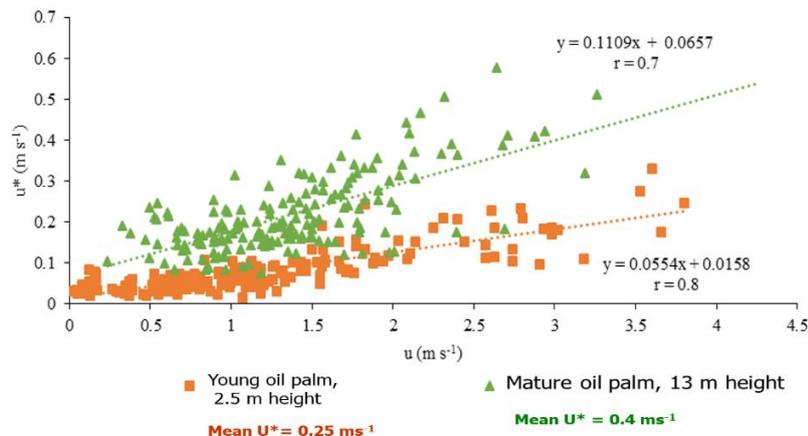
Zero plane displacement ( $d$ ) increased with age of the plantation with an average value of 1.87 m and 11.13 m for the young and mature oil palm plantation, respectively (Figure 4) revealing that  $d$  value depends on both vegetation height and density. Beside of height and density of the standing vegetation, [17,18] clarified that the mechanical sturdiness of vegetation stem also defines the displacement height where the wind speed is close to zero. Roughness length ( $z_0$ ) as well as friction velocity ( $u^*$ ) follow similar pattern, where the highest  $z_0$  and  $u^*$  were found in the mature compared to the young plantation. They were 0.4 m, 0.22 m s<sup>-1</sup> and 0.2 m, 0.08 m s<sup>-1</sup> respectively (Figure 4, Figure 5). The value of  $d$  tends to be more persistent in comparison with  $z_0$  and  $u^*$ . The values of  $z_0$  dropped with increasing wind velocity. The values of  $z_0$  varied largely during calm wind conditions, particularly in the 12 years-old plantation. Friction velocity ( $u^*$ ) was strongly positively related to wind speed.



**Figure 4.** Zero plane displacement ( $d$ ) and roughness length ( $z_0$ ) of the young and mature oil palm plantation.

The value of  $d$  describes the height inside the canopy where wind speed starts to be extinguished due to the friction imposed by the plant canopy. The value of  $z_0$  shows the position where momentum is well absorbed by the roughness element. Unlike these two roughness parameters, which characterize the unique dimension

of the surface roughness,  $u^*$  explains a tangential velocity of air parcel movement primarily due to mechanical turbulence. That is why  $u^*$  is usually determined under neutral condition, when buoyancy effects are insignificant in the absence of intensive surface heating. Thereby  $u^*$  can completely depict the roughness of the underlying surface. According to [8], the 12 years-old oil palm plantation can be classified as a very rough surface (terrain category: 3, class: 6) which is the same as orchards and bushes, whereas the 1 years old oil palm plantation tended to be classified between a smooth surface (terrain category: 1, class 2) and an open surface (terrain category: 2, class 3). The roughness length of a vegetated surface can be a function of wind speed [19, 6]. Strong gusts of wind can bend the stems of plants parallel to the wind direction which results in lower  $z_0$ . Unlike flexible stems which are easily bent by gust of wind, the sturdy stems of oil palms with a high density will have a much higher roughness length due to a reduced bending effect. The sparsely vegetated surface of the 1 years old oil palm plantation obviously had a lower roughness length compared to the 12 years old plantation, since it did not have a large absorption area for momentum. In the 1 year old plantation, where plant spacing is of the order of the canopy height or larger (about 8 m distance between palms ) a larger part of the momentum is absorbed by the ground surface. Therefore, the 1 year-old plantation had very small roughness length compared to the 12 year old plantation. The higher values of  $u^*$  in the 12 year-old plantation compared to the 1year-old plantation indicate that greater shear stress was generated in the older plantation and triggered bigger turbulence production. The reason for the greater shear stress is the higher surface roughness in the 12 year-old plantation. Shear stress also increases with increasing wind speed, thus explaining the increase in  $u^*$  with wind speed. (Figure 5).



