Agricultural and Forest Meteorology 239 (2017) 71–85

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Controls of water and energy fluxes in oil palm plantations: Environmental variables and oil palm age

Ana Meijide[a,*], Alexander Röll[b], Yuanchao Fan[a], Mathias Herbst[c], Furong Niu[b], Frank Tiedemann[a], Tania June[d], Abdul Rauf[e], Dirk Hölscher[b], Alexander Knohl[a]

[a] University of Goettingen, Bioclimatology, Büsgenweg 2, 37077, Göttingen, Germany
[b] University of Goettingen, Tropical Silviculture and Forest Ecology, Büsgenweg 1, 37077, Göttingen, Germany
[c] Thünen Institute of Climate-Smart Agriculture, Bundesallee 50, 38116 Braunschweig, Germany
[d] Bogor Agricultural University (IPB), Department of Geophysics and Meteorology, Bogor, Indonesia
[e] University of Tadulako (UNTAD), Faculty of Agriculture, Palu, Indonesia

ARTICLE INFO

Article history:
Received 24 June 2016
Received in revised form 11 February 2017
Accepted 26 February 2017

Keywords:
Eddy covariance
Sap flux
Albedo
Transpiration
Energy fluxes
Evapotranspiration

ABSTRACT

Oil palm is rapidly expanding, particularly in Indonesia, but there is still very limited information on water and energy fluxes in oil palm plantations, and on how those are affected by varying environmental conditions or plantation age. In our study, we measured turbulent fluxes of sensible (H) and latent (LE) heat and gross primary productivity (GPP) with the eddy covariance technique for 8 months each in a young oil palm plantation (1-year old) and subsequently in a mature plantation (12-year old) in Jambi Province, Sumatra, Indonesia. Simultaneous measurements of transpiration (T) were performed using the sap flux technique. We additionally estimated albedo, the maximum rate of carboxylation (Vc_{max}), the maximum rate of photosynthetic electron transport (J_{max}) and water use efficiency (WUE). LE dominated the energy budget in both plantations, particularly in the mature one, where it accounted for up to 70% of the available energy. In the young oil palm plantation, evapotranspiration (ET) was significantly reduced and H fluxes were higher. The Bowen ratio was higher in the 1-year old plantation (0.67 ± 0.33), where it remained constant during the day, than in the mature plantation (0.14 ± 0.09), where it varied considerably over the day, suggesting the existence of water sources inside the canopy which evaporated during the day. Albedo was similar in both plantations (0.16 ± 0.02 and 0.14 ± 0.01 for the 1 and 12-year old plantation, respectively), while WUE differed with plantation age. Annual T estimates for oil palm were 64 ± 3 and $826 \pm 34\,mm\,yr^{-1}$ for the 1 and 12-year old plantation, respectively. The corresponding annual ET was 918 ± 46 and $1216 \pm 34\,mm\,yr^{-1}$, respectively. The Community Land Model (CLM), a process based land surface model that has been adapted to oil palm functional traits (i.e. CLM-Palm), was used to investigate the contribution of different water sources to the measured fluxes. CLM-Palm differentiates leaf and stem surfaces in modelling water interception and thus is able to diagnose the fraction of dry foliage that contributes to T and the wet fraction of all vegetation surfaces (leaf and stem) that contributes to evaporation. The results of the simulations performed are consistent with the storage of water within the canopy in the mature plantation, and suggest that oil palm trunk surfaces including epiphytes provide water reservoirs for intercepted rain which significantly contribute to ET. The decoupling between GPP and T in the morning and the early decreases of both fluxes at midday point to internal water storage mechanisms in oil palms both in the leaves and in the stem, which delayed the detection of water movement at the leaf petioles. Our measured data combined with the model simulations therefore suggest the existence of both external and internal trunk water storage mechanisms in mature oil palms contributing to ecosystem water fluxes. Oil palm plantations can lead to surface warming at early stages of development, but further assessments should be performed at landscape level. Our study provides data relevant for the parametrization of larger-scale models, which can contribute to understanding the climatic feedbacks of oil palm expansion.

* Corresponding author.
E-mail address: ameijid@gwdg.de (A. Meijide).

http://dx.doi.org/10.1016/j.agrformet.2017.02.034
0168-1923/

1. Introduction

The rapid demand growth for vegetable oils is supporting the expansion of oil palm (*Elaeis guineensis* Jacq.) plantations, particularly in Indonesia, which are currently responsible for about half of the world's palm oil production (OECD-FAO, 2012; FAO, 2012). The surface dedicated to oil palm cultivation in Indonesia has increased at a rate of 400 000 ha yr^{-1} from 2008, reaching a total cultivated area of 10.6 million ha in 2015 (USDA, 2016). The existing production is concentrated in Sumatra (OECD-FAO, 2012), where large land-use changes have taken place, e.g. losses of over 21% of forest cover between 2000 and 2012 in the Sumatran lowlands (Margono et al., 2014).

Oil palm expansion affects different ecosystem properties and functions such as biodiversity (Barnes et al., 2014), soil carbon storage (Guillaume et al., 2015), biomass carbon pools (Kotowska et al., 2015) and greenhouse gas cycling (Carlson et al., 2012). A recent study in Borneo found up to 6.5 °C higher air temperatures in oil palm plantations than in primary forests (Hardwick et al., 2015), indicating that the conversion of forest to oil palm plantations and associated changes in canopy coverage can also have severe micro-climatic effects by modulating the land-atmosphere fluxes of energy and water (Alkama and Cescatti, 2016). Forest conversion to oil palm was also reported to impact on water cycling including evapotranspiration (ET) and infiltration rates (Comte et al., 2012; Merten et al., 2016). Understanding the underlying mechanisms of such changes requires a comprehensive assessment of ecosystem energy fluxes in oil palm plantations, particularly the partitioning of available energy into ET (latent heat flux, LE) and sensible heat flux (H). Changes in their magnitude or their ratio could for example, affect regional weather and climate patterns (Aragao, 2012; Pielke et al., 1998). Climate feedbacks due to land conversion have been observed in other regions (Bounoua et al., 2002; Defries et al., 2002), showing changes in albedo (Betts, 2000; Schwaiger and Bird, 2010) or increased temperature in the tropics and subtropics (Bounoua et al., 2002). Conversion to oil palm plantations could trigger thus far unassessed climatic feedback mechanisms.

