Ecohydrological changes after tropical forest conversion to oil palm

Gabriele Manoli1,7, Ana Meijide2,3, Neil Huth4, Alexander Knohl2, Yoshiko Kosugi5, Paolo Burlando1, Jaboury Ghazoul6 and Simone Fatichi1

1 Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland
2 Bioclimatology, University of Göttingen, Göttingen, Germany
3 Department of Ecology, University of Granada, Granada, Spain
4 CSIRO Agriculture and Food, Toowoomba, Queensland, Australia
5 Graduate school agriculture, Kyoto University, Kyoto, Japan
6 Institute of Terrestrial Ecosystems, ETH Zurich, Zurich, Switzerland
7 Author to whom any correspondence should be addressed.

E-mail: manoli@ifu.baug.ethz.ch

Keywords: oil palm plantations, tropical forests, carbon/water fluxes, biophysical modeling

Supplementary material for this article is available online

Abstract
Given their ability to provide food, raw material and alleviate poverty, oil palm (OP) plantations are driving significant losses of biodiversity-rich tropical forests, fuelling a heated debate on ecosystem degradation and conservation. However, while OP-induced carbon emissions and biodiversity losses have received significant attention, OP water requirements have been marginalized and little is known on the ecohydrological changes (water and surface energy fluxes) occurring from forest clearing to plantation maturity. Numerical simulations supported by field observations from seven sites in Southeast Asia (five OP plantations and two tropical forests) are used here to illustrate the temporal evolution of OP actual evapotranspiration (ET), infiltration/runoff, gross primary productivity (GPP) and surface temperature as well as their changes relative to tropical forests. Model results from large-scale commercial plantations show that young OP plantations decrease ecosystem ET, causing hotter and drier climatic conditions, but mature plantations (age > 8–9 yr) have higher GPP and transpire more water (up to +7.7%) than the forests they have replaced. This is the result of physiological constraints on water use efficiency and the extremely high yield of OP (six to ten times higher than other oil crops). Hence, the land use efficiency of mature OP, i.e. the high productivity per unit of land area, comes at the expense of water consumption in a trade of water for carbon that may jeopardize local water resources. Sequential replanting and herbaceous ground cover can reduce the severity of such ecohydrological changes and support local water/climate regulation.

1. Introduction
Oil palm (Elaeis guineensis) plantations expansion has boomed over the last decades (global planted area increased from 6–16 Mha between 1990 and 2010 (Pirker et al 2016)), mostly in Southeast Asia (Koh et al 2011, Dislich et al 2017) at the expense of biodiversity-rich tropical forests (Koh et al 2011, Pirker et al 2016) and other land-covers such as pastures or pre-existing plantations (Gaveau et al 2016, Austin et al 2017, Furuno and Aide 2017). Oil palm (OP) is the most profitable and land-efficient oil crop in the world (Wahid et al 2005, Dislich et al 2017, Yan 2017) thanks to low management costs and high fruit productivity per hectare, i.e. yield (t ha−1) six to ten times higher than rapeseed and soy (Shay 1993, Yan 2017). Moreover, palm oil finds extensive use in both food and non-food industries for its qualities and comparatively cheap price (Dislich et al 2017, Pirker et al 2016). Hence, OP expansion is projected to increase across the entire tropics where an additional 19 Mha of suitable land are potentially available for OP cultivation (Pirker et al 2016). However, such an ability to provide food and raw material...
(Dislich et al. 2017), while contributing to rural development and poverty alleviation (Sayer et al. 2012), has driven deforestation and generated negative environmental impacts which earned OP the label of ‘world’s most hated crop’ (Yan 2017).

Forest conversion to OP is responsible for significant biodiversity losses and carbon emissions (e.g. Koh and Wilcove 2008, Koh et al. 2011, Carlson et al. 2013, Dislich et al. 2017, Vijay et al. 2016). Due to high fruit productivity OP plantations have been documented to uptake more carbon than tropical forests (Kotowska et al. 2015) but carbon storage in OP biomass is insufficient to balance the carbon losses caused by forest clearing (Kotowska et al. 2015, Dislich et al. 2017) and, over a 30 year period, OP establishment might result in carbon emissions from 702 t CO$_2$ ha$^{-1}$ to 3452 t CO$_2$ ha$^{-1}$ depending on the soil type (Farigone et al. 2008, Dislich et al. 2017). The different structure of OP plantations, having lower and less dense canopies compared to native forests, is also known to alter local climate, by increasing air/soil temperature and modifying air humidity (Hardwick et al. 2015, Drescher et al. 2016, Meijide et al. 2018), and hydrology, by increasing the risk of flooding, soil erosion and nutrient leaching (Dislich et al. 2017). However, there is a knowledge gap on the magnitude of such ecohydrological changes and their variations across plantation ages (Dislich et al. 2017).

