CHANGES IN ECO-HYDROLOGICAL FUNCTIONING AFTER TROPICAL RAINFOREST TRANSFORMATION TO RUBBER AND OIL PALM PLANTATIONS

Dissertation
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Zusammenfassung

Dieser Arbeit bündelt die Ergebnisse ökohydrologischer Forschung in Jambi, Sumatra, Indonesien, die im Rahmen des SFB990 (Sub-Projekt A02) durchgeführt wurden. Sie deuten auf substanzielle Veränderungen zentraler Ökosystemwasserflüsse nach der Transformation tropischer Regenwälder zu monokulturellen Plantagen hin. Dies beeinflußt die Verfügbarkeit von Wasser in der Landschaft und hat somit auch Auswirkungen auf das Wohlbefinden ruraler Bevölkerungen. Generell kann die Transformation von Regenwäldern in landwirtschaftliche Systeme lokale und regionale Wasserkreisläufe verändern. Transpiration, also der Wasserverbrauch durch Pfanzen, ist eine zentraler Prozess des Wasserkreislaufs und für Rückkopplungsmechanismen zwischen Biosphäre und Atmosphäre. Im Amazonas führten deutliche Reduktionen der Land-Atmosphäre-Wasserflüsse nach der Transformation von Regenwäldern zu Weideland beispielsweise zu Veränderungen in Niederschlagszyklen. Der derzeitige ‘Hot-Spot’ solcher Transformationsprozesse ist der ‘Maritime Kontinent’ Indonesiens. Im Gegensatz zu Transformationsprozessen im Amazonasgebiet zu Weideland oder Sojaplantagen werden die Regenwälder Indonesiens überwiegend in Kautschukbaum (*Hevea brasiliensis* Müll.) und Ölpalm (*Elaeis guineensis* Jacq.) Monokulturen umgewandelt. Dazwischen verbleiben vereinzelte traditionelle agroforstliche Systeme in der Landschaft (z.B. sog. ‘Jungle Rubber’); sie sind ein potentieller Hoffnungträger hinsichtlich der Synthese ökologischer und ökonomischer Aspekte. In den ‘maritimen’ Tropen wurden die ökohydrologischen Auswirkungen von Regenwaldtransformationsprozessen zu den dominanten Landnutzungssystemen (also Kautschuk und Ölpalme) bislang nicht hinreichend erforscht.

Um Veränderungen in der Magnitude sowie in der räumlichen und zeitlichen Variabilität des zentralen Ökosystemwasserflusses Transpiration zu analysieren, untersuchten wir gleichzeitig vier tropische Tiefland Landnutzungssysteme in Jambi, Indonesien, mit einer Saftflussmessungsmethode. 39 Probeflächen waren auf Referenzflächen im Regenwald, ‘Jungle Rubber’ Agroforsten sowie Kautschuk- und Ölpalmplantagen verteilt. Die Ziele dieser Arbeit waren (1) eine häufig benutze Saftflussmessungsmethode für Messungen an verschiedenen Arten in der tropischen Tieflandforschungsregion zu verifizieren oder falls nötig anzupassen, (2) die bislang überwiegend unbekannten Wassernutzungscharakteristia von Ölpalmen als einer global rapide expandierenden Plantagenart zu erforschen, und (3) die ökohydrologischen Auswirkungen der fortschreitenden ‘maritimen’ Regenwaldtransformationsprozesse zu monokulturellen Plantagen zu beurteilen.

Zuerst wurde eine häufig angewandte Saftflussmessungsmethode, die sog. ‘Thermal Dissipation Probe’ (TDP) Methode, getestet und für Messungen an verschiedenen tropischen Arten angepasst. Experimente bestätigten, dass die Methode für Messungen an bisher nicht untersuchten Arten kalibriert werden sollte. Mit der originalen Gleichung der TDP Methode (Granier 1985) wurden

im Vergleich mit gravimetrischen Referenzmessungen gute Schätzungen für Messungen an Bäumen erreicht (u.a. auch an Kautschuk), doch bei der Applikation der Methode an Ölpalmblattstielen wurden systematische Unterschätzungen festgestellt. Wir leiteten folglich neue, ölpalmspezifische Parameter für die TDP Gleichung ab. Nach extensiven Saftflussmessungen an 56 Ölpalmblättern konnten wir ausserdem ein System vorschlagen, um relativ präzise Schätzungen für die Bestandestranspiration und auch eine Abschätzung möglicher Ungenauigkeiten der Schätzung zu erhalten. Analytisch hergeleitete, statistisch 'optimale' Probegrößen waren ein Minimum von 13 Ölpalmblättern an vier verschiedenen Palmen in einem unstratifizierten Probeverfahren; der resultierende potentielle Messfehler der Bestandestranspiration (aufgrund limitierter Probegröße) war 13%. In den drei anderen, 'baum-dominierten' Landnutzungssystemen maßen wir Saftfluss im Norden und Süden von mindestens sechs (Kautschuk Monokultur) bzw. acht (Wald und 'Jungle Rubber') Stämmen pro Probefläche; diese Probegrößen führten zu potentiellen Messungenauigkeiten von <10% bzw. bis zu 35%.

Als nächsten Schritt nutzten wir das beschriebene Messsystem für Ölpalmen, um die bislang relativ unbekannten Wassernutzungscharakteristika von Ölpalmen näher zu erforschen. Wir untersuchten die Effekte von Bestandescharakteristika auf die Bestandestranspiration entlang eines Altersgradienten in 15 Ölpalm Plantagen in Jambi, Indonesien. Von einem Plantagenalter von zwei bis fünf Jahren erhöhte sich die Bestandestranspiration um mehr als das Achtfache, blieb dann aber mit weiter steigendem Plantangenalter relativ konstant. Die Variabilität der Bestandestranspiration zwischen mittel-alten Plantagen war sehr ausgeprägt. Andere Wasserflüsse als Transpiration (z.B. Evaporation) leisteten einen starken und variablen Beitrag zur Gesamtevapotranspiration (von Eddy Covariance Messungen abgeleitet); ein mehr als zwölffacher Unterschied zwischen den Beständen mit der niedrigsten bzw. der höchsten Transpiration wurde so zu einem weniger als zweifachem Unterschied in Evapotranspiration reduziert. Unsere Ergebnisse legen nahe, dass sowohl Transpiration als auch Evapotranspiration von Ölpalmplantagen unter bestimmten Standorts- oder Managementbedingungen sehr hoch sein können (d.h. so hoch wie z.B. von Regenwäldern).

Relativ hohe Wassernutzungsraten von Ölpalmplantagen wurden auch durch einen Vergleich von 32 Probeflächen in vier verschiedenen Landnutzungstypen (Regenwald, 'Jungle Rubber' Agroforsten, Kautschuk- und Ölpalmplantagen) bestätigt. Die Bestandestranspiration von Kautschukplantagen lag weit unter der von Regenwäldern und 'Jungle Rubber', u.a. auch wegen saisonalen Laubabwurfs. Die Bestandestranspiration von Ölpalmplantagen war hingegen fast so hoch wie in den 'natürlicheren' Landnutzungssystemen, obwohl z.B. die Biomasse pro Hektar viel niedriger ist als in Regenwäldern. Ausserdem erschien die Variabilität der Ölpalmtranspiration von Tag zu Tag 'gepuffert', d.h. selbst ausgeprägte Schwankungen mikrometereologischer Bedingungen resultierten in relativ geringen Schwankungen der Ölpalmbestandestranspiration.

Die ausgeprägten Unterschiede in den ökohydrologischen Charakteristika zwischen Ölpalm- und Kautschukplantagen spielen eine wichtige Rolle bei der Erklärung periodisch auftretender, lokaler Wasserknappheit in Ölpalm dominierten Landschaften, auf welche z.B. von Dorfbewohner während einer qualitativen sozialen Studie in Jambi hingewiesen wurde. Bodenerosion und somit auch Reduktionen in der Infiltrationskapazität der Böden waren von ähnlichem Ausmaß in Kautschuk- und Ölpalmplantagen; somit waren die Wasserverluste aus der Landschaft durch Oberflächenabfluss nach Niederschlägen in beiden monokulturellen Landnutzungssystemen hoch. Im Gegensatz zu Kautschuk- hatten Ölpalmplantagen jedoch relative hohe Wassernutzungsraten. In Kombination mit der reduzierten Wasserspeicherkapazität der erodierten Böden unter Ölpalmen kann dieser relative hohe Wasserverbrauch zu Wasserknappheit in Trockenphasen führen, d.h. zu niederigen Fluss- und Grundwasserpegeln in von der Ölpalme dominierten Landschaften. Unsere Ergebnisse deuten somit auf potentiell schwerwiegende und bisher vernachlässigte hydrologische Auswirkungen der anhaltenden ‘maritimen’ Regenwaldtransformation zu Monokulturen hin, besonders im Falle der Transformation zu Ölpalmplantagen.

Abstract

This work presents findings from eco-hydrological research carried out in Jambi, Sumatra, Indonesia in the framework of the CRC990 (Sub-Project A02). Our results point to substantial changes in central ecosystem water fluxes after tropical rainforest transformation to monoculture plantations, which affects the availability of water at the landscape scale and thus impacts on the well-being of rural communities.

Rainforest transformation to agricultural systems is generally expected to alter ecosystem water cycles at local and regional scales. Transpiration, i.e. water use by plants, is central to the hydrological cycle and biosphere-atmosphere feedback mechanisms. In Amazonia, e.g., substantial reductions in land-atmosphere water fluxes after large-scale rainforest transformation to pasture altered precipitation patterns. The hot spot of current rainforest transformation is the ‘Maritime Continent’ of Indonesia. In contrast to Amazonian rainforest transformation to pasture or soy-bean, rainforests in Indonesia are largely being transformed to rubber (*Hevea brasiliensis* Müll.) and oil palm (*Elaeis guineensis* Jacq.) monocultures. Scattered in between, locally some traditional agroforestry systems (e.g. ‘jungle rubber’) remain in the landscape. They are considered a glimmer of hope regarding the balancing of economics and ecosystem services. For the ‘maritime’ tropics, eco-hydrological consequences of rainforest transformation to the prevalent productive systems (i.e. oil palm and rubber) have not yet been convincingly addressed.

To assess changes in the magnitude of the central water flux of stand transpiration as well as in its spatial and temporal variability after rainforest transformation, we simultaneously studied four tropical lowland land use types in Jambi, Indonesia with a sap flux technique. Our 39 study sites were located in reference forests, ‘jungle rubber’ agroforests and rubber and oil palm monocultures. The main objectives were (1) to verify and if necessary adjust a broadly used sap flux technique for measurements on different species in a lowland landscape in Jambi, Indonesia, (2) to shed first light on the thus far relatively unknown water use characteristics of oil palm as a globally rapidly expanding crop species, and (3) to assess the consequences of the continuing ‘maritime’ rainforest transformation to monoculture plantations for landscape-scale eco-hydrological functioning.

First, a commonly applied sap flux technique, the thermal dissipation probe method (TDP, Granier 1985), was tested and adjusted for measurements on several tropical monocot and dicot species. Experiments confirmed that the method should be calibrated when working on previously unstudied (monocot) species. Using the original Granier calibration equation, good agreement was found between TDP derived water use rates and reference gravimetric measurements for four tropical tree species including rubber, but substantial deviations became apparent for oil palm leaves. We thus derived new, oil-palm specific parameters for the TDP calibration equation. Based on sap flux measurements on 56 leaves on ten oil palms, we derived a sampling scheme for

soundly estimating stand-level transpiration rates of oil palms including error margins. Statistically-derived ‘optimal’ sample sizes suggest measurements on a per-site minimum of 13 leaves on four different palms in an un-stratified scheme, which results in sample-size related estimation errors of stand transpiration of 13%. In tree based land use types, we measured sap flux in the North and South of the trunks of six (rubber) and eight trees (jungle rubber, forest) per site, which was associated with potential estimation errors of less than 10% and up to 35%, respectively.

We subsequently focused on investigating the thus far little explored eco-hydrological characteristics of oil palms with the newly-established measurement scheme. We studied effects of stand characteristics on transpiration along an age gradient in 15 oil palm plantations in Jambi, Indonesia. Stand transpiration rates increased almost eight-fold from an age of two to an age of five years and then remained constant with further increasing age, but were highly variable among medium-aged oil palm plantations. Other water fluxes than transpiration (e.g. evaporation) contributed substantially and variably to evapotranspiration (eddy covariance derived), reducing a 12-fold difference between the stands transpiring at the lowest and highest rates, respectively, to a less than two-fold difference in evapotranspiration. Our results suggest that both transpirational and total evapotranspirational water fluxes from oil palm plantations can be substantial (i.e. as high as from rainforests) under certain site or management conditions.

Relatively high water use rates of oil palm plantations were confirmed by an assessment of sap flux derived transpiration rates of 32 sites in four land use types in Jambi (forest, jungle rubber, rubber, oil palm). Stand transpiration rates of rubber plantations were much lower than those of rainforests and jungle rubber agroforests, partly due to (partial) leaf shedding. Oil palm transpiration, on the other hand, was almost as high as in the more ‘natural’ land use types despite e.g. a much lower biomass per hectare than in forests. Additionally, the transpirational day-to-day response of oil palm was ‘buffered’ compared to tree based land use types, i.e. even pronounced fluctuations in micrometeorological conditions resulted in relatively low temporal heterogeneity of oil palm transpiration rates.

The pronounced differences in eco-hydrological characteristics that we observed between oil palm and rubber plantations were found to play a key role in explaining periodically occurring local water scarcity in oil palm dominated landscapes, as was reported by villagers in a qualitative social study in Jambi. Soil erosion and thus reductions in soil water infiltration capacity were similar in oil palm and rubber plantations; landscape-scale water losses by run-off after pronounced precipitation were thus high in both plantation types. In contrast to rubber, however, oil palms had relatively high water use rates and transpired relatively constantly despite fluctuating environmental conditions. Paired with the reduced water storage capacity of the eroded soils under oil palms, their relatively high water use can lead to local water scarcity during pronounced dry periods, i.e. low streamflow and groundwater levels in oil palm dominated landscapes. Our work thus points to potentially severe and thus far neglected social- and eco-hydrological consequences of ‘maritime’ rainforest transformation to monoculture plantations, particularly in the case of transformation to oil palm.

Table of Contents

Chapter 1: Introduction

1.1 Hydrological consequences of rainforest transformation

Rainforest transformation to agricultural systems alters ecosystem water cycles at local and regional scales (Aragoa 2012). Transpiration, i.e. water use by plants, is central to the hydrological cycle and biosphere-atmosphere feedback mechanisms (Jasechko et al. 2013). E.g., in Amazonia substantial reductions in land-atmosphere water fluxes after large-scale rainforest transformation to pasture ultimately altered regional precipitation patterns (Zhang et al. 2001, Brown et al. 2005, Sampaio et al. 2007, Aragoa 2012). Currently, the hot spot of (lowland) rainforest transformation is the 'Maritime Continent' of Indonesia (Hansen et al. 2013, FAO 2015). In contrast to the transformation of Amazonian rainforests to pasture or soy-bean (Sampaio et al. 2007, Barona et al. 2010), rainforests in Indonesia are largely being transformed to rubber tree (*Hevea brasiliensis* Müll.) and oil palm (*Elaeis guineensis* Jacq.) monocultures (Koh and Wilcove 2008, Carlson et al. 2012, FAO 2015). Scattered in between these highly productive agricultural systems, locally some traditional agroforestry systems (e.g. 'jungle rubber') remain in the landscape (Ekadinata and Vincent 2011). They are considered a glimmer of hope in the context of balancing economics and ecosystem services (Wibawa et al. 2005, Shibu 2009). Reported losses in ecosystem functioning after large-scale rainforest transformations to monoculture oil palm and rubber plantations (e.g. Barnes et al. 2015, Guillaume et al. 2015) may also include changes in hydrological functioning (e.g. Ziegler 2009, Comte et al. 2012).

Loss of tropical rainforest cover is often associated with a loss of the hydrological 'sponge' effect of rainforests (e.g. Malmer et al. 2010) due to erosion-induced soil degradation (e.g. de Blécourt et al. 2013, Gharibreza et al. 2013, Chiti et al. 2014, Guillaume et al. 2015), which can result in decreased soil water infiltration and storage capacities in transformed landscapes (e.g. Malmer and Grip 1990, Bruijnzeel 2004, Ilstedt et al. 2007, Yimer et al. 2008). According to the 'infiltration-(evapo)transpiration trade off hypothesis' (Bruijnzeel 1989, 2004, Krishnaswamy et al. 2013), on the landscape scale, the hydrologic net effect of rainforest transformation depends on the magnitude of (evapo)transpirational fluxes from the land use type replacing the forest. It is often much lower than in forests (e.g. Zhang et al. 2004), which consequently leads to increased run-off from some transformed landscapes (e.g. Aragao 2012). However, high evapotranspiration from transformed landscapes as e.g. reported for some tropical tree plantations (e.g. Calder et al. 1992, Tan et al. 2011) paired with the mentioned soil degradation after forest conversion can e.g. lead to significantly reduced (dry season) streamflow from transformed landscapes (e.g. Bruijnzeel 2004, Krishnaswamy et al. 2013). Stand evapotranspiration and particularly transpiration as the component that can directly be influenced by management (i.e. choice of land cover) thus play a key role in determining consequences of rainforest transformation on landscape-scale water cycling (e.g. Bruijnzeel 2004, Jasechko et al. 2013).