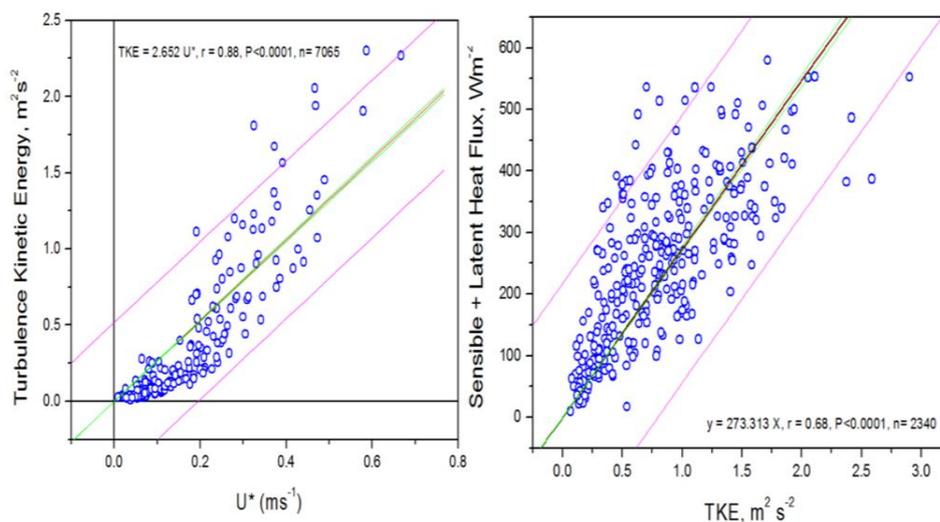
**Figure 5.** Friction velocity ( $u^*$ ) versus horizontal wind speed ( $u$ ) at the young and mature oil palm plantations.

Environmental problems such as soil erosion either by wind gust or run off are expected to occur more often when an oil palm plantation is still young, short, sparse and relatively flexible in terms of bending moment. However, this problems will be gradually reduced by the growth of the plants (the increase of roughness characteristics). At the optimum growth phase when the oil palm canopies will fully cover the ground,  $z_0$  and  $d$  are expected to reach maximum values, and may act as windbreaker reducing wind erosion.

### 3.2. Turbulence and Heat Fluxes (Sensible and Latent heat fluxes)

Sensible and latent heat fluxes as well as  $u^*$  are positively correlated with turbulent kinetic energy (TKE, Figure 6). During the day, incoming short wave radiation is absorbed by the surface and warms the

atmosphere upwards, the potential air temperature gradient becomes negative (unstable atmospheric condition) as the sensible heat flux transfers heat from warmer surface to the cooler atmosphere above. On the contrary, at night, when the ground is usually cooler than the air, the potential air temperature gradient becomes positive (stable atmospheric condition) and the flux direction changes from the atmosphere to the surface. In case of neutral conditions, the vertical gradient of potential air temperature is close to zero, meaning no or negligible sensible heat transfer, neither from the surface to the atmosphere or in opposite direction. The sensible heat flux was larger in the young compared to the mature plantation. One of the main drivers of heat flux variation is turbulence production. If we talk about turbulence, we usually relate it to atmospheric stability which is represented by the Richardson number  $Ri$ . A negative  $Ri$  refers to unstable condition, this is when the turbulences are intensively generated, whereas a positive  $Ri$  refers to stable condition when the turbulence is damped. Rougher surface such in mature plantation usually has greater turbulence production due to bigger shear stress (can be shown by the higher  $u^*$  in Figure 5).