A limited literature suggest that the conversion of forests to young plantations decreases evapotranspiration (ET) and infiltration rates (Merten et al. 2016, Dislich et al. 2017). Decreased infiltration reduces water storage (Dislich et al. 2017) and increases surface runoff (Comte et al. 2012) potentially jeopardizing the access to usable water and increasing the risk of flooding. There is also anecdotal evidence that OP plantations are ‘water greedy’ (Merten et al. 2016) with farmers and villagers from OP-dominated landscapes reporting water scarcity issues (e.g. decreasing water levels in wells during the dry season) as well as changes in stream flow levels and water quality (Larsen et al. 2014, Merten et al. 2016), which, in part, are corroborated by field observations (Carlson et al. 2014, Merten et al. 2016, Dislich et al. 2017). However, contrasting results on the water requirements of OP exist in the literature and it is unclear whether young and mature plantations have similar or different ET rates when compared to native forests (Dislich et al. 2017). In a review by Comte et al. (2012), ET fluxes of 1000–1300 mm yr$^{-1}$ for mature OP and 1000–1800 mm yr$^{-1}$ for lowland forests have been reported. However, Carr (2011) indicates a palm water use of 1277–2007 mm yr$^{-1}$ (i.e. 3.5–5.5 mm d$^{-1}$) with comparable transpiration rates (i.e. 2–5.5 mm d$^{-1}$) while Röll et al. (2015) reported ET values of 1022 and 1715 mm yr$^{-1}$ (i.e. 2.8–4.7 mm d$^{-1}$) with traspiration rates of 0.2 and 2.5 mm d$^{-1}$ for a 2 and 12 year old stand, respectively.

Given the dynamic nature of OP plantations, which are cleared and replanted every two to three decades (Dislich et al. 2017, Drescher et al. 2016), an improved understanding of age-dependent changes is needed. Existing studies (e.g. Luskin and Potts 2011, Hardwick et al. 2015, Röll et al. 2015, Merten et al. 2016, Hardanto et al. 2017, Sabajo et al. 2017) focused on limited observations from sites with different ages where topography, edaphic conditions, and microclimate heterogeneities potentially act as confounding effects, and the dynamic behaviour of a forest-OP plantation chronosequence is still poorly understood (Dislich et al. 2017). Modeling efforts to simulate OP behaviour and development also exist but they are mostly focused on agronomic variables (e.g. carbon allocation, yield, fertilization) and neglect carbon/water relations and surface energy fluxes (van Kraalingen et al. 1989, Combres et al. 2013, Huth et al. 2014, Hoffmann et al. 2014, Fan et al. 2015, Okoro et al. 2017, Pardon et al. 2017). Only recently, Meijide et al. (2017) employed a land surface model adapted to OP (CLM-Palm (Fan et al. 2015)) to simulate water/energy fluxes at two OP plantations but changes with comparison to native forests were disregarded.

Here we provide evidence of the ecohydrological impacts of forest conversion to OP by addressing the knowledge gap through model simulations constrained with field observations. With respect to OP monocultures (typical of large-scale plantations, i.e. 3000–20000 ha (Dislich et al. 2017)), we specifically show (i) how much ecosystem ET and GPP change when a representative tropical forest is replaced by an OP plantation; (ii) we quantify how these changes are modified by plantation age; (iii) and we demonstrate the role of OP understory vegetation. This is obtained by assessing the temporal changes in water, carbon and energy fluxes relative to tropical forests, which is the typical ecosystem replaced by OP (Koh and Wilcove 2008, Dislich et al. 2017).

2. Methods

To evaluate the ecohydrological changes induced by forest conversion to OP, model simulations by means of the ecohydrological model Téthys & Chloris (T&C) (Fatichi et al. 2012) were combined with field data. T&C resolves surface mass and energy budgets at the land surface at the hourly-scale accounting for soil moisture dynamics and biophysical/biochemical vegetation attributes coupled with modules to simulate plant phenology, carbon allocation, and tissue turnover (Fatichi et al. 2012, Fatichi and Ivanov 2014, Fatichi et al. 2016, Pappas et al. 2016, Fatichi and Pappas 2017, Mastrotheodoros et al. 2017). The existing T&C model version has been expanded to describe OP growth by including a time-variable crown area and OP allometric relations (see supplementary material available.
Figure 1. Comparison between simulated and observed latent heat fluxes (LE) at sites PSO (a), PA (b), and PTPN6 (c–f). See supplementary material for details on the study sites. The diurnal cycle of LE is shown in panels (a)–(c) (TOD = time of day). Average (blue) and standard deviation (red) of LE fluxes are calculated over the observational period. Colors in panels (d)–(f) indicate the density of observations (points per pixel). The correlation coefficient R is also shown in panels (d)–(f).