In contrast to pasture and soy bean in Amazonia, the mentioned ‘maritime’ rubber and oil palm transformation systems have a ‘forest-like’ stand structure. As first put forward by Roberts (1983), transpiration is a rather conservative process for such ecosystems. Accordingly, similar stand transpiration estimates have been presented for several tree-based tropical land use systems, e.g. cacao agroforest, bamboo and reforestation stands (Dierick and Hölscher 2009, Köhler et al. 2009, Kunert et al. 2010, Dierick et al. 2010, Komatsu et al. 2010, Köhler et al. 2013). First available estimates for oil palm plantations in South East Asia suggest a similar magnitude of land-atmosphere water fluxes as e.g. reported for tropical rainforests in the region (Tani et al. 2003, Henson and Harun 2005, Kumagai et al. 2005, Yusop et al. 2008). However, severe changes in landscape-scale hydrological functioning after rainforest transformation to oil palm plantations (e.g. periodic local water scarcity) have recently been reported (Obidzinski et al. 2012, Larsen et al. 2014). Also, reported land-atmosphere water fluxes from rubber plantations on the Asian mainland even exceed those of natural forests (Tan et al. 2011). Such high (evapo)transpirational water fluxes from transformed landscapes can potentially result in severe negative impacts on essential hydrological ecosystem services, e.g. periodically reduced (dry season) streamflow and ground water discharge (Bruijnzeel 1989, 2004, Ziegler 2009). However, for the ‘Maritime Continent’ eco-hydrological consequences of rainforest transformation to the prevalent productive agricultural systems (i.e. oil palm and rubber monocultures) remain largely unknown. Currently available studies for the greater region (i.e. South East Asia) encompass a variety of methodological approaches and varying climatic regimes; deriving over-arching scientific conclusions is further often hindered by a lack of sufficient spatial replication and reference systems (see e.g. review in Comte et al. 2012).

Generally, (changes in) certain or total land-atmosphere water fluxes can be assessed with a variety of methods, from the leaf to the global level (Wilson et al. 2001). To derive total evapotranspirational water fluxes of a given ecosystem, approaches operating at the stand-level (e.g. eddy covariance technique, Baldocchi 2003) or above (e.g. catchment-based approaches, Ford et al. 2007) are often employed. For deriving (stand) transpiration rates, sap flux techniques are commonly applied; they provide estimates of plant water use at relatively high spatial and temporal resolution (Lu et al. 2004). The thermal dissipation probe (TDP, Granier 1985) method is a frequently applied and reliable method to estimate whole-plant water use rates based on sap flux density measurements; the relatively low cost of the method allows for a high number of spatial replicates within- and between stands (Lu et al. 2004). However, the empirically-derived nature of the TDP method makes it necessary to confirm or re-calibrate the original sap flux equation (Granier 1985) when working with previously unstudied species (see review in Vandegehuchte and Steppe 2013); also, the process of extrapolating from point sap flux measurement to the water use of a whole stand demands for an appropriate sampling scheme that quantifies and minimizes estimation errors, e.g. associated with limited sample size (e.g. Kume et al. 2010). While information for many (tropical) dicot and some monocot species is available (e.g. Granier et al. 1996, Kallarackal et al. 2013), no studies have thus far dealt with the applicability of the TDP method to oil palms.

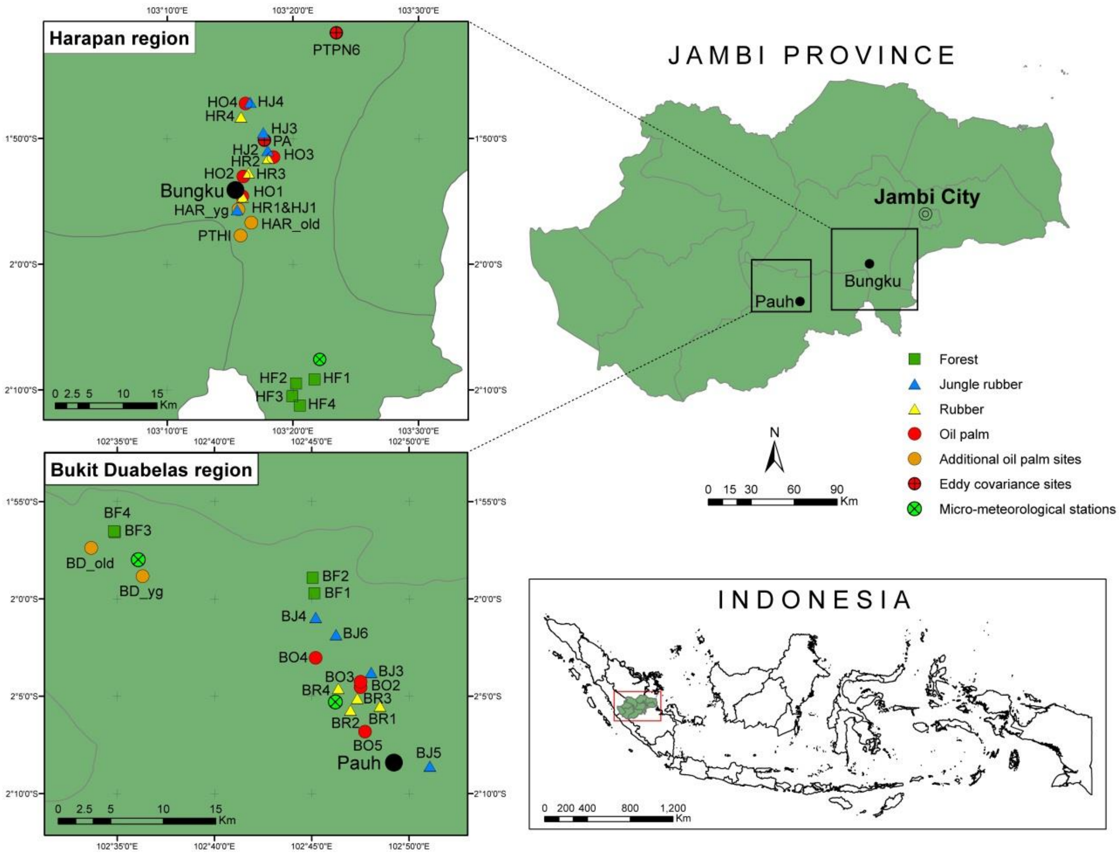

Figure 1.1. Location of the sap flux study sites in Jambi Province, Sumatra, Indonesia. Locations comprise 32 'core sites' in forest, jungle rubber, rubber and oil palm (eight replicates each), as well as seven additional oil palm sites (including two eddy covariance sites).

The first part of this work thus focuses on verifying and if necessary adjusting the TDP method for field measurements on tropical tree and monocot species in general (**Chapter 2**) and on oil palm in particular (**Chapter 3**). The approach is subsequently applied to 15 different monoculture oil palm plantations of varying age in lowland Jambi, Sumatra, Indonesia (**Figure 1.1**) to shed first light on the thus far relatively unknown eco-hydrological characteristics of oil palms as a globally rapidly expanding crop species (**Chapter 4**). The Jambi region is a 'maritime' hotspot of recent and current deforestation and strongly resembles the Indonesian rainforest transformation process to agricultural systems (Laumonier et al. 2010, Singh et al. 2013, FAO 2015). The central part of this work (**Chapter 5**) expands the scale with respect to studying and comparing the water use characteristics of forest and various transformation systems (including oil palm plantations). To assess changes in the magnitude of the central water flux of stand transpiration as well as in its spatial and temporal variability after rainforest transformation, four tropical lowland land-use types in Jambi were studied simultaneously; 32 study sites were equally distributed over forest reference sites, 'jungle rubber' agroforests and rubber and oil palm monoculture plantations (**Figure 1.1**). **Chapters 6 and 7** of this work put the observed changes in stand transpiration after rainforest transformation (**Chapter 5**) in a broader context and provide an interdisciplinary multi-component assessment of consequences of rainforest transformation on the water cycle. This work thus sheds first light on changes in central ecosystem water fluxes associated with the rapidly continuing rainforest transformation to monoculture plantations on the 'Maritime Continent'.

1.2 Scope and outline of this work

The methods and results presented in this Dissertation are embedded into the interdisciplinary framework of the CRC 990 ('Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems on Sumatra, Indonesia'; www.uni-goettingen/crc990), and more particular the eco-hydrological Sub-Project A02 ('Tree and palm water use characteristics in rainforest transformation systems'). The A02 sub-project was further divided into two 'work packages', one of them focusing on 'water use rates' of rainforests and transformation systems; the main findings from this work package in the first project phase (2012-2015) are brought together in this Dissertation.

The main objectives were (1) to verify and if necessary adjust a broadly used sap-flux technique for measurements on different species in a lowland landscape in Jambi, Indonesia, (2) to shed first light on the thus far relatively unknown water use characteristics of oil palms as a globally rapidly expanding crop species and (3) to evaluate the consequences of the continuing rainforest transformation to agricultural monocultures on landscape-scale hydrological functioning.

To tackle these objectives, five manuscripts (**Chapters 2-6**, see **Chapter 1.3** for detailed author contributions) are included in this Dissertation; the results are subsequently synthesized in **Chapter 7**.

Chapters 2 and 3 focus on the methodological approach of estimating plant water use of different tropical species. A commonly applied sap flux method, the thermal dissipation probe (TDP) method (Granier 1985) was first thoroughly tested and adjusted for measurements on tropical tree and bamboo species in extensive exploratory experiments in the common garden of Bogor Agricultural University (IPB, Indonesia); a manuscript reporting the results is 'in review' in *Frontiers in Plant Science* and forms **Chapter 2** ('Water use characteristics of four tropical bamboo species derived from sap flux measurements'). **Chapter 3** ('Oil palm water use: a calibration and a field measurement scheme') then moves the methodological experiments into the CRC990 study region (Jambi, Sumatra, Indonesia), with the main objectives of (1) calibrating the TDP method for measurements on oil palm leaves and (2) of deriving an appropriate scheme for estimating oil palm stand transpiration. It was published as a ‘technical note’ in *Tree Physiology* and constitutes the methodological basis for further TDP-based studies on oil palm water use characteristics throughout the **Chapters 4-6**.

Given the general lack of eco-hydrological studies on oil palms thus far, **Chapter 4** (‘Transpiration in an oil palm landscape: effects of palm age’) applies the oil-palm specific field measurement scheme to derive first water use characteristics of oil palms (published in *Biogeosciences*). It compares the leaf-, palm- and stand-level transpiration rates of 15 different monoculture oil palm plantations between two and 25 years old in the lowlands of Jambi, Indonesia. The main objectives are (1) to assess the influence of stand characteristics (e.g. plantation age) on (evapo)transpiration rates of oil palm plantations and (2) to give a first impression of the oil palm transpiration response to fluctuations in micrometeorological conditions (i.e. radiation and vapor pressure deficit).

Chapter 5 (‘Transpiration changes after tropical rainforest transformation to rubber and oil palm plantations’) then shifts away from the sole focus on oil palms and puts their water use characteristics in relation to that of rainforests and other transformation systems (i.e. rubber monoculture plantations and ‘jungle rubber’ agroforests). Based on sap flux measurements at 32 sites in Jambi, changes in the central ecosystem water flux of stand transpiration after rainforest transformation are assessed regarding (1) the magnitude of fluxes, (2) their spatial variability and (3) their temporal heterogeneity. The manuscript is at a complete draft stage; submission is projected for the end of 2015.

Chapter 6 (‘Oil palm expansion and water scarcity: social perceptions and environmental processes’) puts the results of Chapter 5 into a greater context and shifts the focus from (evapo)transpiration rates in forests and transformation systems to a multi-component analysis of the hydrological consequences of rainforest transformation. It is currently ‘in review’ in *Ecology and Society* and confronts local perceptions connecting oil palm expansion to periodic water scarcity with empirically-derived environmental measurements within the same region. It constitutes an interdisciplinary effort (1) to gain deeper insight into the social- and eco-hydrological processes accompanying rainforest transformation and (2) to identify and separate environmental processes leading to changes in the water cycle during rainforest transformation to agricultural monocultures.

In light of the further increasing intensification of tropical land use practices, at least partly at the expense of remaining natural forests, the discussion of changes in major hydrological processes after rainforest transformation also constitutes the central part of the synthesis of this work (**Chapter 7**). For the ‘Maritime Continent’ of Indonesia, where rainforest transformation currently occurs at the world-wide highest rates, there is thus far a substantial knowledge gap about consequences of rainforest transformation on the water cycle; this work intends to contribute to starting to close that gap.

1.3 Author contributions

This work is substantiated by five manuscripts (**Chapters 2-6**) at various stages of the publication process (i.e. 'final draft', 'submitted', 'in review', 'published'). The status as well as the contribution to each manuscript by the author of this Dissertation (in the following simply referred to as 'the author') is indicated for each manuscript. **Chapters 1 and 7** were solely compiled by the author.

** Indicates a shared first co-authorship,*
^ *Indicates the corresponding author*.

Chapter 2:
Water use characteristics of four tropical bamboo species derived from sap flux measurements
Mei, T.*^, Fang, D.*, Röll, A., Niu, F., Hendrayanto, Hölscher, D.
Manuscript status: In review in Frontiers in Plant Science, MS-No. 165778
The concept and research priorities for this bamboo and tree study in Bogor, Indonesia were developed by Dirk Hölscher. Setup and maintenance of the field installations and data collection were performed by Tingting Mei, Dongming Fang and the author. The author also contributed substantially to the writing and final evolution of the manuscript, in close cooperation and coordination particularly with Tingting Mei, Dongming Fang and Dirk Hölscher.

Chapter 3:
Oil palm water use: a calibration and a field measurement scheme
Niu, F.*^, Röll, A.*, Hardanto, A., Meijide, A., Hendrayanto, Hölscher, D.
Manuscript status: Published in Tree Physiology (2015) 35: 563-573, doi: 10.1093/treephys/tpv013.
The concept and research priorities for this study in Jambi, Indonesia (CRC990, A02) were developed by Dirk Hölscher. Setup and maintenance of the field installations and data collection were performed by the author. The author substantially contributed to data analyses, manuscript writing and the revision process, in close cooperation and coordination particularly with Niu Furong and Dirk Hölscher.

Chapter 4:

Transpiration in an oil palm landscape: effects of palm age

Röll, A.*^, Niu, F.*, Meijide, A., Hardanto, A., Hendrayanto, Knohl, A., Hölscher, D.

Manuscript status: Published in Biogeosciences (2015) 12, 5619-5633, doi: 10.5194/bg-12-5619-2015

The concept and research priorities for this study in Jambi, Indonesia (CRC990, A02) were developed by Dirk Hölscher. Setup and maintenance of the field installations and data collection were performed by the author for nine of the 15 research plots analyzed in the study. The author substantially contributed to data analyses, manuscript writing and the revision process, in close cooperation and coordination particularly with Niu Furong and Dirk Hölscher.

Chapter 5:

Transpiration changes by transforming tropical rainforest to rubber and oil palm plantations

Röll, A.^, Niu, F., Meijide, A., Hendrayanto, Knohl, A., Hölscher, D.

Manuscript status: Complete draft - projected submission in November 2015.

The concept and research priorities for this study in Jambi, Indonesia (CRC990, A02) were developed by Dirk Hölscher. Setup and maintenance of the field setup and data collection were performed by the author for all of the 32 study plots. The author was also largely responsible for the according data analyses and the manuscript writing process, in close cooperation and coordination particularly with Dirk Hölscher.