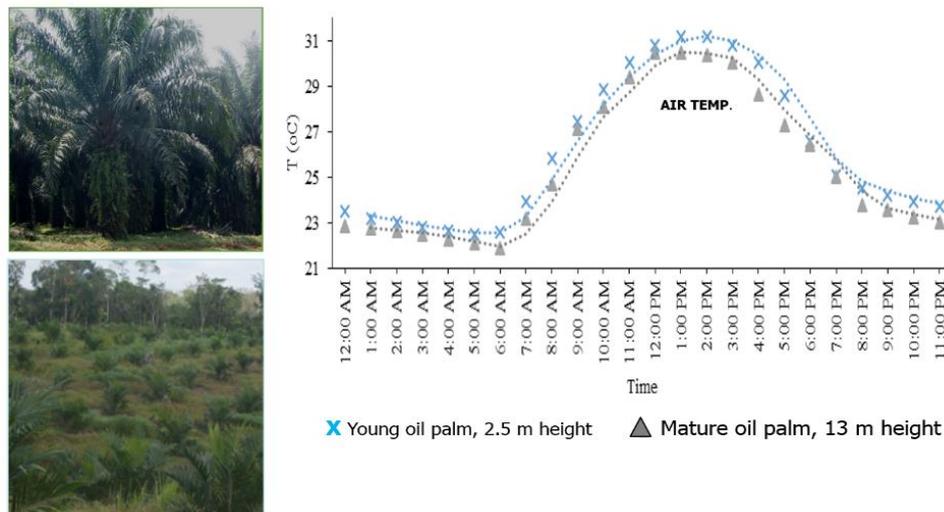


**Figure 6.** Influence of TKE on heat fluxes, both sensible and latent heat fluxes (right). TKE was significantly correlated with  $u^*$  (left).

The existence of turbulence (TKE) advances the flux transfer process (Figure 5). Various factors have simultaneously a role in the heat flux process, such as surface roughness, air temperature gradient, turbulence generation, and solar radiation (peak time and maximum surface heating during day time). Turbulence indicates an irregular behavior of wind speed deviating from its mean velocity profile. Generally, turbulent motion is generated by two main factors, i.e. buoyancy production and wind friction between air movements and the rough surface [7]. Turbulence reaches a maximum when surface heating is at maximum under unstable condition resulting in high buoyant productions as well as when wind shears near the surface is high. We found that TKE above the mature plantation was greater than TKE above the young plantation. Under unstable conditions, beside of buoyancy production and wind shears, the tendency of TKE to increase or decrease can be affected by transport of TKE advected by mean wind speed from one location to another. TKE also can be transported vertically, where the excess of TKE near the surface will tend to be moved up to a higher location by turbulent motions [16].