Model simulations were therefore run for each of the five OP sites considering (i) the existing OP cover with two possible ground covers, i.e. with or without understory, and (ii) a land cover representing a tropical forest, for a total of 15 model runs. Bare soil or herbaceous/leguminous/crop plants are generally maintained as ground covers below OP and both scenarios were therefore modeled here. In the vegetated understory scenario a tropical C4 grass (i.e. Brachiaria brizantha) was used. Although different species (e.g. Mucuna bracteata (Rutherford et al 2011)) can be employed as herbaceous ground cover, our choice is motivated by the availability of field observations needed to constrain model simulations (see supplementary material for details). The five analyzed sites have different soil and climate characteristics thus providing a general description of OP landscapes in the broader Southeast Asia region, where the highest density of OP plantations is observed (see figure S1 in the supplementary material). It has to be noted that peatland conditions and nutrient limitations were not considered in this study. However, the presence of peat mostly influences carbon stock changes and subsidence (Dislich et al 2017), the detailed modeling of which is beyond the scope of this study, while fertilizers are generally employed in large-scale plantations to ensure nutrient availability (Fowler et al 2011), so that considering OP in nutrient equilibrium is a reasonable assumption. Also, possible changes in soil hydraulic properties resulting from OP establishment and management (Dislich et al 2017) were neglected due to a lack of quantitative evidence (see discussion in section 4). Additional information on model equations, site characteristics and simulations setup are provided in the supplementary material.

3. Results

Model simulations successfully reproduce the observed daily and seasonal dynamics of water/energy fluxes of tropical forests, young, and mature OP (figure 1...
Figure 2. Rainfall (Pr), simulated evapotranspiration (ET) and runoff/recharge (R) at the Sangara site (Papua New Guinea) assuming a forest cover (a). Note that ET is plotted on top of R to illustrate the sum of the two. A rainfall threshold of 100 mm mo\(^{-1}\) is also shown (blue dashed line) to highlight dry periods (Pr < 100 mm mo\(^{-1}\)). Simulated changes in ET and R induced by OP establishment and development are shown in (b). OP growth is illustrated by modeled and observed LAI dynamics (data by Huth et al. (2014)). Simulation results for the case of OP with ground cover are shown. Additional information on the study site can be found in Huth et al. (2014) and the SI. Subscripts OP and F refer to oil palm and forest, respectively.

The results in figure 3 show that the impacts of OP on local climate and hydrology depend on plantation age and become less pronounced as plantations grow (Comte et al. 2012, Sabajo et al. 2017). Compared to forests, young plantations show low ET (−40% without understory, −20% when ground cover is considered), and increased recharge/runoff (up to 400% without understory, consistently with the changes in water yield reported in the literature Dislich et al. (2017)), while mature plantations increase ET up to 10% (figure 3(e)) thus reducing infiltration/runoff. This transition occurs at a plantation age of 8–9 yr, i.e. when plantations become mature and LAI reaches a plateau at values of 3–7 m\(^2\) m\(^{-2}\), and is consistent across sites/climates (figure 3). As a consequence of such age-related changes, the overall difference in the long-term water balance over the plantation lifecycle is small with cumulative changes in ET and R approaching zero at a plantation age of ∼20 yr (see supplementary material). Simulation results also confirm that OP plantations are susceptible to water stress (Carr 2011, Dislich et al. 2017) and a mean annual precipitation (MAP) of at least 2000–2500 mm spread evenly during the year (i.e. monthly precipitation >100 mm) is required to support OP productivity (Carr 2011) as illustrated by the decrease in LAI for lower MAP values (figure 2(b) and results in the supplementary material). ET fluxes by mature OP reach maximum values (up to 1800–2000 mm yr\(^{-1}\)) at MAP ∼2500 mm yr\(^{-1}\) and decrease linearly for drier conditions (−15% at a MAP of 1500 mm yr\(^{-1}\), see supplementary material). Forest ET is mostly lower than for mature OP but the water fluxes are sustained even during dry periods suggesting and supplementary material) as well as the long-term evolution of leaf area index (LAI), yield, and above ground biomass measured at the OP sites (figure 2 and supplementary material). The simulated hydrological regime of a tropical forest and the changes induced by OP establishment are illustrated in figures 2 and 3. After forest logging, OP establishment decreases ET due to the open canopy made of young and small palms (figure 2(b)). The reduction in ET increases the amount of rainfall that either infiltrates into the soil (recharge) or flows on the surface as excess water (runoff). While the ET reduction is rather evenly distributed across months, changes in runoff and recharge are concentrated in a few wet months and have larger magnitude. On average, simulated ET fluxes are between 1000–1600 mm yr\(^{-1}\) for young OP (age <5 yr) and 1200–1800 mm yr\(^{-1}\) for mature plantations (age >8 yr) with recharge+runoff (R) varying between 300 and 2800 mm yr\(^{-1}\) depending on the local rainfall regime (see supplementary material). Note that infiltration/runoff partitioning depends on soil hydraulic characteristics and catchment geomorphology (e.g. Ivanov et al 2004, Faticchi et al. 2014). Therefore, given the focus on plot-scale processes and the lack of knowledge on how soil properties change after forest conversion, recharge and runoff are here combined and illustrated together. However, monthly dynamics in figure 2 reveal that changes in recharge/runoff peak after very wet months, suggesting that both infiltration and saturation excess mechanisms may act to increase runoff, thus supporting the increased risk of flooding reported in the literature (Bradshaw et al. 2007, Dislich et al. 2017).
a higher tolerance to drought due to water access by deep roots (results shown in figures S10 and S12 in the supplementary material).