Chapter 6:

Oil palm expansion and water scarcity: social perceptions and environmental processes

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1.4 References Chapter 1

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Chapter 2

Water use characteristics of four tropical bamboo species derived from sap flux measurements

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Abstract Chapter 2

Bamboos belong to the grasses, Poaceae, and are widespread in tropical and subtropical regions. We aimed at exploring water use characteristics of some tropical bamboo species by means of sap flux techniques. It was previously suggested that the stem heat balance (SHB) method is well suited for bamboos but that thermal dissipation probes (TDP) need to be calibrated. This was confirmed in our experiment with potted *Bambusa vulgaris* culms and gravimetric readings. Subsequently, four bamboo species (*B. vulgaris*, *Dendrocalamus asper*, *Gigantochloa atroviolacea* and *Gigantochloa apus*) were simultaneously measured by TDP and SHB and parameters for TDP calibration equations were derived. Finally, the four bamboo and three tree species were monitored by TDP for seven months in a common garden in Bogor, Indonesia. Some bamboo species reached high maximum sap flux densities; across bamboo species, maximal sap flux density increased with decreasing culm diameter. In the diurnal course, sap flux densities in bamboos peaked much earlier than radiation and VPD, and also much earlier than sap flux densities in trees. There was a pronounced hysteresis between sap flux density and VPD in bamboos, which was less pronounced in trees. Three of the four bamboo species showed reduced sap flux densities at high VPD values during the dry season, which was associated with a decrease in soil moisture content. Possible roles of internal water storage, root pressure and stomatal sensitivity are discussed.

Key words: calibration, environmental drivers, hysteresis, stem heat balance, thermal dissipation probes, trees

2.1 Introduction

Bamboos (*Poaceae*, *Bambuseae*) are abundant in the natural vegetation of tropical and subtropical regions. They have been used for millennia and are still used e.g. as food or construction materials. In addition, a large variety of bamboo usages have been developed in recent decades, e.g. for pulp and paper or clothing (INBAR 2014). This goes along with a considerable expansion of bamboo plantations in some regions (Chen et al. 2009, FAO 2010). However, unlike for tree species, studies focusing on water use characteristics of bamboos are relatively rare thus far (Pereira and Hosegood 1962, Dierick et al. 2010, Komatsu et al. 2010, Kume et al. 2010, Ichihashi et al. 2015).

The eco-hydrological characteristics of bamboos and trees potentially differ in several aspects. E.g., in contrast to trees bamboos are monocotyledonous species and thus lack secondary growth (Zimmermann and Tomlinson 1972), i.e. vascular conduits of bamboo xylem should remain functional throughout the ontogeny of a bamboo culm. Bamboos thus have a high restoration ability to maintain functioning conduits (Cochard et al. 1994, Cao et al. 2012, Petit et al. 2014). Root pressure mechanisms may contribute to repairing embolized conduits at night (Cao et al. 2012). Such features and structural traits may lead to special water use characteristics.

In general, plant water use is driven by micrometeorological factors and at times limited by soil water content (O'Brien et al. 2004, Bovard et al. 2005, Kume et al. 2007); it is regulated by stomata (Jarvis 1989) and can be influenced by inner water storage (Waring and Running 1978, Goldstein et al. 1998, Carrasco et al. 2014). Xylem sap flux reflects these factors; e.g., in trees hystereses in the diurnal sap flux density response to radiation and vapor pressure deficit of the air have been reported (Goldstein et al. 1998, O'Brien et al. 2004).Thus, sap flux measurements in bamboos appear suitable to study their water use characteristics.

The thermal dissipation probe method (TDP; Granier 1985) is a widely used sap flux technique for studies of water use characteristics of trees. Several studies suggest calibrating the method before studying new species (Lu et al. 2004, Wullschleger et al. 2011, Vandegehuchte and Steppe 2013). To our knowledge, only two studies have applied the TDP method on bamboos so far; they reported underestimation of derived bamboo sap flux densities compared to gravimetric measurements (GM) and stem heat balance (SHB) reference measurements if the method was not calibrated (Dierick et al. 2010, Kume et al. 2010). The SHB method was proposed to be well suited for sap flux measurements on bamboos (Dierick et al. 2010); due to the hollow bamboo culms heat loss in the form of heat storage inside culms is marginal, i.e. steady thermal conditions as a main assumption of the method are met (Baker and Van Bavel 1987).

The aim of this study was to analyze water use characteristics of tropical bamboo species such as the response patterns of sap flux density to different environmental drivers. As an initial step, we tested the SHB and the TDP method against gravimetric measurements in an experiment with potted bamboo culms (*Bambusa vulgaris*). We then monitored sap flux density in the field in four bamboo species including *B. vulgaris* by simultaneously employing the TDP and SHB method and tested different ways of calibrating the TDP method for measurements on bamboo. After calibration of the TDP method, we applied it to monitor sap flux density in four bamboo and three tree species in a common garden in Bogor, Indonesia. Differences in the sap flux response to fluctuations in environmental conditions were assessed. The study intends to contribute to expanding the yet limited knowledge on eco-hydrological functioning of bamboos.

2.2 Materials and methods

2.2.1 Study sites

The experiment with potted bamboo culms was conducted in Guangzhou, China. The field experiment was carried out in a common garden in Bogor, Indonesia (6°33′40″S, 106°43′27″E, 182 m asl). Average annual temperature in Bogor is 25.6 °C and annual precipitation amounts to 3978 mm (1989-2008, SACA&D, 2014). Relatively dry conditions with consecutive rainless days can occur between June and September. In Bogor, four bamboo species (*Bambusa vulgaris*, *Dendrocalamus asper*, *Gigantochloa atroviolacea*, *Gigantochloa apus*) and three tree species (*Gmelina arborea*, *Shorea leprosula* and *Hevea brasiliensis*, **Table 2.1**) were monitored with the TDP method for seven months.

2.2.2 Calibration of the TDP method

2.2.2.1 Potted bamboo experiment: TDP, SHB & GM

Five *B. vulgaris* culms (5.3-7.3 cm in diameter, 2.2-3.2 m in height) were planted into 20 L plastic pots (50 cm in diameter, 65 cm in height) and the pots were fully sealed with plastic cover and aluminum foil to prevent evaporation of water from the pots (**Figure 2.1**). The bamboo culms were equipped with 10 mm-length TDP sensors ~15 cm above the plastic covers; SHB gauges (SGB50, SGA70, Dynagage Inc., USA) were installed ~1.5 m above the TDP sensors. The TDP sensors and SHB gauges were wrapped with thick solar film to reflect radiation and with plastic foil for protection from rain. At the beginning of the experiment, the water level in each pot was determined. During the experiment, water was added into the pots every 30 min through a U-type tube until the pre-determined levels were reached; the necessary respective amounts of water were recorded by manual gravimetric measurements (GM). TDP and SHB signals were sampled every 30 s and stored as 10 min averages by a data logger (CR1000, Campbell Scientific Inc., USA).

For a comparison to reference GM, 10-min TDP and SHB derived values were aggregated to half-hourly values.

2.2.2.2 Field calibration: TDP & SHB

Five culms per bamboo species (*B. vulgaris*, *D. asper*, *G. atroviolacea*, *G. apus*) were selected for TDP measurements (**Table 2.1**), three to four of which were additionally measured with SHB for a field calibration of the TDP method. TDP sensors were installed at 1.3 m height. SHB gauges (SGB50, SGA70, Dynagage Inc., USA) were installed at 3.8 m for a minimum of five days of simultaneous TDP-SHB measurements per culm (**Figure 2.1**) before being moved to a different culm. Heat storage inside bamboo culms is assumed to be negligible, which was confirmed by installing a thermocouple wire inside the measured segment of the respective bamboo culm to detect fluctuations in heat storage (Dierick et al. 2010). We observed only marginal fluctuations of the temperature inside bamboo culms, i.e. no significant effects of heat storage. Signals of the two sap flux methods (TDP and SHB) were sampled every 30s and 1 min averages were stored by data loggers and multiplexers (CR1000, AM16/32, Campbell).

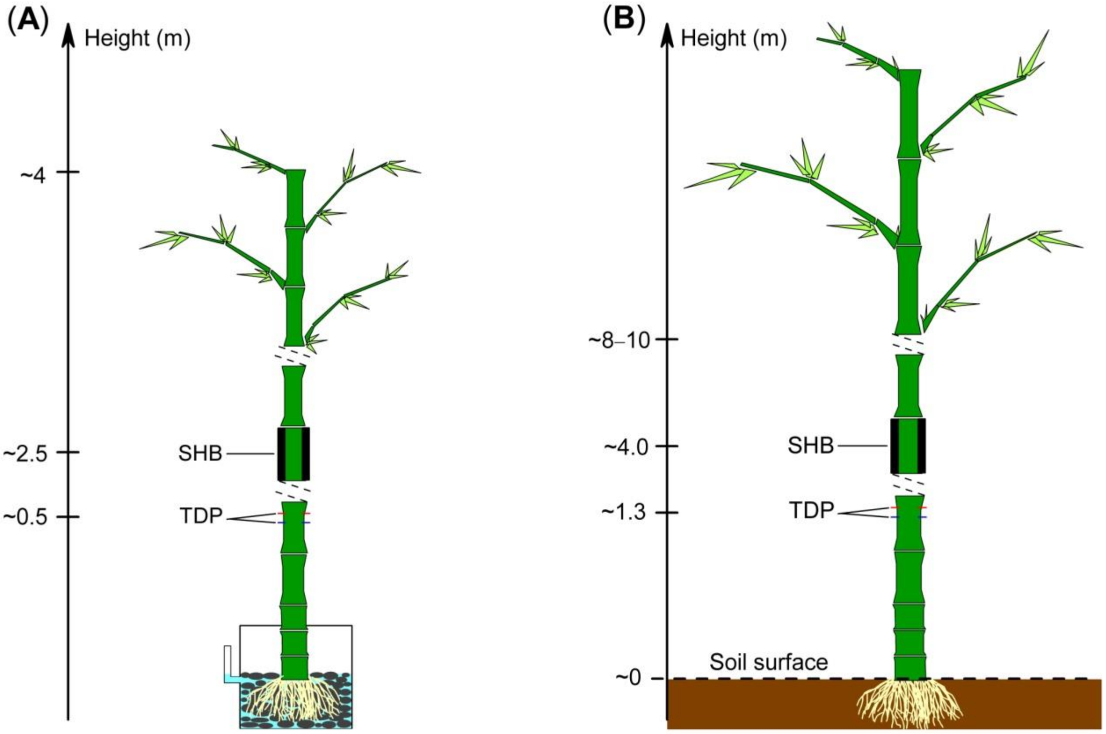

Figure 2.1. Installation of thermal dissipation probe (TDP) and stem heat balance (SHB) sensors on bamboo culms for the calibration experiments on potted plants (A) and for field calibration

2.2.2.3 Parameter setting for TDP calibration

We derived cross-sectional water conductive areas from the wall thickness at the location of TDP sensor installation (A_{TDP}). Having established water conductive areas of each culm (cm^2), sap flux densities (J_S, g cm^{-2} h^{-1}) were calculated from the water flow rates (g s^{-1}) provided by reference SHB and gravimetric measurements during the potted plant and field calibration experiments. These reference sap flux densities were then used to calibrate TDP-derived sap flux densities. For the field calibration, nighttime values were excluded.

Three factors were considered for obtaining a TDP calibration formula from reference (SHB, GM) measurements: time step of the data, formula specificity, and calibration formula type. To examine effects of varying time steps, the formulas were built and tested on data at varying intervals (1-, 10-, 30-, and 60-minute averages, respectively). The effects of formula specificity were examined by using common (i.e. all bamboo species pooled), species-specific and culm-specific formulas, respectively. Regarding the calibration formula type, two formulas were compared: one was nonlinear formula ($J_S = a\ K^b$) and generated by deriving new *a* and *b* parameters for the original Granier (1985) formula, as performed e.g. by Niu et al. (2015). The second was a linear formula ($J_{S\text{-}SHB} = A\ J_{S\text{-}TDP}$) which was derived from the linear relationship between TDP and SHB derived sap flux densities ($J_{S\text{-}TDP}$ and $J_{S\text{-}SHB}$, respectively).

To obtain calibration formulas of high stability, pooled data sets were split in half for calibration and independent validation, respectively. This approach was previously applied to calibrate TDP on oil palm (Niu et al. 2015). At first, on each time step (1-, 10-, 30-, and 60-minute, respectively), a data pool was built. Three culms of each bamboo species were randomly chosen and for each, three days of data were randomly chosen from an initial common dataset. With these data pools, formula specificity was examined. For the common calibration, culms of all four species were selected for calibration. For species-specific and culm-specific calibration, only the data of the respective species or culm was selected. Next, the selected data was randomly split in half, for building the calibration formula and testing it, respectively. When testing the formula, the difference between the $J_{S\text{-}SHB}$ and predicted $J_{S\text{-}TDP}$ was examined with the Wilcoxon Signed-Rank Test (no significant differences at $P > 0.05$). The process of randomly building and testing the formula was iterated 10.000 times. Final formula parameters were derived by averaging the formula parameters of those iterations which passed the Wilcoxon Signed-Rank Test ($P > 0.05$).

For an evaluation of the performance of the different formulas and the influence of the three factors (time scale, formula specificity and calibration formula type), differences in normalized Root-Mean-Square Errors (nRMSE) were assessed for each culm, species and formula factor, respectively. Firstly, the RMSE for each day was derived with the $J_{S\text{-}SHB}$ and predicted $J_{S\text{-}TDP}$ values, and the nRMSE was derived by normalizing the RMSE with the observed daily range of $J_{S\text{-}SHB}$ (difference between maxima and minimum daily $J_{S\text{-}SHB}$). Then the nRMSEs were analyzed with regard to the three formula factors (data time step, formula specificity and calibration formula type) by ANOVA (Analysis of variance). Additionally, for each day, predicted $J_{S\text{-}TDP}$ with each formula type was tested for significant differences with $J_{S\text{-}SHB}$ with the Wilcoxon Signed-Rank Test. The rates of passing the Wilcoxon Signed-Rank Test ($P>0.05$, i.e. no significant difference between TDP and SHB derived values) were assessed for each formula.

2.2.3 Field study

2.2.3.1 Monitoring bamboo and tree sap flux

Following the potted plant and field calibration experiments, the four mentioned bamboo species as well as three species (*G. arborea*, *S. leprosula* and *H. brasiliensis*) were monitored with the TDP method for seven months (July, 2012 to January, 2013) in the common garden of Bogor Agricultural University, Indonesia. Five bamboo culms and five tree trunks per species were selected for the measurements. On bamboos, three pairs of TDP sensors (10 mm in length) were installed evenly around each culm at 1.3 m height. They were supplied with 0.1 W power, which is half of the 0.2 W applied on the original 20-mm TDP sensors (Granier 1985). On trees, two pairs of 20-mm sensors were installed in the trunks at 1.3 m above the ground, in the North and South, respectively. Signals were sampled every 30s and 1 min averages were stored by the described data loggers and multiplexers. For trees, sap flux densities were derived with the original calibration equation (Granier 1985). For bamboos, sap flux densities derived with the original equation were calibrated with species-specific calibration parameters (from reference SHB field measurements) to obtain final sap flux density values.

2.2.3.2 Environmental measurements and analyses

Micrometeorological variables were measured in an open area near the studied bamboos and trees. Air temperature (Ta, °C) and air relative humidity (RH, %) were measured with a temperature and relative humidity probe (CS215, Campbell) installed in a radiation shield. Vapor Pressure Deficit (VPD, kPa) was calculated from Ta and RH. Photosynthetically active radiation (PAR, J m^{-2} s^{-1}) was measured with a pyranometer (CS300, Campbell). Soil moisture (SM, m-3m-3) at 0-20 cm depth was measured with time domain reflectrometry sensors (TDR, CS616, Campbell). Environmental measurements ran in parallel to the sap flux field campaign; data were recorded with the described data loggers every minute.

For the day-to-day analysis of influences of fluctuations in environmental conditions (i.e. VPD, radiation, SM) on sap flux densities in the studied bamboo and tree species, daily cumulative sap flux densities (kg cm^{-2} d^{-1}) were normalized by setting the highest observed daily observation of each species to one. For a more isolated analysis of potentially limiting influences of soil moisture

on sap flux densities, we focused on ‘dry season’ conditions, i.e. days with a VPD >0.74 kPa. The 0.74 kPa threshold was chosen because it constituted the average ‘turning point’ in the sap flux response to VPD in three of the four studied bamboo species (except D. asper, see **Figure 2.4.B**).
For the diurnal analysis of influences of fluctuations in environmental conditions on sap flux densities, time lags between sap flux density and micrometeorological drivers (i.e. PAR and VPD) were assessed. Sap flux densities (average values of three sunny days) of each species were plotted against PAR and VPD to examine occurrence of hysteresis.
All data analyses were performed with SAS 9.3 software (SAS Institute Inc., 2013)..

Table 2.1. Structural characteristics of the studied bamboo and tree species (n= 5 per species; mean ± SD). Culm wall thickness (derived from five culms per species) and culm height (derived from three cut culms per species) of the studied bamboos.

