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Spatial variability in soil water under adjacent mature oil palm and rubber plantations: application of a new dielectric method in evaluating soil water

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Abstract Many people have commonly addressed that oil palm plantations release much more water from the ground by evapotranspiration compared to other crops. The current research evaluated the spatial variability in soil water content under adjacent oil palm and rubber plantations established in 2005 and 1995, respectively. We collected ten pairs of soil electrical impedance data (Z, in kΩ) from the oil palm and rubber sites using a newly-developed electrical impedance meter, then converted to soil water content (θ, in $g.g^{-1}$) using the equation of $\theta = 0.45.Z^{-0.2}$. The impedance measurements took place at 0-10 and 10-20 soil depths to allow the comparisons of actual soil wetness between the two crops at the rooting zones. At the same time, we also collected disturbed soil samples from the measurement points for the laboratory determination of soil water using the standard gravimetric method. Results showed that soils under oil palm plantation were consistently more wet than under rubber in all pairs of measurements. At the 0-10 cm depth, the average soil water content at the time of measurements was 0.04 $g.g^{-1}$ higher for oil palm than for rubber. The field water content ranged from 0.310 to 0.384 and 0.268 to 0.318 $g.g^{-1}$ for oil palm and rubber, respectively. The standard deviations of samples were about 0.02 $g.g^{-1}$ for both crops indicating the statistical confidence that the oil palm site contained more water than the rubber site. Similar trends were found at the 10-20 cm soil depth suggesting the consistent benefit of the oil palm plantation in preserving soil water in the 0-20 cm rooting zone. Results in soil water variability gained from the dielectric method were similar to those obtained using the standard gravimetric method.

Keywords: Electrical impedance, oil palm, rubber, soil water

Introduction

Increasing demand in the European Union biofuels market is stimulating a vast expansion of oil palm (*Elaeis guineensis* Jacq.) cultivations in Indonesia,

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particularly in Sumatera and Kalimantan Islands. The expansion may lead to unsuccess efforts of government in safeguarding the water resources on which the local livelihoods depend on (Larsen *et al*., 2014). In oil palm plantations, water supply is the main limiting factor that controls the crop growth and yields. Therefore, this phenomenon has been widely adopted to frame the opinion that the plantations have caused a significant shortage of water resources in many countries. In many cases in Indonesia, the substantial expansion in oil palm plantations often takes place by conversing the water-converting forest and arable land as reported by Anggraini and Grundmann (2013).

Limited studies are focusing on the relations between oil palm production and the soil water use, therefore, it is difficult to conclude oil palm plantations as a factor responsible for the shortage of water resources. A study by Carr (2011), however, reveals the rates of 4-5 mm d^{-1} in the evapotranspiration from the mature oil palm trees in the monsoon months. The study also shows the 10 per cent loss of fresh fruit bunch for every 100 mm increase in soil water deficit. Kospa *et al.* (2017) report that total water use in all stages of the production of crude palm oil (CPO) and kernel was 1.36 m^3 ton^{-1} of fresh fruit bunch produced, while the wastewater in the production area was approximately 306.81 m^3 ton^{-1}. A question raised from these findings is whether any possible shortage of water resources can be related directly to the use of water for oil palm growth and yield or indirectly to the loss of water by land conversions.

In Sumatera, Indonesia, many studies have been conducted regarding the effects of tropical rainforest conversion into annual crop plantations especially oil palm and rubber plantations. Microbiological biomass, including the fungi and bacteria species, is the first soil characteristics to change when the rainforest is converted to farms (Krashevska *et al*., 2016). Direct exposure of the soil surface to rainfall water as a consequence of leaving the soil surface uncovered at the crop plantations during the rainy seasons may cause the physical degradation of soils such as the soil aggregate disintegration and the presence of pounding water following the rainy season (Hermawan and Bomke, 1997). The effects of converting the protected land into more exposed arable land to chemical properties of soils particularly the nitrogen cycle have been reported elsewhere by Allen *et al*. (2015). The above findings suggest that the accelerated expansion of oil palm and rubber plantations in Sumatera and other parts of Indonesia may lead to land degradation and low crop production.

The areas of plantations in Bengkulu Province is about 557,000 ha, including those owned by private and state companies as well as by the local people in a smallholders scale. The oil palm and rubber plantations occupy about 75 per cent of the planting areas, i.e. 290,000 and 125,000 ha, respectively (BPS, 2016). Therefore, comparing the soil water use of oil palm cultivation to the use by other crops is urgent, as the water dependence of these two major crop yields also applies to all crop production systems. Intensive production in the oil palm and rubber commodities of Bengkulu Province may affect the hydrological characteristics of arable land and the sustainability of crop yields.