The fact that mature OPs transpire more water than native forests is directly linked to the high productivity of palms and the high fertilization rates at commercial plantations. At maturity, the GPP of OPs ranges between 3000 and 4400 gC m\(^{-2}\) per year, i.e. up to 25\% higher than forest (figure 3(c), (g)) and the fresh fruit bunch yield is between 20 and 40 t ha\(^{-1}\) (see supplementary material). However, the water use efficiency (WUE) is constrained between 2.2 and 3.2 gC m\(^{-2}\) mm\(^{-1}\), i.e. only 10\%–20\% increase with respect to forest (figure 3(g)), and the carbon-water trade-off of photosynthesis results in higher water losses. These changes in ET also affect the surface energy budget. Young plantations have lower latent heat (LE) and higher sensible heat (H) fluxes (see supplementary material), resulting in a higher surface temperature (+2–3 °C, figures 3(d), (h)) and a different partitioning of energy at the land surface (i.e. higher Bowen ratio, \(Bo = H/LE\)). Mature plantations show reversed conditions when compared to forests, with lower Bo and small changes in temperature (as also found by Sabajo et al (2017)).

Simulated changes during the initial stages of OP development are mitigated when ground cover is maintained (figure 3). Understory vegetation reduces the impact of young plantations on ET, recharge/runoff and temperature and maintains an overall higher GPP. C4 grasses have higher WUE and GPP than forests (e.g. Ludlow 1985, Wolf et al 2011) if water and nutrients are available. However, as OPs grow, competition for light and water significantly suppresses the vegetated ground cover which becomes negligible when OPs reach a mature state at LAI >5 m\(^{2}\) m\(^{-2}\).

4. Discussion

4.1. Impacts on water resources and microclimate

The ecohydrological impacts of forest conversion to OP are summarized in figure 4. Young plantations transpire less water than native forests, thus increasing surface temperature (+2 °C–3 °C), soil moisture and the risk of flooding. On the contrary, mature plantations increase ET fluxes (up to 10\%), reproducing a microclimate similar to forests (in terms of \(T_s\) as potential changes in air humidity are not modeled here) but depleting more water and thus reducing recharge/runoff. These results are consistent with field observations, e.g. Hardwick et al (2015) reported temperature changes up to +6.5 °C, Fowler et al (2011) and Meijide et al (2017) reported lower Bo in mature compared to young plantations, and Sabajo et al (2017) observed much higher surface temperatures in young plantations compared to forests (+6.0 ± 1.9 °C) but similar values in mature plantations (+0.8 ± 1.2 °C). The magnitude of the simulated impacts is also in agreement with variations in surface temperature observed at the global scale after changes in land use and land management (Luyssaert et al 2014). Our simulations confirm that: (i) impacts on surface climate are enhanced in young plantations (Luskin and Potts 2011) and (ii) this type of ecosystem functioning recovers as plantations mature (Dislich et al 2017). However, our results also corroborate local knowledge and perception of water scarcity reported in Indonesia and attributed to OPs, considered ‘water-greedy’ by farmers and villagers in OP-dominated landscapes (Merten et al 2016). The fact that cumulative changes in ET and R decrease with plantation age and become negligible over a plantation lifecycle should not be misleading since water run off in a
Further research should clarify possible implications of OP expansion on land-atmosphere interactions at the regional scale. In addition, the results here demonstrate that the current best practice of planting ground covers is a considerable mitigation option to reduce local warming, confirming the role of land management in regulating surface temperature (Davin et al. 2014, Luyssaert et al. 2014). Adopting sequential replanting rather than clear-cutting the entire plantation can also reduce negative hydrological and microclimatic effects by maintaining a range of palm ages (Luskin and Potts 2011). Our simulations corroborate the benefit of this practice also providing a quantification of its impact. However, the same practice can spread diseases and reduce agronomic efficiency prompting the need for a more extensive cost-benefit analysis (Luskin and Potts 2011).