	Species	DBH (cm)	Bamboo culm wall thickness (cm)	Height (m)
Bamboo	*B. vulgaris*	7.0±0.3	1.3±0.1	17.9±0.8
	G. apus	8.6±0.4	1.2±0.2	16.2±2.7
	D. asper	11.9±1.9	2.4±0.2	21.1±0.9
	G. atroviolacea	8.9±0.6	1.6±0.1	17.0±1.0
Tree	*H. brasiliensis*	27.4±2.3	-	25.2±3.0
	G. arborea	26.3±7.7	-	26.5±2.3
	S. leprosula	20.7±4.8	-	19.2±2.5

2.3 Results

2.3.1 TDP calibration

In the pot experiment with *B. vulgaris*, SHB yielded similar absolute values as GM (6% underestimation of average daily accumulated J_S), whereas TDP estimates, with the original parameters of the calibration equation (Granier 1985), differed substantially from values derived by the other two methods at both the daily (60% underestimate of average accumulated J_S) and 30 min scale (Figure 2.2.A, values largely deviate from 1:1 relationship with $J_{S\text{-}GM}$). When using our newly derived TDP calibration parameters from the field calibration experiment (**Table 2.2**) for the data from the potted bamboo experiment, daily accumulated TDP-derived J_S deviated only 5% from reference SHB measurements, and the 30-min J_S were much more in line with the other two methods (e.g. with $J_{S\text{-}GM}$ in **Figure 2.2.B**).

In the field calibration experiment, TDP-derived daily accumulated J_S was on average 66% lower than SHB-derived reference values. This deviation was reduced to a 10% underestimation by using bamboo-specific calibration parameters (**Table 2.2**). Differences between calibrated $J_{S\text{-}TDP}$ and reference $J_{S\text{-}SHB}$ were tested with the Wilcoxon Signed-Rank test. For 96% of observations, calibrated $J_{S\text{-}TDP}$ values were not significantly different from $J_{S\text{-}SHB}$.

Formula type and data time-scale had no significant influence on the performance of the calibration formula, but it mattered whether culm- or species-specific or a common calibration parameter was used (**Table 2.2**, **Table 2.4**). Based on the nRMSE and the passing rate of the Wilcoxon test between calibrated $J_{S\text{-}TDP}$ and $J_{S\text{-}SHB}$ culm-specific formulas performed better than species-specific and common formulas, respectively. In our study, there was no statistically significant difference between species-specific and the common calibration parameters (**Table 2.2**, P>0.05). For two of the four studied bamboo species (*G. apus* and *B. vulgaris*), however, using species-specific formulas slightly improved the quality of predictions as compared to applying the common formula (P=0.06 and 0.07, respectively, **Table 2.2**). Confronting this insight with results from sap flux studies on other bamboo species (Dierick et al. 2010, Kume et al. 2010), differences among species become even more apparent. We thus used the derived species-specific formulas for further analysis.

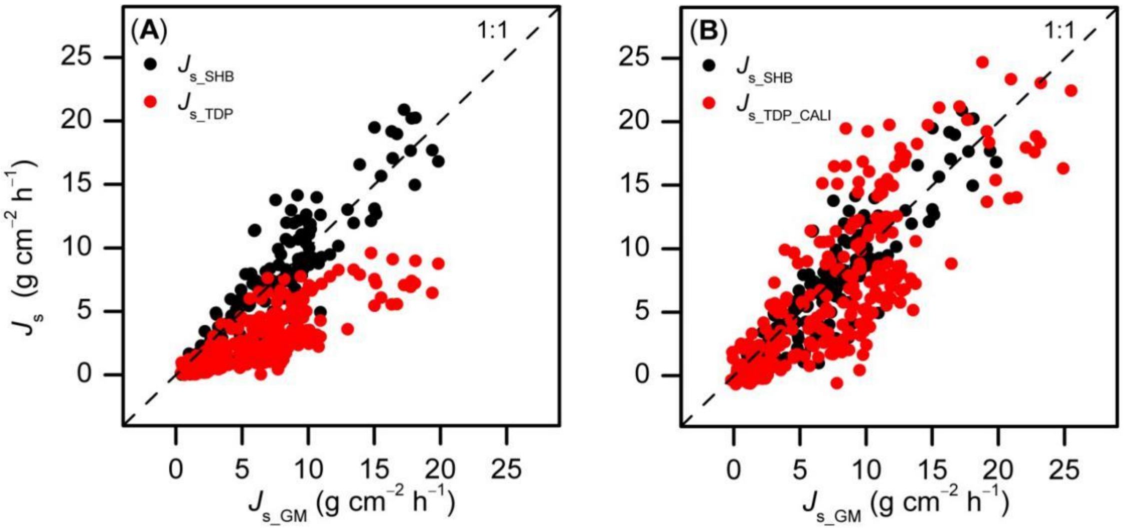

Figure 2.2. Half-hourly sap flux densitiy (J_s) measured with thermal dissipation probes (TDP, red dots) and stem heat balance sensors (SHB, black dots) on five potted *Bambusa vulgaris* culms plotted against gravimetrically-derived reference sap flux densities (J_{s_GM}) before (A) and after (B) bamboo-specific calibration (from the field calibration) of the TDP method. Pooled data from two days of simultaneous TDP and SHB measurements.

Table 2.2. Parameters A of different bamboo calibration formula types (species-specific/common) for calibration of TDP sap flux estimates. Significant differences between species-specific and common A estimates (Tukey's test, $P<0.01$) are indicated by superscripted letters. Normalized Root-Mean-Square Error (nRMSE) of species-specific A and nRMSE using common A. P-values < 0.05 indicate significant differences between nRMSEs of species-specific A and common A.

Formula specificity	Species	**A**	nRMSE		
			species	common	P value
Species	*B. vulgaris*	2.79^{a}	0.10	0.11	0.07
	G. apus	3.32^{b}	0.10	0.12	0.06
	D. asper	2.42^{c}	0.18	0.18	0.97
	G. atroviolacea	2.53^{d}	0.12	0.13	0.81
Common		2.74^{e}			

2.3.2 Water use characteristics of bamboos

Maximum observed sap flux densities (J_{s_max}) in the studied bamboo species (averages from five individuals per species) were 70.5, 21.6, 49.7 and 56.2 g cm^{-2} h^{-1} for *B. vulgaris*, *D. asper*, *G. apus* and *G. atroviolacea*, respectively. In trees, corresponding values were 17.7, 10.5 and 23.3 g cm^{-2} h^{-1} for *H. brasiliensis*, *G. arborea* and *S. leprosula*, respectively. Across bamboo species, J_{s_max} decreased with increasing culm diameter ($R^2= 0.97$, $P=0.02$, **Figure 2.3**).

The normalized daily accumulated J_S of all studied species increased with increasing PAR (day-sums). This relationship did not fully hold up for accumulated J_S and VPD (daily means), however. In several species, daily J_s increased with increasing VPD only to a certain VPD threshold (approx. 0.74 kPa, **Figure 2.4**); after this threshold, accumulated J_S decreased with further increasing VPD. The conditions of high VPD (>0.74 kPa) are mainly characteristic of the dry season, when soil moisture was at times limiting: For days with VPD >0.74 kPa, daily accumulated J_S of most studied species (except in *D. asper* and *G. Arborea*, which were located right next to each other) declined with decreasing soil moisture content ($R^2=0.39$, 0.44 and 0.4 for *B. vulgaris*, *G. apus* and *G. atroviolacea*, respectively; $P<0.05$, **Figure 2.5**).

Diurnal peaks in sap flux density in the studied bamboo species occurred relatively early (on average at about 11am), i.e. significantly earlier than peaks of PAR and VPD (20-82 min and 131-206 min, respectively) (**Table 2.3**). In the studied tree species, maximal hourly J_s values were observed after the peak of radiation (3-97 min), but still before (51-108 min) VPD peaked. All time lags were significantly different from zero minutes except the time lag to PAR for the tree species *S. leprosula*.

In the diurnal course, we observed partly pronounced hysteresis of hourly J_s to PAR and VPD, respectively, for the studied species. Direction of rotation (i.e. order of observations) was counter-clockwise for PAR (**Figure 2.6.A**) and clockwise for VPD (**Figure 2.6.B**). The area of the hysteresis to VPD was on average 32% larger in bamboos than in trees, while the area of hysteresis to PAR was on average 50% smaller in bamboos.

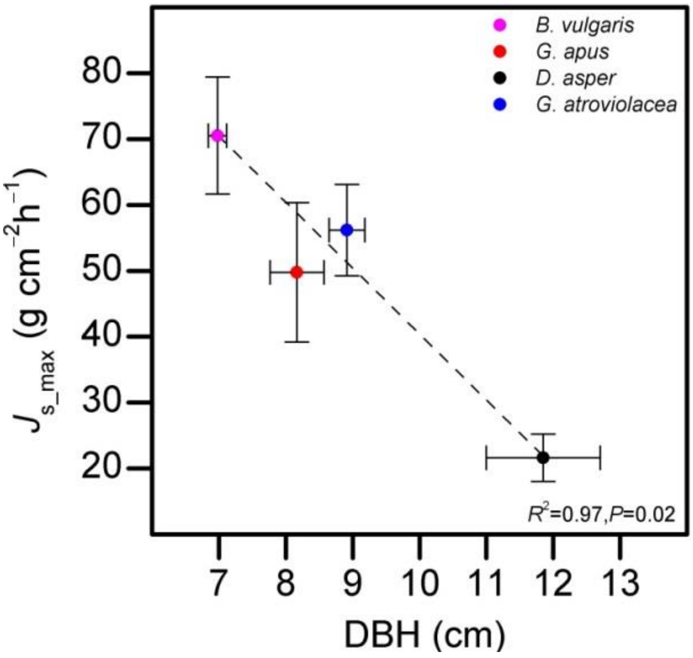

Figure 2.3. Relationship between diameter at breast height (DBH) of bamboo culms and maximum observed sap flux density (J_{s_max}) in four bamboo species. Horizontal error bars indicate DBH standard errors, vertical bars standard errors of J_{s_max}. Data of five culms pooled per species, average of the highest 10% of daily J_{s_max} values of each culm used for the analysis ($R^2=0.97$, $P=0.02$).

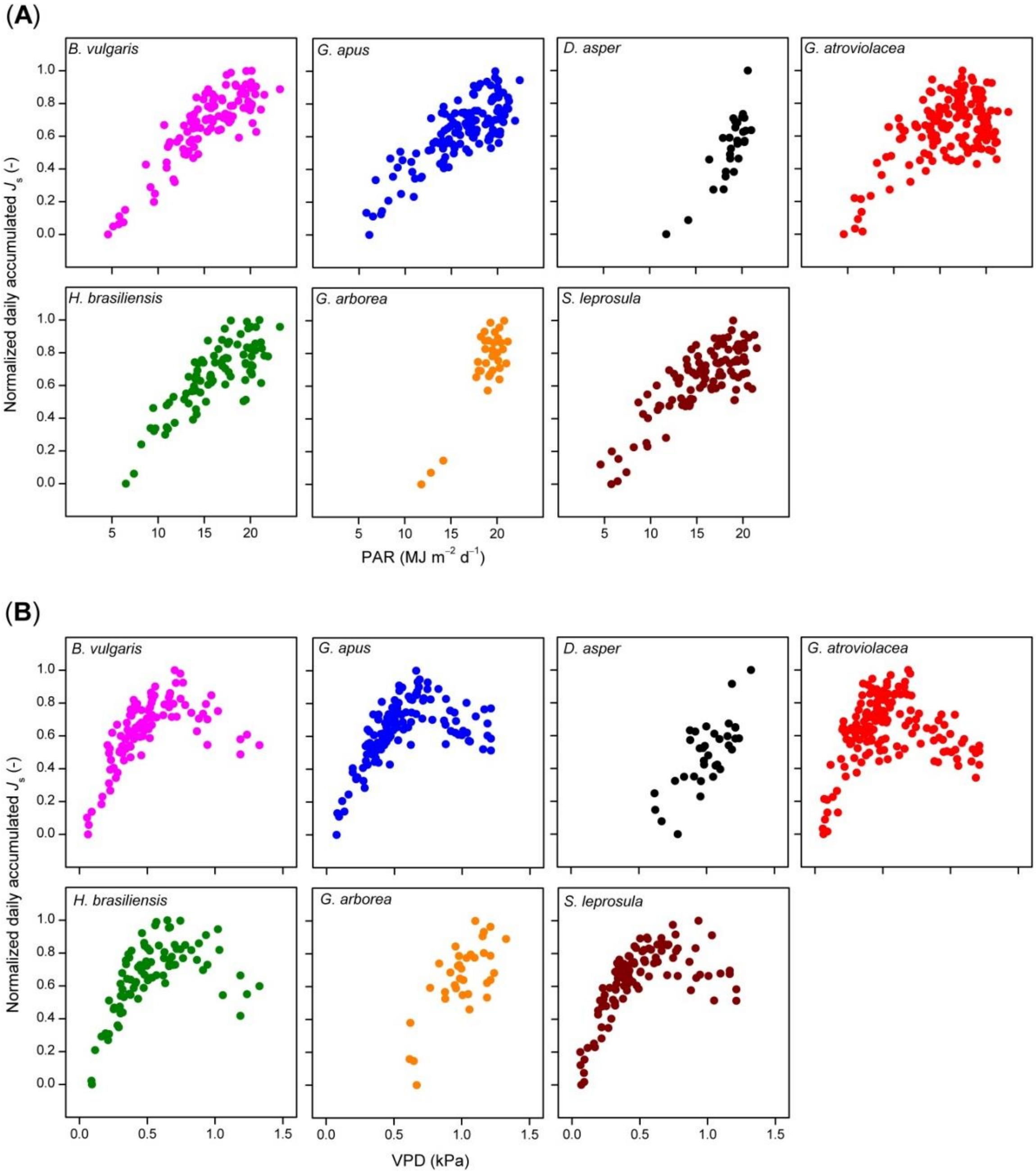

Figure 2.4. Normalized daily accumulated sap flux density (JS) plotted against absolute values of integrated daily photosynthetically active radiation (PAR) (A) and average daily vapor pressure deficit (VPD) (B). Daily values of four bamboo (upper row) and three tree species (lower row); data from seven months of measurements (July 2012-January 2013) encompassing both wet and dry conditions (except for D. asper and G. arborea, mainly dry conditions). Daily averages derived from measurements of five culms per species.

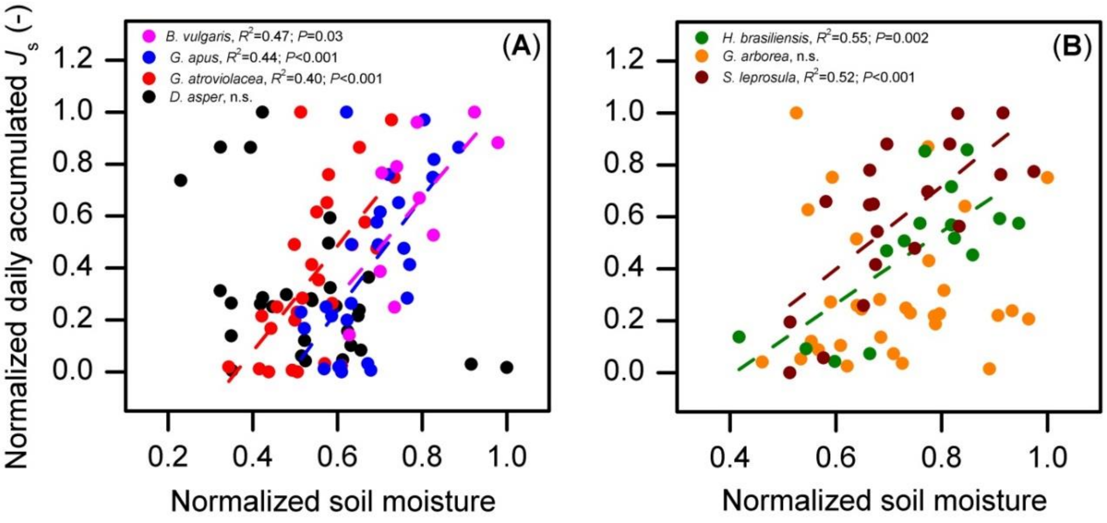

Figure 2.5. Normalized daily accumulated sap flux density (J_S) of four bamboo species in the 'dry period' (mean daily VPD > 0.74 kPa) plotted against mean daily soil moisture content (SM). There was a significant linear relationship between J_S and SM (P<0.05) for all species except *D. asper*. Normalized values do not reach 1.0 for all species as the normalization was performed by setting maximum values of the full measurement period of each species (including wet season) to one, while the figure displays values under conditions of VPD > 0.74 kPa. Daily averages derived from measurements on five culms per species, data of at least 10 dry season days per species.