Generally, oil palm has been attributed qualitatively as a high water-consuming crop that is responsible for the degradation of water resources. Studies on quantifying the loss of soil water from oil palm and rubber plantations are very limited in Indonesia. However, the common assumption suggests that oil palm rather than rubber plantations are responsible for decreasing water resources. On the other hand, a study by Nodichao *et al.* (2011) indicated that oil palm plants with a high total root length might uptake soil water more efficiently, as well as cause a slower drying out of soils surrounding the roots compared to those with less rooting systems.

This research aimed to compare the spatial variability in soil water under adjacent oil palm versus rubber plantations. The comparisons between both crop plantations involved soil water data determined by using a dielectric method in the field and a standard gravimetric method in the laboratory. Theoretically, both crops should have contrasting patterns of soil water uptake due to differences in the root characteristics, such as shallow-fine root systems for the oil palm versus deep-coarse conditions for the rubber.

Materials and methods

The study took place in the adjacent mature oil palm and rubber plantations in Bengkulu Province, during a dry period in August 2017. The dual study of oil palm and rubber plantations were established about 11 and 20 years ago, respectively, by the local people, occupying about 20 ha of undulating areas (slopes of less than 15 per cent) on Inceptisols at the altitude of about 100 m above sea level (Figure 1). Both areas of these smallholder plantations were located at the latitude of -3.697699 S and 102.316371 E, about 10 km to the north of the provincial capital, Bengkulu City.

The physical and chemical characteristics of study soils at three positions of slopes are available in Table 1. Study soils were characterized by high sand fractions, medium levels of total nitrogen, low phosphorus and potassium, high organic carbon, and deficient aluminium. High contents of sand in the study soils indicated that both crops might not be severed to water logging during the rainy seasons due to good drainage conditions in the root zones. However, the land in the plantation areas might suffer from nutrient deficiences such as phosphorous and potassium, as well as lead to yield dissatisfaction for farmers.

Figure 1. Sites of soil water measurements (inside the box) at adjacent oil palm and rubber plantations

Table 1. Physical and chemical characteristics of study soils at three slope positions

Variables	Slope positions		
	Upper	Middle	Lower
pH (H2O)	4.60	4.90	4.85
C-org (%)	3.35	3.73	3.33
N-tot (%)	0.28	0.33	0.30
P-Bray (ppm)	14.11	10.32	10.44
K (me/100g)	7.76	2.98	6.53
Al (me/100g)	2.39	2.64	1.98
Sand (%)	49.62	47.23	48.17
Silt (%)	30.43	27.95	27.01
Clay (%)	19.95	24.82	24.82

Data collection

Data were obtained using a purposive sampling technique, as the sample crops were chosen according to the closest distance between a pair of oil palm and rubber. Ten pairs of measurement and sampling points of study soils were assigned for the bordering oil palm and rubber plantations, respectively, during a discharged period of soil water or about ten days after the last rain event. Fundamental physical and chemical characteristics of study soils were provided from a previous study by Hermawan *et al.* (2017a). The pair of sample crops were at a distance of about 20 m to each other, assuming that they grew in a similar soil type. Therefore, any differences in soil water content were attributed to the crop factor. Both measurement and soil sampling were conducted at about 1 m from each tree.

For each crop, gravimetric soil water content data were collected from the 0-10 and 10-20 cm depths by measuring the soil electrical impedance. The measurement was conducted according to a newly developed dielectric method by using the impedance meter. The working mechanism of the technique in determining soil water content in the field has been reported by authors elsewhere (Hermawan *et al*., 2017b). A pair of sensors connected to the impedance meter was inserted into the soil up to a depth of 10 cm, and then the device was switched on to allow the electric current to travel at a frequency of 300 kHz. The soil electrical impedance value appeared within five seconds on the LCD screen of the device (as illustrated in Figure 2) and recorded. At the same time, a disturbed soil sample was taken from the same depth using an earth borer, put into a plastic bag and tightened with rubber for the laboratory measurement of water content. Both impedance measurement and soil sampling at the 0-10 cm depth were repeated for the 10-20 cm layer.