### 4.2. Challenges and perspectives

In this study we have focused on OP temporal dynamics (i.e. growth, water consumption), assuming spatial homogeneity within large-scale plantations. Future studies need to focus on the role of spatial fragmentation (i.e. smallholder plantations) and heterogeneous OP age distributions across the landscape, as the role of spatial heterogeneities is largely unexplored and can likely contribute to mitigate impacts on the hydrological cycle. Nutrient limitation was also neglected in this study. This is a reasonable assumption for large-scale plantations but not in the case of smallholders where fertilization rates are often suboptimal and lower yields are obtained (Huth et al. 2014, Röll et al. 2015). This can explain the fact that ET rates slightly lower than forests were recently observed in mature smallholder-run plantations (Sabajo et al. 2017). Hence, the impact of different management practices (e.g. fertilization rates, large-scale plantations vs smallholders) on OP water consumption, surface energy fluxes, and changes in local microclimate need to be further investigated.

---

**Figure 4. Conceptual model of the ecohydrological changes induced by forest conversion to OP (considering large-scale plantations and full nutrient availability).** Replacing tropical forests (a) with OP plantations (b) impacts ecosystem carbon assimilation (CO$_2$) and evapotranspiration (H$_2$O) fluxes, surface temperature, atmospheric humidity (and potentially cloud formation mechanisms), aquifer recharge and surface runoff (with implications on the risk of flooding). Symbols within circles illustrate whether variables/fluxes increase (+), decrease (−), are unaltered (=) or can both increase and decrease (±). Question marks (?) highlight aspects not directly addressed by this study (i.e. impacts on surface water and soil hydraulic properties).
Furthermore, at the catchment scale, OP establishment can decrease infiltration (Merten et al. 2016) and aquifer recharge (Brujinzeel 2004, Dislich et al. 2017), concurrently increasing the risk of floods (Bradshaw et al. 2007) and erosion (Guillaume et al. 2015). The deep recharge/fast runoff partition largely depends on catchment geomorphology and soil hydraulic characteristics (Dislich et al. 2017), which could not be fully accounted for in the plot scale analysis here. Similarly, it has been shown that different management strategies and soil compaction due to mechanical clearing can alter soil physical characteristics and reduce infiltration (Brujinzeel 2004, Matthews et al. 2010, Moradi et al. 2015, Dislich et al. 2017), but the relevant changes in hydraulic properties are still poorly quantified, prompting the need for further field investigations. With regard to the effect of the ground cover, we have considered a tropical C4 grass for the sake of convenience, but different crops and herbaceous species are often employed. According to a survey by Rutherford et al. (2011), planting of a cover crop is a common management strategy in Southeast Asia. When the ground cover is maintained, a mixture of legume (e.g. *Mucuna bracteata*) and grass species is often used (Rutherford et al. 2011, Huth et al. 2014) as nitrogen-fixing leguminous plants can improve soil fertility (Dislich et al. 2017). However, targeted data are needed to assess the differential capabilities of understory species to regulate local microclimate, increase infiltration, and reduce soil erosion (Dislich et al. 2017).

4.3. Broader impact

Over the last decade oil palm expansion has partly shifted from forested to non-forested lands providing an opportunity for increasing sustainability (Gaveau et al. 2016, Furumo and Aide 2017). In Indonesia, the proportion of OP plantations directly replacing forests declined from 54%–18% between the 1995–2000 and 2010–2015 (Austin et al. 2017) and 79% of OP expansion in Latin America occurred on previously cleared land (Furumo and Aide 2017). Such a transition from non-forested land to OP seems promising for a sustainable development of OP, but a cautious assessment and management of water resources is still needed. Hence, while more research is required to understand the ecohydrological impacts of different land cover transitions to OP (e.g. pastures, croplands, savannas), our results highlight the importance of including water resources in the debate on OP sustainability and foreshadow the key role of water availability in constraining OP plantations expansion across the tropics.

More generally, given the ‘hybrid’ socio-natural dimension of water (Linton and Budds 2014, Merten et al. 2016), the impact of OP expansion goes beyond the biophysical dimension illustrated here and is directly linked to population dynamics, social inequality issues, technological development and market regulation (Yan 2017, De Pinto et al. 2017). Despite the local awareness, OP water requirements have been marginalized or neglected in the OP controversy, which mostly focused on carbon emission mitigation and biodiversity conservation (Sayer et al. 2012, Larsen et al. 2014). However, large scale land acquisitions can potentially drive groundwater depletion and streamflow reduction (Merten et al. 2016, Dalin et al. 2017), which we could quantify as remarkable. Hence, there is a need to integrate ecohydrological studies with participatory approaches (e.g. Castelletti and Soncini-Sessa 2006, Étienne 2013) to model the coupled ‘hydrosocial cycle’ (Linton and Budds 2014) and support sustainable development of OP landscapes by quantifying the trade-offs among different management alternatives.