Table 2.3. Time lags between diurnal peaks of PAR and VPD and peaks of sap flux density in studied bamboos and trees. Positive values indicate a peak of PAR/VPD after the peak of J_s, negative values indicate a peak before J_s; N culms/trunks per species averaged (mean ± SD). Significant differences in bamboo/tree mean time lags are indicated by different superscripted letters (Tukey's test, P<0.01). Significant differences between species are indicated by capital letters (P<0.01).

Species	N	Time lag with PAR (min)	Time lag with VPD (min)
B. vulgaris	5	82±62	171±63
D. asper	5	41±57	206±57
G. apus	4	20±61	131±53
G. atroviolacea	5	64±30	170±35
Bamboo mean	**19**	**51^{A}**	**169^{A}**
H. brasillensis	5	-37±12a	51±9
G. aborea	5	-97±87b	67±87
S. leprosula	5	-3±25a	108±20
Tree mean	**15**	**-46^{B}**	**75^{B}**

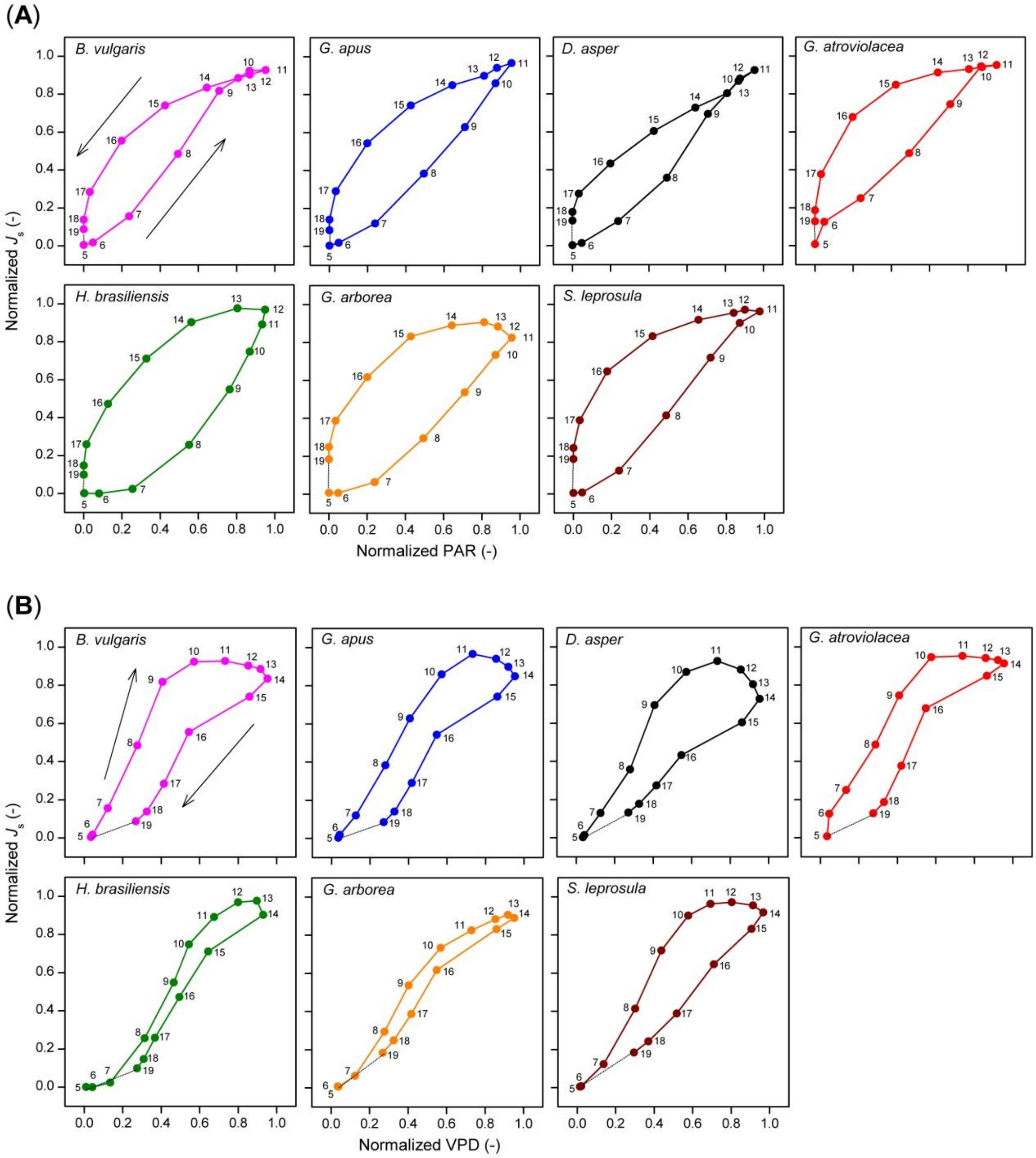

Figure 2.6. Normalized hourly sap flux densities (J_s) plotted against normalized hourly photosyntetically active radiation (PAR) (A) and vapor pressure deficit (VPD) (B). Data of four bamboo (upper row) and three tree species (lower row). Hourly averages derived from simultaneous measurements on five culms per species and by averaging the values of three sunny days to minimize influences of weather The numbers in the sub-figures indicate the respective time of the day.

2.4 Discussion

In our study, the TDP method was found to substantially underestimate sap flux densities of bamboos. Large underestimations by TDP were also reported in two other bamboo studies: they reported respective average underestimations of 13% for *Bambusa blumeana* (Dierick et al. 2010) and 31% for Moso bamboos (*Phyllostachys pubescens*, Kume et al. 2010). Reasons for the observed underestimations could lie in the distinct hydraulic and physiological features of bamboos. E.g., diurnal variations of stem water storage could affect the accuracy of TDP measurements, which require stable zero-flux night time conditions (e.g. Oishi et al. 2008). Bamboos have approx. 50% parenchyma in culm walls (Dransfield and Widjaja 1995), which potentially provides substantial reservoirs for stem water storage. The depletion and refilling of the stem during the day and night, respectively, could cause diurnal fluctuations in culm thermal diffusivity. Higher water content during the night could lead to a lower maximum temperature difference (ΔT_{max}) of TDP under 'zero flux nighttime conditions'; as ΔT_{max} constitutes the basis for calculations of daytime J_S, J_S could be substantially underestimated when using the original calibration parameters (Granier 1985, Vergeynst et al. 2014).

We originally expected the calibration formula type (linear vs. nonlinear) and data time step to have an impact on the performance of TDP predictions; however, both were not as important as the factor formula specificity. Even though species-specific calibration formulas generally did not perform significantly better than the common formula ($P>0.05$), species-specific formulas tended to show slightly better performance (at $P<0.1$) for two of the studied species (*G. apus and B. vulgaris*). Also, the calibration parameters were significantly different among the four studied bamboo species (**Table 2.2**). These differences may be indicative of highly heterogeneous wood anatomical properties among bamboo species. E.g., size and shape of vascular bundles and parenchyma of 15 bamboo species were reported to be highly variable (Rúgolo de Agrasar and Rodríguez 2003). For two further bamboo species (*Chusquea ramosissima* and *Merostachys claussenii*), it was suggested that differences in the numbers of vascular bundles per unit area (1000 vs. 225 per cm^2) and vessel length (~1m vs. 20cm) might lead to differences in xylem hydraulic conductivity between the species (Saha et al. 2009). Differences in wood anatomical properties may lead to heterogeneous heat conductive properties, which potentially affects applicability and accuracy of the TDP method (Wullschleger et al. 2011). In our study, culm-specific formulas performed better at predicting sap flux density than species-specific and common calibration formulas (**Table 2.4 and 2.5**). This result may indicate heterogeneity in conductive properties among culms of the same species, and reasons of this heterogenity may lie in the ontogeny of culms. Even though we carefully tried to select culms of similar age (i.e. approx. two years old), the exact age of individual bamboo culms within a given clump was difficult to assess depending on culm diameters. Like all monocot species, bamboos lack secondary growth (Zimmermann and Tomlinson 1972), culm diameters are thus not age-dependent. However, (age-related) processes over the ontogeny of a certain culm, e.g. conductive circuit failure (e.g. drought- or metabolism-related) (Cochard et al. 1994, Liese and Weiner 1996), lignification (Lin et al. 2002) or increasing hydraulic limitations due to increasing culm height (Renninger and Phillips 2010, Cao et al. 2012) could potentially result in overall reduced hydraulic conductivity and thus lower sap flux densities with progressing culm age.

Maximum observed half-hourly sap flux densities (J_{s_max}) in the four studied bamboo species lay between 21.6 to 70.5 g cm^{-2} h^{-1} and were almost two-fold higher (on average) than those of the studied tree species. The observed range for both bamboos and trees falls into the range of J_{s_max} values reported for tropical tree species in a variety of sap flux studies (5-70 g cm^{-2} h^{-1}, Meinzer et al. 2001, O'brien et al. 2004). For *D. asper*, the J_{s_max} (21.6 g cm^{-2} h^{-1}) was similar to values reported for *Bambusa blumeana* culms (25.7g cm^{-2} h^{-1}, Dierick et al. 2010) and Moso bamboos (approx. 20 g cm^{-2} h^{-1}, Kume et al. 2010) of similar size. Our four studied bamboo species showed significant differences in J_{s_max}, which was negatively correlated to species-specific differences in DBH (**Figure 2.3**). Consistent with this, in a study on 27 tropical tree species, the negative relationship between J_{s_max} and DBH was also observed, and assumed to be related to a decline of the 'leaf area to sap wood area ratio' with increasing tree size (i.e. DBH) (Meinzer et al. 2001). This relationship was also observed in a study on Eucalyptus grandis trees (Dye and Olbrich 1993). In our study, we harvested leaves of three bamboo species (*B. vulgaris, D. asper, and G. apus*) and found that the leaf weight to sap wood area ratio was positively correlated to J_{s_max}; differences in leaf area may thus explain the increasing J_{s_max} with decreasing DBH (i.e. with decreasing water conductive area) that we observed across bamboo species. Additionally, the higher J_{s_max} in species with smaller DBHs could also be achieved by adaptions in the anatomical structure of culms (e.g. a higher density of vascular bundles), which was reported to be highly variable among species (e.g. Rugolo de Agrasar and Rodriguez 2003). However, studies connecting anatomical and eco-hydrological properties of bamboos are just at the beginning (e.g. Saha et al. 2009).

On the day-to-day level, accumulated sap flux densities of both the studied bamboo and tree species were significantly influenced by PAR and VPD (**Figure 2.4**). During the long rainy season, the relationship for most examined species was linear, i.e. higher average daily VPD and integrated radiation induced higher accumulated sap flux densities. Likewise, linear relationships in the day-to-day behavior of sap flux density to micrometeorological drivers have been reported for some tropical bamboo and dicot tree species (e.g. Dierick and Hölscher 2009, Köhler et al. 2009). During the dry season, however, which is characterized by PAR and VPD levels much higher than during the rainy season, the observed linear relationship to micrometeorological drivers did not hold. Further increasing VPD ('dry period conditions') lead to decreases in accumulated sap flux densities of several studied species (**Figure 2.4.B**). Similar decreases after a certain peak value have been reported for some previously studied tree species (e.g. Kubota et al. 2005, Jung et al. 2011). However, in most thus far studied species maximum daily VPD and radiation, respectively, coincide with (near) maximum sap flux densities or water use rates (Wullschleger and Norby 2001, Tang et al. 2006, Kume et al. 2007, Hernández-Santana et al. 2008, Peters et al. 2010, Horna et al. 2011), which was also true for Moso bamboo in Japan (Komatsu et al., 2010). The decreasing accumulated sap flux densities in bamboos under high VPD that we observed were related to fluctuations in soil moisture (for three of the four bamboo and two of the three studied tree species). During the dry season, VPD was generally much higher and soil moisture became a limiting factor after several days without rainfall: Accumulated daily sap flux densities decreased strongly and linearly with decreasing soil moisture content under 'dry period conditions' (i.e. > 0.74 kPa) for the studied bamboo (except *D. asper*) and tree species (except *G. arborea*) (**Figure 2.5**). For the studied bamboo species, this could be attributed to a generally relatively shallow rooting depth of bamboos, which could potentially result in restricted water uptake during dry periods (Bréda et al. 2006). However, as two out of three studied tree species (on directly adjacent sites) showed similar reductions in accumulated daily sap flux densities at VPD > 0.74 kPa, generally low soil water storage capacities at our study sites likely limit water uptake of all species after several days without rainfall, which occurred several times during our measurement period. Our study sites in the common garden of Bogor Agricultural University were highly frequented and partly located in between roads and buildings. Additionally, several sites were located on (slightly) sloped terrain. Water storage capacities of these compacted soils can thus not be expected to be high, which is strongly reflected in reduced sap flux densities under dry period conditions in five of seven studied tree and bamboo species.

Regarding the diurnal course of sap flux density, the studied bamboo species showed a rather early peak (10:21-11:23 am), i.e. before the micrometeorological drivers PAR (11:43 am) and VPD (13:31 am) peaked. In the studied tree species, peaks of J_S occurred much closer to the respective PAR and VPD peaks. Previous studies on tropical trees also reported rather small time-lags between peaks of J_S and PAR and VPD, respectively (e.g. Dierick and Hölscher 2009, Köhler et al. 2009, Horna et al. 2011). Pre-noon peaks of sap flux density have only been described for few species thus far, e.g. for *Acer rubrum* (Johnson et al. 2011) and oil palms (Niu et al. 2015). The early sap flux peaks result in substantial hysteresis (i.e. integrated diurnal differences between micrometeorological 'input' and transpirational 'output') of J_S particularly to VPD (pronounced in two of four studied bamboo species). For another monocot species, i.e. oil palm, it has been suggested that such pre-noon peaks of J_S and the resulting large hysteresis to VPD could be related to internal trunk water storage and/or root pressure mechanisms (Niu et al. 2015, Röll et al. 2015). Early peaks of J_S might be explainable by a pre-noon contribution of internal water storage to bamboo transpiration. Likewise, the decoupling of hourly sap flux density values particularly from VPD in the afternoon, i.e. a drop in bamboo sap flux densities (after an early peak) despite further rising VPD could be connected to the depletion of internal water storage at a certain time of the day. The pre-noon water losses from the stem may then be compensated for during night time hours. Root pressure mechanisms, which have been observed on several bamboo species (e.g. Cao et al. 2012), could contribute to such night-time recharging and thus support the observed high water use rates relatively early in the day (Cao et al. 2012, Yang et al. 2012). Night-time root pressure mechanisms may also help xylem recover from cavitation and thus likely contribute to the maintenance of stem xylem and leaf conductivity in monocot species in general (e.g. Saha et al. 2009, Wang et al. 2011, Cao et al. 2012, Yang et al. 2012). However, despite first potential indications of stem water storage related mechanisms, the controlling factors of bamboo water use yet remain to be revealed. E.g., down-regulating mechanisms from the leaf-level, i.e. leaf water conductivity loss due to stomatal control mechanisms in the afternoon hours, may prevent stem water potential loss and consequent severe xylem cavitation (e.g. Saha et al. 2009, Yang et al. 2012) and could thus also potentially be responsible for the observed diurnal decoupling of the afternoon bamboo sap flux response from micrometeorological drivers and particularly VPD.

2.5 Conclusions

Adjusting and applying the TDP method for sap flux measurements on four bamboo species pointed to substantial differences in water use characteristics between the studied bamboos and three studied tree species. Bamboos had higher sap flux densities, and respective hourly maxima were reached earlier in the day than in tree species. This resulted in strong diurnal hysteresis, particularly to VPD, and in significant time lags between the peaks of sap flux density in bamboos and the peaks of radiation and VPD, respectively. Both may point to internal water storage mechanisms. There were substantial differences in the day-to-day sap flux density response of most studied bamboo and tree species to fluctuations in environmental drivers between the dry and the rainy season. Reduced sap flux densities in the dry season could largely be explained by limiting soil moisture content. The regulation of bamboo water use could thus involve mechanisms at the leaf-, culm- and root-level. However, these mechanisms remain to be inter-connected convincingly.

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2.6 References Chapter 2

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2.6 Appendix Chapter 2

Table 2.4. The influence of the three factors formula type, time step and formula specificity on the performance of the linear calibration model. Results of multi-ANOVA of the three factors against normalized Root-Mean-Square Error (nRMSE, calculated by normalizing the RMSE with the observed range of sap flux densities from stem heat balance (SHB) measurements; RMSE derived from SHB measurements vs. model-predicted values of each day). Data of 63 days were used. P<0.01 indicates significant difference.