Figure 2. A newly developed impedance meter for measuring soil water content using the dielectric method in the field

Gravimetric soil water content (θ in $g.g^{-1}$) was calculated from the measured soil electrical impedance (Z in kΩ) using the following nonlinear equation.

$$\theta = a.Z^{b} \quad (1)$$

Where a was intercept and b slope in the θ-Z line graphic. The intercept value was 0.45 and slope was -0.2 as found from a previous study on the same soil (Hermawan *et al*., 2017a). Therefore, Equation 1 was written as

$$\theta = 0.45.Z^{-0.2} \quad (2)$$

The proposed model has been tested for hundreds of pairs of soil water and impedance data and indicated the closeness of their relations (R^2>0.80).

The laboratory measurement of soil water content was applied to the soil samples taken at the same depths of the impedance readings. Soil water content was determined using a standard gravimetric method (Gardner, 1986), while its calculation was based on the ratio between the weight of water existing at soil samples and that of soils subjected to the oven drying treatment for at least 24 hours. The mass of water in the soil was determined from the weight differences between the field moist and oven-dried soil samples. Soil water content determined using this method has been usually used as the corrector for any alternative techniques in measuring soil water. The corrections were required since the alternative methods in determining soil water content, including the procedure proposed in the current study, predict the amount of water in soils by measuring other variables, while the laboratory gravimetric scheme directly measures the soil water content.

Data analyses

Soil water data obtained from the new device were analyzed descriptively by comparing the patterns of their spatial variability under mature oil palm and rubber plantations. The comparisons were made by plotting pairs of soil water data for both crops on the line graphs. This analysis technique allowed us to calculate the gaps in soil water content between pairs of oil palm and rubber trees chosen as study samples.

Differences in predicted soil water content under oil palm and rubber plantations were then compared to those for the laboratory measured soil water. This data analysis technique was used to evaluate the accuracy of the new device in predicting soil water content in the field. The accuracy of the proposed method was evaluated according to the closeness of the spatial variability patterns in soil water between the two methods.

Results

Spatial variability in soil water

Spatial variability in soil electrical impedance, as a dependent variable to calculate the in-situ soil water content in the field under mature oil palm and rubber canopies, was presented in Figure 3. The electrical impedance values under oil palm were consistently lower over ten measurement points compared to those under rubber plantations. The differences in the impedance for each pair of oil palm and rubber readings ranged from 3.0 to 9.0 kΩ for the uppermost 0-10 cm soil depths and 0.5 to 9.0 kΩ at the lower layers. The results suggested that the electric current injected from the impedance meter travelled with less significant resistance under oil palm than under rubber trees. The trend in the electrical impedance variability existed up to the depth of 20 cm from the soil surface. The spatial variability in soil electrical impedance values might indicate the distribution of soil components at the measuring zones such as variations in soil wetness, the presence of plant roots, (Wang *et al*., 2019) as well as lime, bentonite, and polymer (Raheem *et al*., 2017).

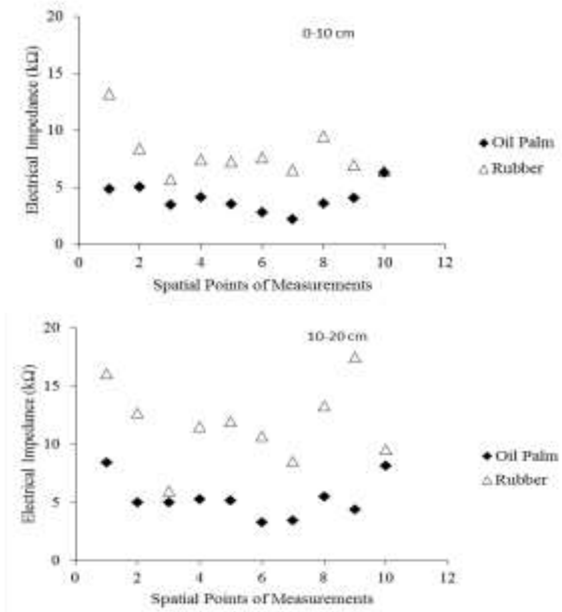

Figure 3. Spatial electrical impedance of soils measured under oil palm and rubber plantations

In the current study, the soil electrical impedance was measured using a newly developed impedance meter operated at a low (3.0 kHz) frequency of sinusoidal voltage generator. Since soil dielectric variables such as impedance and capacitance were frequency dependent (Kelleners and Verma, 2010), the electrical impedance data presented in Figure 3 might indicate the real values of the dielectric properties, despite different frequency bases of the measurement devices. In relations to soil water content, the electrical impedance had negative exponential correlations with the proportion of water occupying the soil pores. Increasing electrical impedance in the porous media, including soils, would be followed by decreasing content of soil water and increasing occupation of highly-resistant air to the electricity transmission. The exponential relations between soil electrical impedance and soil wetness were similar to those found by Wang *et al.* (2019), indicating that this dielectric parameter can serve as an indicator of the substrate's water content.