Regarding changes in the water cycle after conversion to oil palm, some hydrological studies showed changes mainly during the first years after land clearing, which subsequently seemed to dissipate in mature oil palm plantations (Comte et al., 2012). Attempts to assess the effects of oil palm age on some of the most relevant ecosystem water fluxes, i.e. transpiration (T) and ET, indicated large increases of T with increasing oil palm age during the first 10 years of cultivation, and ET rates increased 1.7 fold from young to mature oil palm plantations (Röll et al., 2015). Microclimatic effects, on the other hand, seem to be strongest during the early stages of oil palm development (Luskin and Potts, 2011). Consequently, for a comprehensive assessment of the effects of oil palm expansion on energy fluxes, changes in their partitioning need to be evaluated at different stages of plantation development. Young oil palms, during the first years after plantation establishment, do not produce fruits. After 2–3 years, the palms mature, and fruits can be harvested (Dislich et al., 2016), making plantations productive in terms of yield.

Evapotranspiration and energy partitioning are currently being studied across a variety of ecosystems using the eddy covariance (EC) technique as part of an international network of flux measurements (Aubinet et al., 1999; Running et al., 1999). The EC technique allows for simultaneous quantification of LE, H and carbon dioxide (CO_2) fluxes, and, in combination with meteorological measurements, can provide information on the environmental and physiological controls of the studied fluxes. Only a few studies using the EC technique have so far been carried out in oil palm plantations, and they were limited to very short periods of time (Röll et al., 2015; Fowler et al., 2011; Henson and Harun, 2005). They therefore provide only limited information on the variation of these fluxes under changing environmental conditions.

Ecosystem carbon and water cycles are intimately coupled by gas exchange through plant stomatal conductance (g_s), which regulates photosynthesis and T rates (Collatz et al., 1991). Previous studies on oil palms have shown that T peaks early in the morning, which may be facilitated by internal trunk water storage mechanisms (Röll et al., 2015). Early peaks followed by subsequent declines of oil palm T indicate stomatal closure, which not only affects water fluxes (ie. T and ET), but also CO_2 uptake. The analysis of canopy conductance (g_c) derived from EC measurements together with leaf measurements of g_s can provide insight on some of the underlying physiological controls of stomatal closure and its impact on water and carbon fluxes.

A further relevant ecosystem indicator of carbon-water interaction is the water use efficiency (WUE), i.e. the ratio of carbon uptake during CO_2 assimilation to water loss during T (Ehleringer, 1993). It is a major factor for the survival, productivity and fitness of plants (Osmond et al., 1982) and an indicator of their resilience to changing climatic conditions (Chaves, 2004). Comparative studies of WUE can give insight on how future climatic changes may affect ecosystems carbon and energy budgets (Ponton et al., 2006). For oil palms, it is expected that ecosystem scale WUE varies substantially between highly productive and non-productive plantations.

In order to predict long-term weather and climate changes associated to the rapid expansion of oil palm plantations in many tropical areas, large-scale models are required to upscale effects from the stand and watershed level to the global scales (Granier et al., 2000). However, parametrization of such large-scale models should be informed by field measurements (see Tenhunen et al., 1998), but despite the extent of oil palm expansion and associated deforestation and land-use change, information on key eco-physiological variables is still relatively scarce. For maritime conditions such as in Indonesia, climatic impacts due to land-use change are expected to be even stronger than under continental conditions, as 40% of the global tropical latent heating of the upper troposphere takes place over the Maritime Continent (van der Molen et al., 2006). Thus, there is a need for field measurement of essential variables such as the photosynthetic capacity of oil palms (i.e. Vc_{max}, the maximum rate of carboxylation, and J_{max}, the maximum rate of photosynthetic electron transport) and crop coefficients to estimate ET (Allen et al., 1998) derived from field measurements. One land-surface model that allows for a systematic process-based simulation of carbon, water and energy exchanges between land and atmosphere as well as of microclimatic effects is the Community Land Model (CLM, Oleson et al., 2013). Recently, a CLM-Palm sub-model (Fan et al., 2015) has been developed to simulate palm species within the framework of the CLM4.5. It can therefore be used to facilitate the understanding of the underlying mechanisms of water and energy flux regulation and partitioning. The parameterization of canopy hydrology is critical for modelling water fluxes and for partitioning the available energy into H and LE. However, there is a lack of understanding of the fraction of intercepted precipitation and its effects on leaf gas exchange among the major land-surface models and even among different versions of the CLM (De Kauwe et al., 2013; Lawrence et al., 2007).

Our research question in this study was understanding energy fluxes and their environmental controls in oil palm plantations and how they differ with plantation age. Therefore, the objectives were 1) to quantify oil palm characteristics relevant for water and energy exchange, e.g. albedo, WUE, crop coefficients; 2) to evaluate water and energy fluxes at different stages of oil palm development; and 3) to identify the controlling physiological mechanisms and environmental factors of the studied fluxes. To achieve these objectives, we carried out EC measurements in a 1-year old oil palm plantation in the Jambi Province, Sumatra, Indonesia for 8 months.