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**P**
Formula type	1	0.0046	0.0046	0.68	0.4093
Time step	3	0.0046	0.0015	0.23	0.8777
Formula specificity	2	7.7675	3.8838	577.54	<.0001

Table 2.5. Performance of culm-specific vs. species-specific vs. common linear formulas for a simple linear field calibration of the thermal dissipation probe (TDP) method with the stem heat balance (SHB) method on five bamboo species Normalized Root-Mean-Square Errors (nRMSE) and passing rates of the Wilcoxon Signed-Rank test for each species and formula specificity type. Superscripted letters indicate significant differences between nRMSEs and passing rates, respectively, within each species (Tukey's test, P<0.05).

Species	**Formula specificity**	**nRMSE**	**Passing rate (%)**
B. vulgaris	common	0.11^{a}	83^{a}
	culm	0.04^{b}	94^{b}
	species	0.10^{a}	84^{a}
G. apus	common	0.12^{a}	77^{a}
	culm	0.06^{b}	90^{b}
	species	0.10^{a}	81^{a}
D. asper	common	0.18^{a}	74^{a}
	culm	0.04^{b}	94^{b}
	species	0.18^{a}	70^{a}
G. atroviolacea	common	0.13^{a}	74^{a}
	culm	0.06^{b}	89^{b}
	species	0.12^{a}	74^{a}

Chapter 3

Oil palm water use: calibration of a sap flux method and a field measurement scheme

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Abstract Chapter 3

Oil palm (Elaeis guineensis Jacq.) water use was assessed by sap flux density measurements with the aim to establish the method and derive water use characteristics. Thermal dissipation probes were inserted into leaf petioles of mature oil palms. In the laboratory, we tested our set-up against gravimetric measurements and derived new parameters for the original calibration equation which are specific to oil palm petioles. In the lowlands of Jambi, Indonesia, in a 12-year-old monoculture plantation, 56 leaves on 10 palms were equipped with one sensor per leaf. A 10-fold variation in individual leaf water use among leaves was observed, but we did not find significant correlations to the variables trunk height and diameter, leaf azimuthal orientation, leaf inclination or estimated horizontal leaf shading. We thus took an un-stratified approach to determine an appropriate sampling design to estimate stand transpiration (E_s, mm day^{-1}) rates of oil palm. We used the relative standard error of the mean (SE_n, %) as a measure for the potential estimation error of E_s associated with sample size. It was 14% for a sample size of 13 leaves to determine the average leaf water use and four palms to determine the average number of leaves per palm. Increasing these sample sizes only led to minor further decreases of the SE_n of E_s. The observed 90-day average of E_s was 1.1 mm day^{-1} (error margin ± 0.2 mm day^{-1}), which seems relatively low, but does not contradict Penman-Monteith-derived estimates of evapotranspiration. Examining the environmental drivers of E_s on an intra-daily scale indicates an early, pre-noon maximum of E_s rates (11 am) due to a very sensitive reaction of E_s to increasing vapor pressure deficit in the morning. This early peak is followed by a steady decline of E_s rates for the rest of the day, despite further rising levels of vapor pressure deficit and radiation; this results in pronounced hysteresis, particularly between E_s and vapor pressure deficit.

Keywords: sample size, thermal dissipation probes, transpiration, error margins, environmental drivers

3.1 Introduction

Oil palms (*Elaeis guineensis* Jacq.) are cultivated in large areas of humid tropical lowlands and a further expansion is predicted (FAO 2014). Information on oil palm water use characteristics is limited and the available studies are based on micrometeorological, soil water budget or catchment approaches (e.g. Radersma and de Ridder 1996, Kallarackal et al. 2004). Sap flux techniques may contribute to generating further information, e.g. on a smaller spatial scale, but to our knowledge have not yet been applied to oil palms.

A widely used sap flux technique is the thermal dissipation probe (TDP) method (Granier 1985, 1987). It has been applied to study water use characteristics of dicot trees (e.g. Wilson et al. 2001, Kunert et al. 2012) and relatively recently also of monocot species such as bamboos (Dierick et al. 2010, Kume et al. 2010a) or palms (e.g. Renninger et al. 2010, Sperling et al. 2012). If the TDP method is calibrated, it can give reliable results (Bush et al. 2010, Sun et al. 2012), is less costly than other methods and can therefore be used at a relatively high number of spatial replicates within or between stands.

For palms, insights on hydrological characteristics remain scarce. Measuring sap flux density in the trunk of palms, radial variations in sap flux density have been observed in date palms (*Phoenix dactylifera* L.) (Sellami and Sifaoui 2003, Sperling et al. 2012), while it was constant at all depths for coconut palms (*Cocos nucifera* L.) (Roupsard et al. 2006). Axial variations of sap flux density have also been observed, from the roots over different heights of the trunk to leaf petioles, revealing certain time lags in the response of sap flux density that may point towards internal water storage mechanisms (Sellami and Sifaoui 2003, Renninger et al. 2010).

In many palms, the large dimensions of leaf petioles and their presumably higher vessel density compared to the trunk, as well as the presumed homogeneity in the distribution of vascular bundles, make petioles a suitable location for measurements with thermal methods (Madurapperuma et al. 2009, Renninger et al. 2009). Extrapolated to water use per palm, measurements on leaf petioles have proven to compare well to those from the trunk (Renninger and Phillips 2010).

When scaling up from leaves to the transpiration of a whole stand, the sample size (i.e. the number of leaves measured) should be large enough to capture the variability that is likely to occur. In some cases, stratification, e.g. with respect to azimuth, plant size or other variables, may be advisable. Among others, Kume et al. (2010b) statistically derived potential errors in estimates of stand transpiration associated with sample sizes and suggested an "optimal" sample size after which the decrease in error with increasing sample size is marginal.

In our study, we tested the TDP method on oil palm leaf petioles in the laboratory and applied this method to oil palms in a small-holder plantation in the lowlands of Jambi, Indonesia. The objectives were (1) to test and if necessary derive oil-palm-petiole-specific parameters for the original calibration equation by Granier (1985), (2) to derive an appropriate measurement scheme for field studies with respect to the positioning and number of sensors, (3) to estimate stand transpiration including error margins, and (4) to evaluate the transpiration response to fluctuations in vapor pressure deficit and radiation. The study may thus contribute to optimizing sap flux based field measurement schemes and to generating insight on the water use characteristics of oil palms.

3.2 Methods

3.2.1 Laboratory calibration experiment

3.2.1.1 Basic considerations and technical specifications

Sensors were installed in leaf petioles rather than in the trunk because vessel density is presumably higher and distributed more homogeneously. We used thermal dissipation probes (TDP, Granier 1987, 1996a) of 12.5 mm in length and 2.0 mm in diameter (36 windings of heating wire) to measure sap flux density (J_s, g cm^{-2} h^{-1}) in oil palms. We diverged from the original probe length (12.5 instead of 20 mm) to reduce the spatial variability of sap flux density and of water conducting properties along the sensor (Clearwater et al. 1999, James et al. 2002). The downstream probe of each sensor was connected to a 12 V power source and heated continuously by the Joule effect, following the specifications by Granier (1987, 1996a). Due to the reduced probe length, and the subsequently reduced electrical resistance, the power output per probe was lower than for the original probes; however, the probe loading, i.e. the power output per cm of probe, was identical (approx. 0.1 W cm^{-1}). The differential voltage between heated probe and reference probe was recorded by a CR1000 data logger (Campbell Scientific Inc., Logan, UT, USA) every 30 sec and averaged and stored every 10 min.

3.2.1.2 Experimental set-up

The calibration experiment was conducted in the laboratory of the University of Jambi, Indonesia. Mature and healthy oil palm leaves were cut from a plantation near campus in the early morning; they were immediately submerged into clean water. In the laboratory, the petiole-segments were re-cut under water and shaved with a razor blade (Renninger et al. 2010, Steppe et al. 2010). The prepared segments were vertically suspended into a PVC pipe (**Figure 3.1**). Eight segments with a length of 60 cm were used for the calibration experiments. A siphon construction (**Figure 3.1**) was used to control the water level in the pipe (also see Steppe et al. 2010). To allow the reading from the TDP sensors to stabilize, each pressure regime was upheld for 30 min before decreasing the water level in steps of 20 cm. The procedure was repeated various times to ensure a broad spectrum of sap flux densities in the recorded data. We used purified water with 20 mM KCl for the calibration experiments to decrease hydraulic resistance (Zwieniecki et al. 2001).

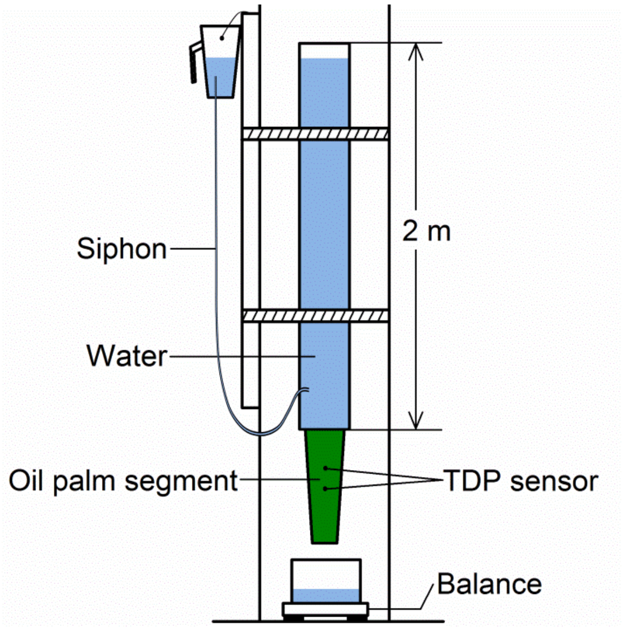

Figure 3.1. Experimental set-up for the comparison of thermal dissipation probe (TDP) measurements with gravimetric readings on oil palm petioles (calibration experiment).

The two probes of each sensor were inserted into pre-drilled holes on the underside of petiole-segments (**Figure 3.2a**), at a distance of 10 cm. Prior to insertion into the leaf, probes were covered with heat conductive paste and slid into tightly fitting aluminum sleeves. To provide a reference measure for the TDP-derived sap flux density, a container was placed on a balance (0.01 g resolution) below the segment to record the water flow (g h^{-1}) through the segment. Dividing the recorded flow by water conductive area (A_c, cm^2) yielded the gravimetric sap flux density (J_g, g cm^{-2} h^{-1}).

To quantify the A_c of leaf petioles and to allow for a visual examination of the variability of vessel density (D_v, cm^{-2}) over this area, seven additional segments were cut and set up in the same way as for the calibration experiment; a 0.1% indigo carmine solution was added to the purified water and the water was pressured through each segment for 4–6 hours. After staining, each segment was sawn into cross-sectional pieces. Photos were taken and the A_c and the baseline length (L_b, cm) (**Figure 3.2a**) of each piece were calculated with Image J (Image J, National Institutes of Health, Bethesda, MD, USA, http://imagej.nih.gov/ij/, 26 February 2015, date last accessed). A linear regression was used to examine the relationship between L_b and A_c. To examine the within-segment variability of D_v, ten 1 cm^2 squares were evenly distributed over the cross-sectional area of each segment, and the vessels that lay within each square were counted on digitally enlarged pictures.

3.2.1.3 Deriving new parameters for the calibration equation

The recorded signals from the TDP sensors were converted into sap flux density (J_s, g cm^{-2} h^{-1}) with the original calibration equation by Granier (1985):

$$J_s = aK^b \tag{3.1}$$

Where a and b are equation parameters (Granier 1985: a = 42.84, b = 1.231), and K is defined as:

$$K = \frac{\Delta T_{max} - \Delta T}{\Delta T} \tag{3.2}$$

Where ΔT_{max} (°C) is the temperature difference between heated and reference probe under zero-flux conditions, and ΔT (°C) is the temperature difference at a given time-step. To determine ΔT_{max} under laboratory conditions, the segments were suspended horizontally for several hours.

For deriving oil-palm-petiole-specific parameters a and b for the calibration equation, we first randomly selected 10 observations from the gravimetric vs. TDP-derived sap flux density data pairs (10-minute-averages) for each segment used in the experiments. This ensured that all segments entered the calibration procedure with the same weights, since the number of observations was not equal for all segments. We then pooled the selected observations of all segments. To create a dataset for a cross validation of the newly-derived parameters, we randomly split the pooled dataset in two halves: one for deriving new parameters, and the other for the validation. In the validation dataset, we tested the performance of the new parameters a and b on a dataset not included in the fitting process. We compared J_s values derived from the original and the new parameters, respectively, to the reference J_g values by using the Wilcoxon signed-rank test. To ensure the stability of the result, we repeated this procedure 10,000 times.

3.2.2 Field study

3.2.2.1 Study site

The field study was carried out in a 12-year-old small-holder monoculture oil palm plantation (2°04′15.2″S, 102°47′30.6″E) in Jambi, Indonesia, at an elevation of 71 m above sea level (a.s.l.) on a southward-facing slope with an inclination of about 20°. The site is part of a larger experimental set-up of the CRC990 (www.uni-goettingen.de/crc990, 26 February 2015, date last accessed) and is referred to as "BO3". At the Jambi airport, approximately 100 km distant from our plot, the average annual temperature was 26.7 ± 1.0 °C (data from 1991 to 2011; mean ± SD), with little intra-annual variation. Annual precipitation was 2235 ± 385 mm; a dry season with less than 120 mm monthly precipitation usually occurred between June and September, but the magnitude of dry season rainfall patterns varied highly between years (A. Meijide et al. unpublished data). Soil type in the plot is a clay acrisol (K. Allen et al., S. Kurniawan et al. unpublished data). The palms are 4.2 ± 0.6 m (mean ± SD) high, with a diameter at breast height (DBH, cm) of 81 ± 7 cm and 40 ± 2 leaves per palm. The stand density is 138 ha^{-1}. Management activities included regular fruit harvest and pruning of lower leaves; fertilizer and pesticides were regularly applied on the plot in quantities typical for small-holder plantations in the region (M. M. Kotowska et al. unpublished data).

3.2.2.2 Environmental measurements

A micrometeorological station was set up approx. 3 km from the BO3 plot. It was placed in open terrain. Air temperature and relative humidity were measured at a height of 2 m with a Thermohygrometer (type 1.1025.55.000, Thies Clima, Göttingen, Germany) to calculate vapor pressure deficit (VPD, kPa). Wind speed was measured with a three cup anemometer (Thies Clima) at a height of 4 m. A net radiation sensor (NR Lite2, spectral range 200–100,000 nm, Kipp & Zonnen, Delft, The Netherlands) and a short wave radiation sensor (CMP3 Pyranometer, spectral range 300–2800 nm, Kipp & Zonen) were installed at a height of 3 m, the latter to measure global radiation (R_g, MJ m^{-2} day^{-1}, from here on referred to as "radiation"). Measurements were taken every 15 sec and averaged and stored on a DL16 Pro data logger (Thies Clima) every 10 min. A soil moisture sensor (Trime-Pico 32, IMKO, Ettlingen, Germany) was placed in the center of the research plot at a depth of 0.3 m into the soil and was connected to a data logger (LogTrans16-GPRS, UIT, Dresden, Germany). Data were recorded hourly. During our observation period soil moisture never fell below 35 vol.%. All data were recorded for our full 90-day sap flux measurement period (from 3 July to 30 September 2013).

Evapotranspiration (mm day^{-1}) was calculated with the FAO Penman-Monteith-equation (FAO 56: Allen et al. 1998) based on the previously described micrometeorological input variables and using a crop coefficient of 0.9 for mature oil palm plantations (Carr 2011).

3.2.2.3 Sap flux measurements

We installed sap flux sensors in 56 oil palm leaf petioles, with one sensor per leaf. 10 palms with a trunk height between 3.2 and 5.3 m were selected. On four palms, we equipped eight leaves in the North, East, South and West with sensors; on the remaining palms, four leaves were equipped (North and South only). In each direction, we installed sensors on one leaf of higher (65–85°) and one leaf of lower (45–65°) inclination (**Figure 3.2b**). The sensors were placed approx. 0.5 m from the base of the petiole at the trunk, approx. 0.4 m (upstream) from the first leaflets. Probe preparation and installation, technical specifications and data logging were identical to the calibration experiments (see 3.2.1); sensors were protected from environmental influences with various layers of insulative materials. The 90-day measurement period lasted from 3 July to 30 September 2013.

The water conductive area of each sample leaf in the field was estimated from the baseline length between upper and lower probe (**Figure 3.2a**) by using the regression derived from staining experiments (see 3.2.1.2). Sap flux densities were calculated with the calibration equation by Granier (1985), but with newly-derived parameters (see 3.2.1.3). To assure that zero-flux nighttime conditions were met under field conditions, we examined the values in our sap flux dataset adjacent to the respective values of ΔT_{max} (following Oishi et al. 2008); they remained stable over several hours during the early morning hours, when VPD was consistently below 0.1 kPa; we thus think that zero-flux nighttime conditions were met during our measurement period.