The purposes of measuring the electrical impedance of study soils was to determine the in-situ soil wetness variations under mature oil palm and rubber plantations. When the dielectric data in Figure 3 were converted to soil water content using Equation 2, the spatially predicted water was higher for oil palm compared to rubber soils (Figure 4). Results showed that soils under oil palm plantation were consistently wetter than soils under rubber in all points of measurements. At the 0-10 cm depth, the average soil water content at the time of measurements was 0.04 $g.g^{-1}$ higher for oil palm than for rubber, ranging from 0.310 to 0.384 and 0.268 to 0.318 $g.g^{-1}$, respectively. The standard deviations of samples were about 0.02 $g.g^{-1}$ for both crops, indicating the statistical confidence that the oil palm site contained more water than the rubber site. The superiority of soil water under mature oil palm plantation might offer crucial information regarding the common assumption among many environmental activists worldwide that the plantation has been responsible for a shortage of water resources, as well as for water pollution due to high fertiliser applications (Comte *et al.*, 2015).

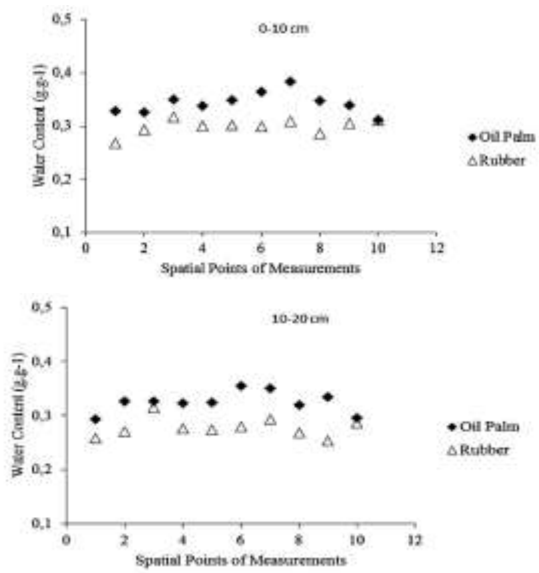

Figure 4. Spatial variability in water content at 0-10 and 10-20 cm soil depths under two crops as calculated from the electrical impedance values

Gravimetrically-measured soil water distribution

The second objective of the current study was to evaluate the comparative differences between dielectric-based predicted and gravimetrically-measured soil water content under two different plantations. As shown in Table 2, the averages in laboratory-measured soil water content were about 0.05 and 0.04 $g.g^{-1}$ higher for mature oil palm trees at the 0-10 and 10-20 cm depths, respectively. Standard deviation for each site was lower at the 10-20 cm depth suggesting that differences in measured water content were statistically more significant at lower rather than upper soil layers.

Table 2. Spatial variability in soil water ($g.g^{-1}$) under oil palm and rubber plantations as determined by the gravimetric method

Points of measurements	0-10 cm depth		10-20 cm depth	
	Oil palm	Rubber	Oil palm	Rubber
1	0,373	0,322	0,282	0,307
2	0,270	0,287	0,275	0,300
3	0,419	0,291	0,327	0,290
4	0,375	0,328	0,358	0,299
5	0,342	0,289	0,320	0,309
6	0,421	0,365	0,416	0,342
7	0,420	0,315	0,398	0,330
8	0,394	0,307	0,363	0,312
9	0,364	0,322	0,310	0,282
10	0,286	0,287	0,298	0,287
Mean	0,336	0,311	0,335	0,306
Stdev.s	0,054	0,025	0,048	0,019

Trends of gravimetrically-measured data in Table 2 were relatively equal to those predicted from Equation 2 (Figure 4), suggesting the closeness between predicted and measured soil water content in the study area. These features indicate that dielectric variables such as the electrical impedance can be used in predicting the field variations in soil water content, in comparison to the conventional technique. Prediction models that determine soil water content in the field are useful tools to help us better understand soil-water interactions, as they can obtain large numbers of soil water data in a short period. The models can be applied to a wide range of soil and water management techniques, such as irrigation, by improving water uptake by the plant (Karandish and Šimůnek, 2016).