5. Conclusion

In conclusion, this study provides a comprehensive quantitative understanding of the ecohydrological changes occurring in OP landscapes from forest logging to OP establishment, growth and maturity. Specifically, our results show the key role of plantation age in regulating ecosystem functioning. Young plantations cause surface warming (+2°C–3°C) and increase the risk of flooding while mature plantations restore local climate but consume more water (+3%–8%) than the forests they have replaced. Thus, the ‘allegedly high water use’ of OP (Merten et al. 2016) is here confirmed by process-based ecohydrological simulations, demonstrating that the high land use efficiency of OP comes at the expense of water consumption in a trade of ‘water for carbon’ (Jackson et al. 2005) that, in the long term, may jeopardize local water resources. The practices of retaining old palms during crop rotation and cultivating ground cover crops can mitigate some of the impacts and are recommended to support water/climate regulation in OP-dominated landscapes.

Acknowledgments

This study was supported by the Swiss National Science Foundation grant no. 152019 (r4d - Ecosystems ‘Oil Palm Adaptive Landscapes’. AM and AK were supported by the Deutsche Forschungsgemeinschaft (DFG) in the framework of the collaborative German-Indonesian research project CRC990 - EFForTS. The authors confirm that they have no interest or relationship, financial, or otherwise that might be perceived as influencing objectivity with respect to this work.

ORCID iDs

Gabriele Manoli © https://orcid.org/0000-0002-9245-2877
References

Austin K, Mosnier A, Pirker J, McCallum I, Fritz S and Kasibhatla P 2017 Shifting patterns of oil palm driven deforestation in Indonesia and implications for zero-deforestation commitments Land Use Policy 69 41–8

Bonetti S, Manoli G, Domec J-C, Putti M, Marani M and Katul G G 2015 The influence of water table depth and the free atmospheric state on convective rainfall predisposition Water Resour. Res. 51 2283–97

Bradshaw C, Ijodi N S, Peh K S-H and Brook B W 2007 Global evidence that deforestation amplifies flood risk and severity in the developing world Glob. Change Biol. 13 2379–95

Bruinjzed L A 2004 Hydrological functions of tropical forests: not seeing the forest for the trees! Agric. Ecosyst. Environ. 104 185–228

Carlson K M, Curran L M, Asner G P, Pittman A M, Trigg S N and Adeney J M 2013 Carbon emissions from forest conversion by Kalimantan oil palm plantations Nat. Clim. Change 3 283

Carlson K M, Curran L M, Pomette-González A, G, Ratnasari D, Lisnawati N, Purwanto Y, Brauman K A and Raymond P A 2014 Influence of watershed-climate interactions on stream temperature, sediment yield, and metabolism along a land use intensity gradient in Indonesian Borneo J. Geophys. Res. Biogeosci. 119 1110–28

Carr M 2011 The water relations and irrigation requirements of oil palm (Elaeis Guineensis): a review Exp. Agric. 47 629–52

Castelletti A and Soncini-Sessa R 2006 A procedural approach to strengthening integration and participation in water resource planning Environ. Model. Softw. 21 1455–70

Clark D E, Asao S, Fisher R, Reed S, Reich P B, Ryan M G, Wood T E and Yang X 2017 Field data to benchmark the carbon-cycle models for tropical forests Biogeosci. Discuss. 14 4663–90

Combes J-C, Pallás B, Rouan L, Milet-Serra I, Caliman J-P, Bracconnier S, Soubie J-C and Dingkuhn M 2013 Simulation of inflow sensitivity dynamics in oil palm and estimation of environment-sensitive phenological phases: a model based analysis Funct. Plant Biol. 40 263–79

Comite I, Colin F, Whalen J K, Grünberger O and Caliman J-P 2012 Agricultural practices in oil palm plantations and their impact on hydrological changes, nutrient fluxes and water quality in Indonesia: a review Adv. Agron. 116 71

Dalín C, Wada Y, Kastner T and Puma M J 2017 Groundwater depletion embedded in international food trade Nature 543 700–4

Davin E L, Seneviratne S I, Ciais P, Olioso A and Wang T 2014 Preferential cooling of hot extremes from cropland albedo management Proc. Natl Acad. Sci. 111 9575–61

De Piento A, Wiebe K and Pacheco P 2017 Commerce: help bigger PALMSIM: model description, evaluation and application J. Adv. Model. Earth Syst. 12 204008