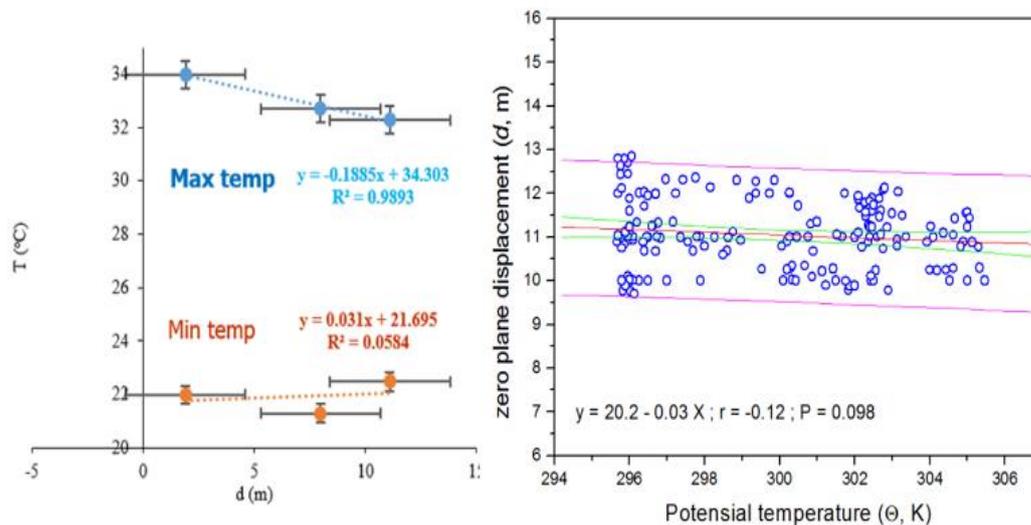
### 3.3. Turbulence and air temperature

One of the driving factors determining the vertical air temperature profile in vegetated areas is the heating process by solar radiation. Similarly to leaf area index, the zero-plane displacement height,  $d$ , which is a function of canopy height and density) can be a good parameter characterizing the effect of plants on microclimate. [20] stated that the increase of  $d$  was proportional to the increase of the Normalized Density Vegetation Index generated from remote sensing data. During day time, a sparse canopy (young plantation) absorbs less solar radiation and thus more radiation reaches the ground compared to the dense canopy of the mature plantation. As a consequence, the surface heats stronger generating more sensible heat. The sensible heat will create buoyancy effects stimulating turbulent mixing forcing hot air parcels to move upwards and thus rapidly increase air temperature above the plantation canopies. Therefore, the mean daily cycle of air temperature in the young plantation was higher than in the mature site (Figure 7). Although turbulence generated above the mature plantation was greater than above the young plantation, the heating process within this denser canopy takes longer than the ground heating process, therefore the air temperature above the young plantation increased faster than the mature site. Additionally, the higher turbulence of the “rougher” mature plantation, was allocated for latent heat fluxes (resulting from the larger water consumption of the mature oil palms), which lowered the surface and hence air temperature of the mature plantation.



**Figure 7.** Mean daily cycle of air temperature at the young and mature oil palm plantations.

Similar to [21], the mean daily maximum air temperature had a strong negative relationship with roughness expressed as  $d$ , while its mean daily minimum did not (Figure 8). This indicates the interplay of surface roughness, water consumption and air temperature dynamics.



**Figure 8.** Increasing roughness characteristic ( $d$ ) results in decreasing maximum air temperature, but had no significant effect on minimum air temperature (left). Weak negative correlation between  $d$  with potential temperature (right).

#### 4. Conclusion

Surface roughness influences the dynamics of the surface boundary layer, including vertical wind speed and temperature profile, momentum flux, sensible and latent heat fluxes, and turbulence. Parameters of surface roughness which include zero-plane displacement ( $d$ ), friction velocity ( $u^*$ ), and roughness length ( $z_0$ ) increased with plant height (and age) as shown by the comparison between a 1 and 12 years old plantation. The 12 years old plantation was 'rougher' than the 2.5 years old plantation generating bigger shear stress indicated by higher  $u^*$ . Proportional to the shear generated, both turbulence intensities and TKE increases towards maximum value with increasing surface heating, when the mixing processes were more effective. Surface roughness ( $z_0$  and  $d$ ) affects the transferred sensible and latent heat by influencing vertical mixing of air, through  $u^*$  and TKE, in the surface boundary layer, thereby contribute to regulating surrounding air temperature.

Young plantations showed higher air temperature and had higher sensible heat fluxes (despite lower roughness characteristics), while mature plantations invest more energy towards latent heat fluxes and have lower surface temperature. Thereby, evaporative cooling is the main determinant of regulating temperature in oil palm as for most vegetated surfaces when water is available [22]. There is a decreasing trend of maximum air temperature with increasing surface roughness ( $d$ ,  $z_0$ ) above the oil palm canopy, indicating the effect of increasing plant volume in reducing air temperature. This is also supported by Landsat derived parameter NDVI [20,23]. We therefore recommend the use of remote sensing (and LIDAR) products for scaling up to larger area.

Research on surface roughness, turbulence, sensible and latent heat fluxes on oil palm is very limited. Therefore it would add valuable information needed to support the analysis of land use change effects on energy, mass fluxes and micro/regional scale climate [24].

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