Discussion

Wetter soils under the oil palm plantation were consistently found at all measurement points, suggesting slower drying processes of rooting-zone soils by this crop during the drying period. Well-distributed fine roots of mature oil palm, in comparison to the coarse roots of rubber, might have better access to a large volume of soil to absorb water, and therefore could slow down the drying process of soil in the rooting zone (Nodichao *et al*., 2011). The presence of massive roots under oil palm might be responsible for the more homogenous soil water profile up to a 20 cm depth, as shown in Table 2. On the other hand, the fast-drying soils under the rubber plantation found in this study could be attributed to the fact that rubberwood absorbed more water vapour than the oil palm trunk (Zaihan *et al*., 2011), and might enhance water loss by evaporation from the soil surface. Canopy openness of plantation trees could also be the reason for soil wetness differences under oil palm and rubber sites. Meijide *et al.* (2018) reported that some microclimate variables were better under oil palm than under rubber canopies, air humidity was 1.1% higher and vapour pressure deficit was 33 Pa lower under oil palm, and likely responsible for less evaporation and soil water loss for oil palm. Our field observation during measurements also found that oil palm canopy covered more land surfaces than rubber trees.

Results shown in Figure 4 suggested that the mature oil palm plantation used in this study conserved more water in the rooting zone of 0-20 cm soil depth compared to the monoculture rubber plantation. The possibility that water penetration might be limited by evapotranspiration at the vegetated soil, as suggested by Wang *et al.* (2008), did not happen for vegetated study soils with well-distributed fine root systems such as oil palm. Lateral-distributed root system development had a greater ability to maintain soil water availability and crop production (Suralta *et al.,* 2015). Also, the application of several water conservation practices under oil palm trees could result in more soil water availability during water deficit periods. Applying the terrace bund in the mature oil palm plantation has increased soil water content and fresh fruit bunch production by 13.4 per cent compared to the control site (Murtilaksono *et al.,* 2011). Mulching application using materials from oil palm residues are often suggested by many researchers to improve water conservation and land productivity in the plantations. Moradi *et al.* (2015), for example, recommended the use of empty fruit bunches for mulching due to an increase in distributed water throughout the soil profile, particularly on hill plantations. Management practices for soil water conservation are the main key to the oil palm development since annual soil water deficit is the most significant limiting factor in the land suitability classification for oil palm production.

Conclusion

Spatial variability of soil water within each plantation as predicted from the measured electrical impedance values was lower than the variability between the two farms. Soils under oil palm plantation were consistently wetter than under rubber in all pairs of measurements. The average soil water content at the 0-10 cm layer was 0.04 $g.g^{-1}$ higher for oil palm than for rubber, ranging from 0.310 to 0.384 and 0.268 to 0.318 $g.g^{-1}$, respectively. The standard deviations of samples were about 0.02 $g.g^{-1}$ for both crops, indicating the statistical confidence that the oil palm site contained more water than the rubber site. Similar trends were found at 10-20 cm soil depth, suggesting the consistent benefit of the oil palm plantation in preserving soil water in the 0-20 cm rooting zone. Predicted water variability gained from the dielectric method were similar to those measured in the laboratory using the standard gravimetric method, suggesting that the laboratory determination of soil wetness variability can be shifted to the field measurement.

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References

Allen, K., Corre, M. D., Tjoa, A. and Veldkamp, E. (2015). Soil nitrogen cycling responses to conversion of lowland forests to oil palm and rubber plantations in Sumatra. PloS one. Retrieved from https://journals.plos.org/plosone/article?id=10.1371/journal-.pone.

Anggraini, E. and Grundmann, P. (2013). Transactions in the supply chain of oil palm fruits and their relevance for land conversion in smallholdings in Indonesia. Journal of environment and development. 22:391-410.

BPS (2016). Bengkulu Province in Figures. Statistics of Bengkulu Province. Catalog: 1102001.17.

Carr, M. K. V. (2011). The water relations and irrigation requirements of oil palm (*elaeis guineensis*): a review. Experimental Agriculture. 47:629-652.

Comte, I., Colin, F., Grünberger, O., Whalen, J. K., Harto Widodo, R. and Caliman, Jean-Pierre. (2015). Watershed-scale assessment of oil palm cultivation impact on water quality and nutrient fluxes: a case study in Sumatra (Indonesia). Environmental Science and Pollution Research International. 22:7676-7695.