Fatichi S, Leuzinger S, Paschalis A, Langley J A, Barracough A D and Hofmann M 2017 Constrained variability of modeled T:ET ratio across biome Geophys. Res. Lett. 44 6795–803

Fatichi S, Zeeman M J, Fuhrer J and Burlando P 2014 Ecophysiological effects of management on subalpine grasslands: from local to catchment scale Water Resour. Res. 50 148–64

Fowler D et al 2011 Effects of land use on surface-atmosphere exchanges of trace gases and energy in Borneo: comparing fluxes over oil palm plantations and a rainforest Phil. Trans. R Soc. B 366 3199–209

Gaveau D L, Sheil D, Salim M A, Arasakasuma S, Ancrenaz M, Pacheco P and Mejiaard E 2016 Rapid conversions and avoided deforestation: examining four decades of industrial plantation expansion in Borneo Sci. Rep. 6 32017

Gavazzoni T, Paris M and Kukuzakov Y 2015 Losses of soil carbon by converting tropical forest to plantations: erosion and decomposition estimated by 613c Glob. Change Biol. 21 3548–60

Hardanto A et al 2017 Oil palm and rubber tree water use patterns: effects of topography and flooding Front. Plant Sci. 8 452

Hardwick S R, Touri M, Pfeiffer M, Turner E C, Ewers R M, Donough C and Whitbread A 2014 Simulating potential growth and yield of oil palm (Elaeis guineensis) with PALM/MSM: model description, evaluation and application Agric. Syst. 131 1–10

Huth N I, Banabas M, Nelson P N and Webb M 2014 Development of an oil palm cropping systems model: lessons learned and future directions Environ. Model. Softw. 62 411–9

Ivanov V Y, Hutrya L R, Wofsy S C, Munger J W, Saleska S R, Oliveira R C and Camargo P B 2012 Root niche separation can explain avoidance of seasonal drought stress and vulnerability of overstory trees to extended drought in a mature amazonian forest Water Resour. Res. 48 W12507

Ivanov V Y, Wofsy S C, Bras R L and Entekhabi D 2004 Catchment hydrologic response with a fully distributed triangulated irregular network model Water Resour. Res. 40 W11102

Jackson R B, Jobbágy E G, Avissar R, Roy S B, Barrett D J, Cook C W, Farley K A, Le Maitre D C, McCarthy B A and Murray B C 2005 Trading water for carbon with biological carbon sequestration Science 310 1944–7

Koh L P, Miettinen J, Liew S C and Ghazoul J 2011 Remotely sensed evidence of tropical peatland conversion to oil palm Proc. Natl Acad. Sci. 108 5127–32

Koh L P and Wilcove D S 2008 Is oil palm agriculture really destroying tropical biodiversity? Conserv. Lett. 1 160–4

Kotowska M M, Leuschner C, Triadati T, Meriem S and Hertl D 2015 Quantifying above- and belowground biomass carbon loss with forest conversion in tropical lowlands of Sumatra (Indonesia) Glob. Change Biol. 21 3620–34

Kumaresan T, Karanam H and Yasumoto T 2013 Deforestation-induced reduction in rainfall Hydro. Process. 27 3811–44