3.2.2.4 Leaf and palm characteristics

For all sample leaves, orientation and inclination at the base of the petiole were recorded. The horizontally projected relative area of each leaf that was covered by overlying leaves at a zenith angle of zero (“horizontal leaf shading”) was roughly estimated by a simultaneous visual assessment from the ground and the canopy. For each of the 10 sample palms, trunk height and DBH were measured and the number of leaves was counted. During the period of measurements, new leaves emerged and old ones were pruned by the farmers; we assumed the number of leaves per palm to be constant over time.

3.2.3 Scheme for scaling up from leaves to stand

Individual leaf water use (Q, kg day^{-1}) rates were calculated by multiplying the respective integrated daily sap flux densities by water conductive areas; the Q values of all leaves measured simultaneously were averaged to obtain the average leaf water use (E_L, kg day^{-1}). To scale up from leaves to stand water use, we used the following equation (adjusted from Granier et al. 1996b):

$$E_{\mathrm{S}} = \frac{E_{\mathrm{L}} \times N_{\mathrm{L}} \times N_{\mathrm{p}}}{A_{\mathrm{g}}} = \frac{(\bar{J}_{\mathrm{S}} \times \bar{A}_{\mathrm{c}}) \times N_{\mathrm{L}} \times N_{\mathrm{p}}}{A_{\mathrm{g}}} \tag{3.3}$$

Where E_S is the stand transpiration (mm day^{-1}), E_L (kg day^{-1}; equals mm m² day^{-1}) is the average leaf water use as a product of average integrated daily sap flux density ($\bar{J}_S$, kg cm^{-2} day^{-1}) and average leaf water conductive area ($\overline{A}_c$, cm²); N_L is the average number of leaves per palm; N_p is the number of palms per ground area (A_g, m²). N_p is constant and can be counted directly, i.e. the sources of error for estimates of E_s come from the estimates of E_L and N_L exclusively.

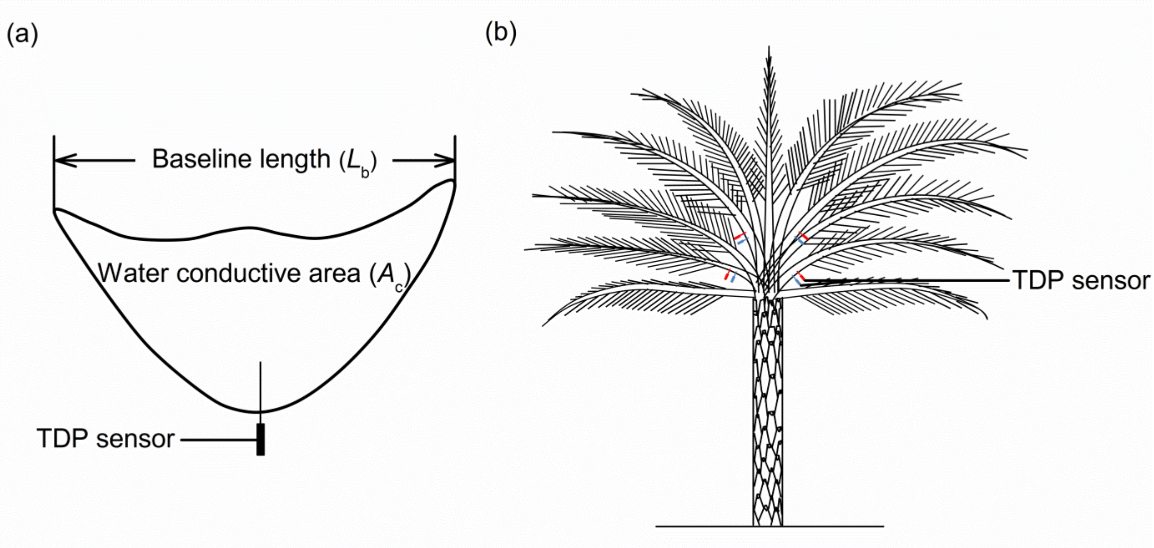

Figure 3.2. Cross-section of an oil palm petiole at location of probe installation (a) and installation of thermal dissipation probes (TDP) on oil palms in the field (b).

3.2.4 Estimation errors associated with sample size

The individual leaf water use Q rates of 47 leaves (nine of 56 installed sensors excluded due to technical problems) on three sunny days (30 May–1 June 2013) were averaged for the analysis in order to minimize weather-induced variability among leaves. In a first step, we tested whether strata such as azimuthal orientation or trunk height had to be taken into account: for all measured field variables (leaf orientation, inclination and shading, trunk height and diameter), linear regressions were performed; multiple linear regressions were used to examine interactions. The Q values of the different strata were compared with the Student's t-test. To test for normality of the distribution of Q values, we performed the Shapiro-Wilk normality test. The distribution of the Q values was normal, so that the relative standard error of the mean (SE_n) serves as a measure of the estimation error associated with sample size. We calculated mean and standard deviation (SD) of the Q values and normalized the SD by the mean to obtain the relative standard deviation (SD_n). To examine how different sample sizes (i.e. number of leaves, n) affect the magnitude of the SE_n, we used n = 1–47 to calculate respective SE_n values of E_L with the equation

$$\mathrm{SE_n} = \frac{\mathrm{SD_n}}{\sqrt{n}} \tag{3.4}$$

Where SE_n is the relative standard error of the mean of E_L in dependence of the sample size (n), and SD_n is the relative standard deviation of E_L for the full sample of 47 leaves.

We defined the statistically “optimal” sample size (n_o), to be that n, at which a further increase of n (dn) results in only marginal gains of precision of the estimate of E_L (i.e. $dSE_n > –0.5\%$). To derive n_o analytically, we set the first derivate of equation (4) equal to –0.005 (i.e. –0.5%) and solved it for n_o:

$$n_{\mathrm{o}} = (\frac{\mathrm{SD_n}}{0.01})^{\frac{2}{3}} \tag{3.5}$$

Where SD_n is the relative standard deviation of E_L for the full sample of 47 leaves and n_o is the analytically-derived “optimal” sample size, where $\frac{\mathrm{dSE_n}}{\mathrm{dn}} > –0.005$.

We counted the number of leaves per palm on our full sample of m = 10 palms. Like E_L, N_L was normally distributed, so that, in analogy to the procedure just explained for E_L, an “optimal” sample size (m_o) for estimates of N_L could be derived. To quantify the total error in estimates of E_s it is assumed that the total variance around E_s is given by the combined variances of E_L and N_L. Hence, as an estimate of the SE_n of E_s, we can add the respective SE_n of E_L and N_L for any given combination of sample sizes (product rule), e.g. for the “optimal” sample sizes n_o and m_o.

3.2.5 Analyzing the environmental drivers of leaf water use

To visualize and examine meteorological drivers of water use over a 90-day-period (3 July to 30 September 2013), daily E_L values were plotted against radiation and VPD. Normalized hourly values of E_L (average of three sunny days) were plotted against normalized radiation and VPD in order to examine the occurrence of hysteresis. All observations with a minimum of 13 TDP sensors running simultaneously were included in the analysis.

Statistical analyses were performed with R version 3.1.1 (R Development Core Team 2014); for graphing, Origin 8.5 (Origin Lab, Northampton, MA, USA) was used.

3.3 Results

3.3.1 Calibration experiment

We observed a linear relationship between L_b and A_c of oil palm petioles: $A_c = 3.95\ L_b - 9.86$ ($R^2 = 0.97$, $P < 0.001$). Average vessel density was 45 cm^{-2}, with an average within-segment coefficient of variation of 12% among ten 1 cm² squares. Our estimates for the parameters of the calibration equation were a = 48.24 and b = 1.60 ($R^2adj = 0.90$, $P < 0.001$), whereas the values by Granier (1985) were a = 42.84 and b = 1.23. The Wilcoxon signed-rank test suggested that J_s calculated with the original calibration equation (Granier 1985) were significantly different ($P < 0.05$) from J_g. Using the newly-derived parameters yielded J_s values that were not significantly different from J_g in 84% of 10,000 times. The linear relationship between J_s values derived from the original parameters (Figure 3.3a) and our new parameters (**Figure 3.3b**) with J_g was strong in both cases ($R^2 > 0.94$, $P < 0.001$, RMSE = 2.48 and 1.81, respectively); however, using the newly-derived parameters increased the precision of predictions from an overestimation of 17.3% (original parameters) to a slight underestimation of 1.6%.

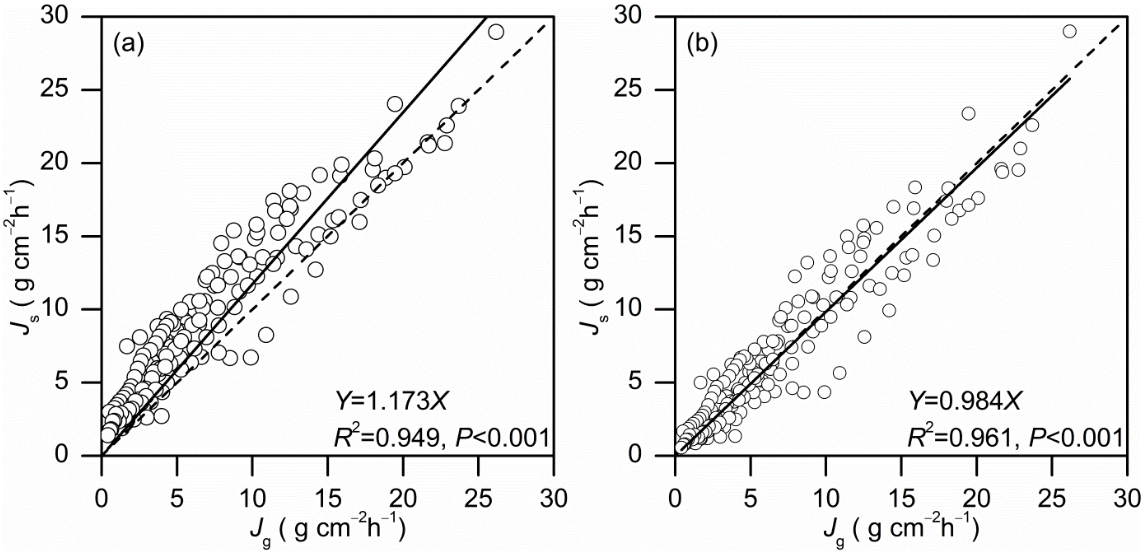

Figure 3.3. Sap flux densities derived from gravimetric measurements (J_g) and thermal dissipation probes (J_s) using the original parameters of the calibration equation (a) and our newly-derived parameters (b). Pooled data from eight oil palm segments, points represent 10-minute-averages, regression lines (solid lines) were forced through the origin, dashed lines indicate a 1:1 relationship.

3.3.2 Field study

3.3.2.1 Spatial variability of leaf water use

Under sunny conditions (three days averaged), there was a 10-fold variation in Q rates of 47 oil palm leaves, ranging from 0.5 to 4.9 kg day^{-1}; average Q was 2.5 ± 1.1 kg day^{-1} (mean ± SD). Linear regressions suggest that there was no significant influence of the factors leaf orientation, inclination and estimated horizontal shading and of trunk diameter and height on Q ($P > 0.5$). Testing for interaction of these single factors with multiple linear regressions again revealed no significant influence of any combination of variables on Q ($P > 0.5$). The mean Q values in different strata of leaf orientation (N, E, S, W), inclination (<, ≥ 60°), shading (<, ≥ 50%) and trunk height (<, ≥ 4.5 m) and diameter (<, ≥ 78 cm) were not significantly different ($P > 0.05$, Student's t-test).

3.3.2.2 Sample size

The analysis of potential estimation errors of E_L associated with sample size (i.e. the number of leaves measured, n) suggests that the SE_n of E_L was high ($SE_n > 30\%$) for very small samples ($n \leq 2$), but decreased relatively fast to a SE_n of 11.7% at the statistically “optimal” sample size, $n_o = 13$. Further increasing n improved the precision of estimation of E_L only under-proportionally (**Figure 3.4a**). As the number of leaves per palm only varied little between palms, the SE_n of N_L was much lower ($SE_n < 5\%$), even at small sample sizes (e.g. $m = 1$ palm); it decreased to 2.5% at the “optimal” sample size, $m_o = 4$ (**Figure 3.4b**). Assuming that the variance around the E_s estimate is given by the combined variances of the estimates of E_L and N_L, we can provide $SE_n = 11.7 + 2.5 = 14.2\%$ as an estimate for the total potential error in the estimate of E_s at $n_o = 13$ and $m_o = 4$. To decrease this total SE_n further (e.g. $SE_n = 10\%$), much larger sample sizes for n are necessary (e.g. $n = 33$, $m = 4$). The full available sample of 47 leaves and 10 palms resulted in a SE_n of E_s of 6.5%.

3.3.2.3 Estimate of oil palm transpiration including error margins

Average E_s during the 90-day measurement period was 1.1 mm day^{-1}, ranging from 0.5 to 1.3 mm day^{-1}, based on a minimum number of 13 leaves measured simultaneously and a leaf count on 10 palms. Under such conditions, the assessment of estimation errors associated with sample sizes suggested a SE_n of E_s of 13.3%. This results in 1.1 ± 0.2 mm day^{-1} as an estimate for E_s including standard error based error margins. The Penman-Monteith-derived estimate of stand evapotranspiration was 2.6 mm day^{-1} for the same period.

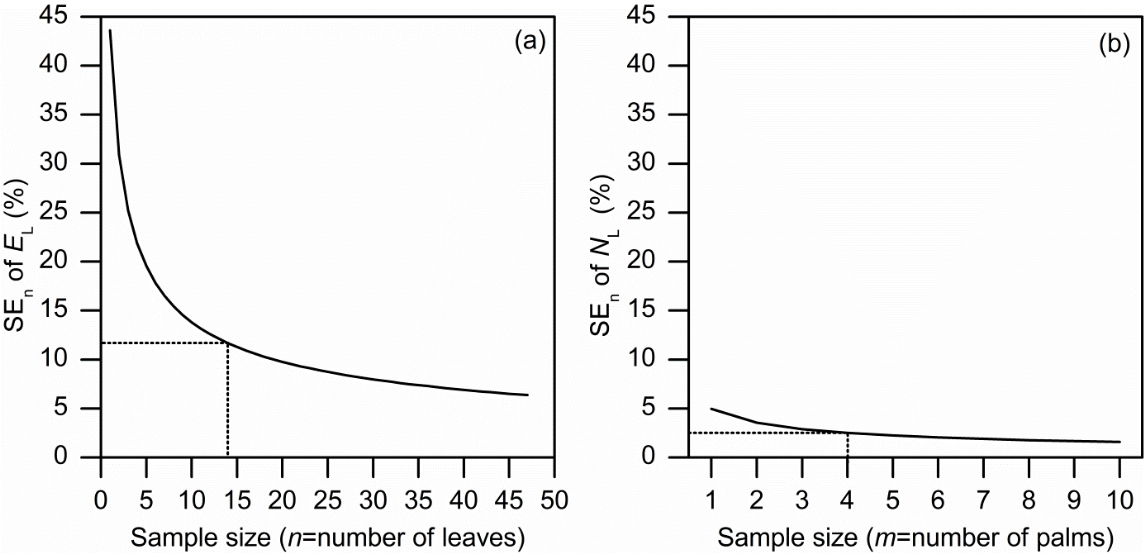

Figure 3.4. Relative standard error of the mean (SE$_n$) of average leaf water use (E$_L$) (a) and of the average number of leaves per palm (N$_L$) (b) in dependence of sample size, the number of measured leaves (n) and sampled palms (m), respectively. The dotted lines indicate “optimal” sample sizes, at which $\frac{\mathrm{dSE_n}}{\mathrm{dn,dm}} > -0.005$.