Gardner, W. H. (1986). Water content. In: Klute, A ed. Methods of soil analysis. Second edition, Madison, Soil Sci. Soc. Am. Inc. Publ. pp. 493-544.

Hermawan, B. and Bomke, A. A. (1997). Effects of winter cover crops and successive spring tillage on soil aggregation. Soil and Tillage Research. 44:109-120.

Hermawan, B., Agustian, I., Suhartoyo, H. and Sukisno. (2017a). Design of Handheld Moisture Meter for Measuring Insitu Water Content in the Field. Research Report, Board of Research and Development, University of Bengkulu.

Hermawan, B., Suparjo, E., Hindarto, K. S., Silalahi, R. and Barchia, F. (2017b). A quick dielectric method to determine insitu soil water content for precision water use under sustainable agricultural practices. International Journal of Advanced Science Engineering Information Technology. 7:910-915.

Karandish, F. and Šimůnek, J. (2016). A field-modeling study for assessing temporal variations of soil-water-crop interactions under water-saving irrigation strategies. Agricultural Water Management. 178:291-303.

Kelleners, T. J. and Verma, A. K. (2010). Measured and modeled dielectric properties of soils at 50 megahertz. Soil Science Society of America Journal. 74:744-752.

Kospa, H. S. D., Lulofs, K. R. D. and Asdak, C. (2017). Estimating water footprint of palm oil production in PTP Mitra Ogan Baturaja, South Sumatera. International Journal of Advanced Science, Engineering and Information Technology. 7:2115-2121.

Krashevska, V., Klarner, B., Widyastuti, R., Maraun, M. and Scheu, S. (2016). Impact of tropical lowland rainforest conversion into rubber and oil palm plantations on soil microbial communities. Biology and Fertility of Soils. 51:697-705.

Larsen, R. K., Jiwan, N., Rompas, A., Jenito, J., Osbeck, M. and Tarigan, Abetnego. (2014). Towards 'hybrid accountability' in EU biofuels policy? Community grievances and competing water claims in the Central Kalimantan oil palm sector. Geoforum. 54:295-305.

Meijide, A., Badu, C. S., Moyano, F., Tiralla, N., Gunawan, D. and Knohl, A. (2018). Impact of forest conversion to oil palm and rubber plantations on microclimate and the role of the 2015 ENSO event. Agricultural and Forest Meteorology. 252:208-219. Retrieved from https://doi.org/10.1016/j.agrformet. 2018.01.013.

Moradi, A., Teh Boon Sung, C., Goh, K. J., Husni Mohd Hanif, A. and Fauziah Ishak, C. (2015). Effect of four soil and water conservation practices on soil physical processes in a non-terraced oil palm plantation. Soil and Tillage Research. 145:62-71.

Murtilaksono, K., Darmosarkoro, W., Sutarta, E. S., Siregar, H. H., Hidayat, Y. and Yusuf, M. A. (2011). Feasibility of soil and water conservation techniques on oil palm plantation. Agrivita. 33:63-69.

Nodichao, N., Chopart, J-L., Roupsard, O., Vauclin, M., Aké, S. and Jourdan, C. (2011). Genotypic variability of oil palm root system distribution in the field. Consequences for water uptake. Plant and Soil. 341:505-520.

Raheem, A. A., Vipulanandan, C. and Joshaghani, M. S. (2017). Non-destructive experimental testing and modeling of electrical impedance behavior of untreated and treated ultra-soft clayey soils. Journal of Rock Mechanics and Geotechnical Engineering. 9:543-550.

Suralta, R. R., Lucob, N. B., Aguelo, A. B., Niones, J. M., Cabral, M. C. J. and Rebong, D.B. (2015). Functional roles of the plasticity in deep root system development in soil water uptake and dry matter production of doubled haploid lines of rice under upland drought condition. International Journal of Agricultural Technology. 13:907-925.

Wang, X. P., Cui, Y., Pan, Y. X., Li, X. R., Yu, Z., and Young, M. H. (2008). Effects of rainfall characteristics on infiltration and redistribution patterns in revegetation-stabilized desert ecosystems. Journal of Hydrology. 358:134-143.

Zaihan, J., Hill, C. A. S., Hashim, W. S., Dahlan, J. M. and Sun, D. Y. (2011). Moisture adsorption isotherms of acacia mangium and endospermum malaccense using dynamic vapour sorption. Journal of Tropical Forest Science. 23:97-105.

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