Larsen R K, Jiwan N, Rompas A, Jenito J, Osbeck M and Tarigan A 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
Linton J and Budds J 2014 The hydrosocial cycle: defining and mobilizing a relational-dialectical approach to water Geoforum 57 170–80
Liu W, Wu J, Fan H, Duan H, Li Q, Yuan Y and Zhang H 2017 Estimations of evapotranspiration in an age sequence of eucalyptus plantations in subtropical china PLoS ONE 12 e0174208
Ludlow M 1985 Photosynthesis and dry matter production in C3 and C4 pasture plants, with special emphasis on tropical C3 legumes and C4 grasses Aust. J. Plant Physiol. 12 557–72
Luskin M S and Potts M D 2011 Microclimate and habitat heterogeneity through the oil palm lifecycle Basic Appl. Ecol. 12 540–51
Luysseert S et al 2014 Land management and land-cover change have impacts of similar magnitude on surface temperature Nat. Clim. Change 4 389–93
Maier C A, Albough T J, Cook R I, Hall K, McNinis D, Johnsen K H, Johnson J, Rubilar R A and Vose J M 2017 Comparative water use in short-rotation Eucalyptus benthamii and Pinus Taeda trees in the southern United States Forest Ecol. Manage. 397 128–38
Manodi G, Christoffersen B, Ivanov V Y and Fatichi S 2018 Dry season greening and water stress in Amazonia: the role of modeling leaf phenology J. Geophys. Res.: Biogeosci. in press
Manodi G, Domec J-C, Novick K, Oishi A C, Noormets A, Marani M and Katul G 2016 Soil-plant-atmosphere conditions regulating convective cloud formation above southeastern US pine plantations Glob. Change Biol. 22 2338–54
Mastrotheodoros T, Pappas C, Molnar P, Burlando P, Keenian T F, Gentine P, Gough C M and Fatichi S 2017 Linking plant functional trait plasticity and the large increase in forest water use efficiency J. Geophys. Res. Biogeosci. 122 2393–408
Matthews G, Laudome G, Gregory A, Bird N, Matthews A and Whalley W 2010 Measurement and simulation of the effect of compaction on the pore structure and saturated hydraulic conductivity of grassland and arable soil Water Resour. Res. 46 W01501
Meijide A, Badu C S, Moyano F, Tiralla N, Gunawan D and Knoll A 2018 Impact of forest conversion to oil palm and rubber plantations on microclimate and the role of the 2015 enso event Agric. Forest Meteorol. 252 208–19
Meijide A, Roll A, Fan Y, Herbst M, Niu F, Tiedemann F, June T, Rauf A, Holscher D and Knoll A 2017 Controls of water and energy fluxes in oil palm plantations: environmental variables and oil palm age Agric. Forest Meteorol. 239 71–85
Mertan J et al 2016 Water scarcity and oil palm expansion: social views and environmental processes Ecol. Soc. 21 5
Moradi A, Sung C T B, Goh K J, Hamif A H M and Ishak C F 2015 Effect of four soil and water conservation practices on soil physical processes in a non-terraced oil palm plantation Soil Tillage Res. 145 62–71
Neelin J D, Männrich M, Su H, Meyerson J E and Holloway C E 2006 Tropical drying trends in global warming models and observations Proc. Natl Acad. Sci. 103 6110–5
Novick K A et al 2016 The increasing importance of atmospheric demand for ecosystem water and carbon fluxes Nat. Clim. Change 6 1023–27
Okoro S U, Schickhoff U, Boehner J, Schneider U A and Huth N 2017 Climate impacts on palm oil yields in the Nigeran Niger Delta Eur. J. Agron. 85 38–50
Pappas C, Fatchi S and Burlando P 2016 Modeling terrestrial carbon and water dynamics across climatic gradients: does plant trait diversity matter? New Phytol. 209 137–51
Pardon L, Huth N I, Nelson P N, Banabas M, Gabrielle B and Bessou C 2017 Yield and nitrogen losses in oil palm plantations: main drivers and management trade-offs determined using simulation Field Crops Res. 210 28–32
Pirker J, Mosnier A, Krauzer F, Havlík P and Obersteiner M 2016 What are the limits to oil palm expansion? Glob. Environ. Change 40 73–81
Restrepo-Coupe N et al 2017 Do dynamic global vegetation models capture the seasonality of carbon fluxes in the amazon basin? A data-model intercomparison Glob. Change Biol. 23 191–208
Röll A et al 2015 Transpiration in an oil palm landscape: effects of palm age Biogeosciences 12 5619–33
Rutherford M, Flood J and Sastroutomo S 2011 Roundtable for sustainable palm oil (RSPO): research project on integrated weed management strategies for oil palm Final Report (www.rspo.org/file/RSPO%20IWM_FINAL%20REPORT%20e0159668 200%20RSP%20) 209 205
Sabajo C R, le Maire G, June T, Meijide A, Roupsard O and Knoll A 2017 Expansion of oil palm and other cash crops causes an increase of land surface temperature in Indonesia Biogeosci. Discuss. 2017 1–43
Sayer J, Ghazoul J, Nelson P and Boedhihartono A K 2012 Oil palm expansion transforms tropical landscapes and livelihoods Glob. Food Secur. 1 114–9
Shay E G 1993 Diesel fuel from vegetable oils: status and opportunities Biomass Bioenergy 4 227–42
van Kraalingen D, Breure C and Spitters C 1989 Simulation of oil palm growth and yield Agric. Forest Meteorol. 46 227–44
Vijay V, Pimm S L, Jenkins C N and Smith S J 2016 The impacts of oil palm on recent deforestation and biodiversity loss PLoS ONE 11 e0159668
Wahid M B, Abdullah S N A and Henson I E 2005 Oil Palm oil palm—achievements and potential Plant Prod. Sci. 8 288–97
Wolf S, Eugster W, Potvin C, Turner B L and Buchmann N 2011 Carbon sequestration potential of tropical pasture compared with afforestation in Panama Glob. Change Biol. 17 2763–80
Wu J et al 2016 Leaf development and demography explain photosynthetic seasonality in amazon evergreen forests Science 351 972–6
Yan W 2017 A makeover for the world’s most hated crop Nature 543 306–8