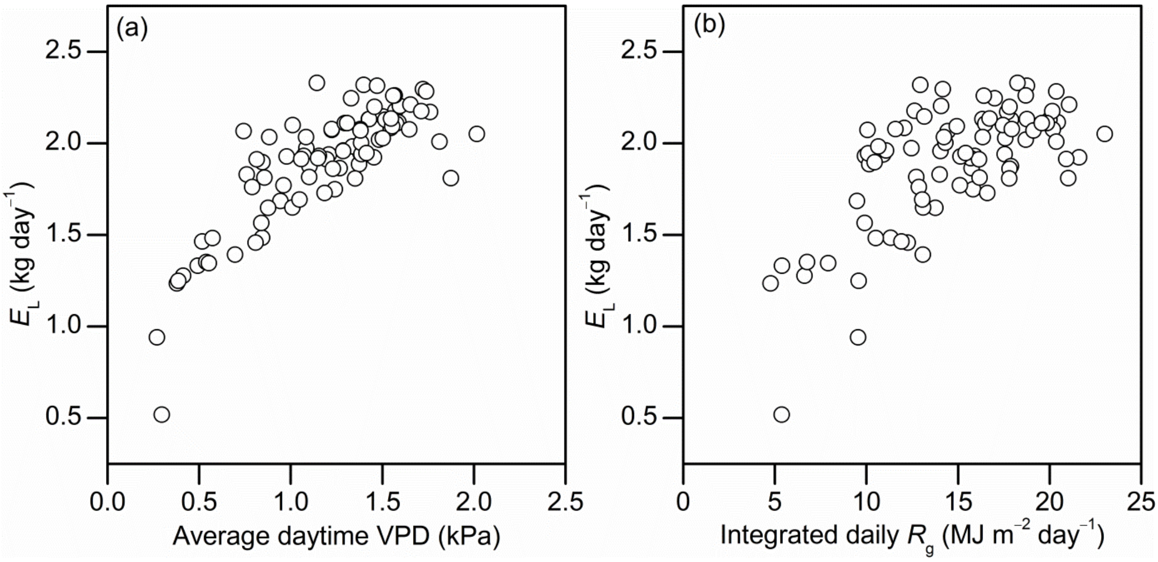

Figure 3.5. Average leaf water use (E$_L$) plotted against average daytime vapor pressure deficit (VPD) (a) and integrated daily radiation (R$_g$) (b). Data of 90 days, E$_L$ estimates based on at least 13 leaves measured simultaneously.

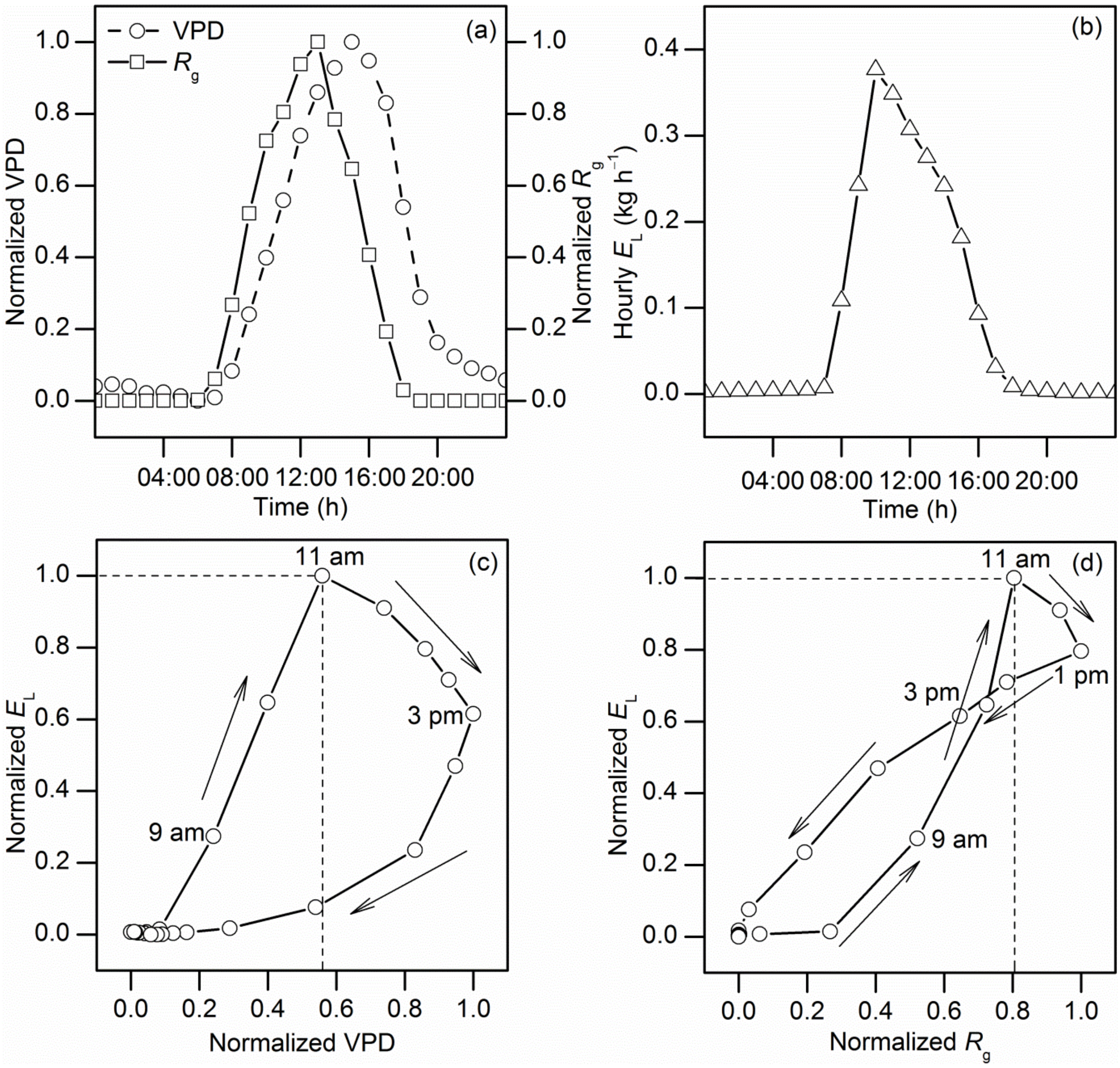

Figure 3.6. The diurnal courses of vapor pressure deficit (VPD) and radiation (R_g) (a) and of average leaf water use (E_L) (b). Normalized E_L plotted against normalized VPD (c) and normalized R_g (d). The points represent hourly means of three sunny days; the arrows indicate the direction in which the next consecutive observation in time occurred. E_L estimates based on at least 13 leaves measured simultaneously.

3.3.2.4 Meteorological drivers of leaf water use

The average leaf water use E_L rates over a 90-day-period was driven by the variables VPD and R_g (**Figure 3.5**); it leveled-off around 2.2 kg day^{-1}, after rising almost linearly with increasing VPD and R_g before that.

The diurnal course of hourly E_L (averages of three sunny days) was also related to VPD and R_g (**Figure 3.6**), but we observed hysteresis in the E_L response to both of these variables. Maximum E_L rates were reached early in the day (around 11:00 am). After this early peak, E_L rates declined relatively consistently, despite rising levels of R_g and VPD. By the time R_g and VPD peaked, around 1 pm and 3 pm, respectively, E_L was already reduced to about 80% and 60%, respectively, of its maximum. Despite similar VPD levels, E_L rates were 10-fold higher at their 11 am peak than in the late afternoon. Likewise but less pronounced, similar R_g levels resulted in 30% lower E_L rates in the early afternoon (2 pm) than at the 11 am peak.

3.4 Discussion

3.4.1 Calibration

We used thermal dissipation probes (Granier 1987, 1996a) to measure sap flux density in oil palms. We measured in leaf petioles rather than trunks because vessel density and size is presumably larger and vessels are presumably distributed more homogeneously (Parthasarathy and Klotz 1976). Also, the large dimensions of oil palm trunks (up to 100 cm DBH) make an assessment of the radial variability of sap flux density difficult. For other palm species, inhomogeneous radial patterns of sap flux density have been shown (Sellami and Sifaoui 2003, Sperling et al. 2012). Within leaf petioles, variations in the vessel density D_v across the cross-sectional area have been observed in some palm species (Parthasarathy and Klotz 1976), suggesting a peripheral increase in D_v and a potentially lower D_v towards the center of the petiole. We did not find references for oil palm. TDP sensors are assumed to integrate variations in sap flux density along their length (Granier et al. 1994), which should account for variations in D_v; however, this may not be the case if changes in sap flux density are abrupt (Clearwater et al. 1999).

To reduce the spatial variability of sap flux density and of water conducting properties along the sensor and thus enhance the precision of sap flux density estimates (Clearwater et al. 1999, James et al. 2002), we diverged from the Granier (1987, 1996a) design with regard to probe length, reducing the number of windings of heating wire to 36, half of the original design. As the Teflon coating around our constantan heating wire was marginally thicker than in the original design, the total length of our heating element was 12.5 mm. Exploratory experiments showed, that differences in probe loading (i.e. power output per cm probe) as the result of such differences in obtainable materials for probe construction did not exceed 0.01 W cm^{-1}.

Our calibration experiments yielded new parameters for the original calibration equation, which significantly improved the prediction of gravimetric measurements compared to the original parameters by Granier (1985). They reduced the divergence between TDP and gravimetric measurements from an overestimation of 17.3% (original parameters) to an underestimation of 1.6% (new parameters). The range of J_g in the calibration experiments covered the range of J_s observed under field conditions very well: despite an almost 40% higher maximum J_s value in the field, only 0.05% of the recorded data lay outside the J_g range we covered in the laboratory

(0–26.2 g cm^{-1} h^{-1}). Additionally, the relationship between J_s and J_g was clearly linear in the covered range; thus, we think an extrapolation of this relationship outside the observed range will most likely not induce large errors in estimates of J_s.

There have been several studies where a species-specific calibration of the TDP method was performed by comparing sap flux densities derived from TDP measurements with gravimetrically-derived values or water flux rates established by other methods. Non-contradictory estimations utilizing the original calibration equation have been reported for some diffuse-porous tree species, but large underestimations became apparent for some ring-porous species (Bush et al. 2010). Substantial deviations from reference readings (+55% to –34%) were also reported when calibrating juvenile trees of six different tree species (Sun et al. 2012). For rainforest palms (*Iriartea deltoidea* Ruiz & Pav.), larger values were obtained for the equation parameters (a and b) than by Granier (1985); however, the original equation yielded values that lay within the 95% confidence bands of the new calibration equation (Renninger et al. 2010). When comparing transpiration rates measured with a lysimeter to TDP-derived values for date palms, a 40% underestimation of sap flux density was reported with the original calibration equation (Sperling et al. 2012).

Possible reasons for the divergence between sap flux density estimates derived from the original calibration equation and reference measurements include physiological (e.g. heterogeneity of vessel density), technical (e.g. sensor type) and other methodological aspects (e.g. calibration set-up). Our new parameters resulted in a slight underestimation of sap flux density of 1.6%. However, a further validation of these new parameters, e.g. on potted oil palms with gravimetric measurements may be called for to further increase the confidence in their reliability.

3.4.2 Spatial variability of leaf water use

In the field study, we found a 10-fold variation in individual leaf water use Q rates among 47 oil palm leaves under sunny conditions. On other palm species, five- to seven-fold variations have been observed between no more than 10 sample leaves (Renninger et al. 2009, Madurapperuma et al. 2009). In our study, leaf orientation, inclination and shading, and trunk height and diameter had no significant influence on Q. We found no other studies assessing influences of leaf orientation or shading on Q; regarding leaf inclination (as a measure of leaf age), young leaves of coco palms (*Syagrus romanzoffiana* Cham.) were reported to transpire at substantially (magnitude of > 7) higher rates than old ones (Madurapperuma et al. 2009). For oil palm, a decline of photosynthesis rates over the lifespan of leaves, but little variability between leaves of the same age has been reported (Dufrene and Saugier 1993), which might be contradictory to the results of our study.

Given the close proximity of our study site to the equator (2° South), the relatively short life span of oil palm leaves before being cut (five to 10 months) and the open and dome-shaped architecture of oil palm crowns, it seems reasonable that the variables leaf orientation, inclination and shading failed to explain the observed variability in Q. Trunk height also did not influence Q in our study; similar findings have been reported for Mexican fan palms (*Washingtonia filifera* Linden ex André H Wendl.) (Renninger et al. 2009) and two Amazonian palm species (*I. deltoidea* and *Mauritia flexuosa* L.) (Renninger and Phillips 2010). We found no statistical interaction of the five single factors leaf orientation, inclination and shading and trunk height and diameter that impact Q (multiple linear regressions, $P > 0.5$ for all combinations of variables). Possibly, some of the examined variables counteract over the lifespan of an oil palm leaf: very young leaves may have a higher water use per area of conductive tissue, but are small and hence have a relatively small cross-sectional conductive area; they are inclined more vertically, so they are shaded less, but also offer less horizontal area to absorb radiation.

3.4.3 Error margins of stand transpiration and “optimal” sample sizes

Based on the previously discussed results regarding the high, but unexplained variability in individual leaf water use values, we took an un-stratified approach to establish a statistically sound measurement scheme for estimating the stand transpiration E_s including error margins. The derived “optimal” sample sizes from an analysis of potential estimation errors of E_s associated with sample size were 13 leaves for estimating the average leaf water use and 4 palms for estimating the average leaf number per palm. Using larger samples improved the precision of estimates of E_s only marginally. Using the “optimal” sample sizes, the SE_n of E_s as a measure for the potential total estimation error was 14%. The SE_n can be compared to, and in our case was similar to, coefficients of variation (CV) derived from numerical Monte Carlo analyses in other studies: in Japanese cypress (*Chamaecyparis obtusa* Siebold et Zucc. Endl.) monocultures, to achieve a CV of E_s of 18%, recommend sample sizes were $i = 15$ and $j = 10$ for estimating sap flux density (on i trees) and sapwood area (on j trees) (Kume et al. 2010b). In a Moso bamboo (*Phyllostachys pubescens* Mazel ex J. Houz.) forest, sample sizes of $i = 11$ and $j = 12$ resulted in a total CV of E_s of 13% (Kume et al. 2010a). However, sample sizes likely have to be much larger than in these monoculture plantations when measuring spatially more heterogeneous stands (e.g. natural forests); small sample sizes may result in very high estimation errors (e.g. CV of $J_s = 40\%$ at $i = 8$, Granier et al. 1996c).

3.4.4 Oil palm transpiration

Our estimate for stand transpiration of oil palm (1.1 ± 0.2 mm day^{-1}; 90-day-mean ± SD) fell into the lower range of transpiration rates derived with similar techniques in tree-based tropical land-use systems (e.g. Cienciala et al. 2000, Dierick and Hölscher 2009) and tropical forests (e.g. Becker 1996, McJannet et al. 2007). Our micrometeorologically-derived estimate for evapotranspiration from the Penman-Monteith equation (FAO 56: Allen et al. 1998) was also relatively low (2.6 ± 0.7 mm day^{-1}, 90-day-mean ± SD), and does not contradict our transpiration value. The divergence between the two estimates can well be explained by the associated uncertainties and by the difference between palm transpiration and total evapotranspiration, the latter of which includes e.g. evaporation from the soil and, after rainfall events, from the palms and the epiphytes covering the trunks.

The relatively low stand transpiration values observed in our study could be due to the low stand density of 138 palms ha^{-1}. The effects of stem density are e.g shown in a study comparing two Acacia mangium Willd. stands with 510 and 990 Acacia trees ha^{-1} on Borneo: the latter had a 70% higher transpiration rate (Cienciala et al. 2000). Also, oil palm plantations have a relatively small stand crown-projection area (M.M. Kotowska et al. unpublished data: 23% gap fraction in the BO3 plot). Leaf area index also seems to be relatively low for oil palm stands (< 4 for mature plantations, Corley and Tinker 2003). We used the methodology presented here in eight further medium-aged oil palm plantations in the lowlands of Jambi (A. Röll et al. unpublished data) and observed more than two-fold higher stand transpiration rates than in the BO3 plot under similar environmental conditions (dry, sunny days). This points to a considerable variability from plot to plot, the underlying reasons of which still need to be explored.

Plotted against VPD and radiation, the average leaf water use E_L levels-off at a certain level between days, here at about 2.2 kg day^{-1} (**Figure 3.5**). Such a response is known from other studies for VPD (O'Brien et al. 2004, Kume et al. 2010b) and has been shown at similar VPD levels as in our study for photosynthesis rates of oil palm leaves (Dufrene and Saugier 1993). Radiation, however, often has a linear relationship with (tree) water use (O'Brien et al. 2004, Dierick and Hölscher 2009). It seems that oil palm, on an inter-daily scale (daily averages of a 90-day-period), can achieve near-maximum rates of E_L even when VPD and R_g levels are not particularly high; on the other hand, better environmental conditions for transpiration (i.e. higher VPD and R_g levels) do not induce further increases in E_L. This is indicative of a conservative behavior of the day-to-day oil palm transpiration response to environmental drivers.

To investigate this further, we examined the relationship between E_L and VPD and R_g on the intra-daily scale (hourly averages of three sunny days, Figure 3.6c and d): The E_L response in the morning was very sensitive to increases in VPD, i.e. a two-fold increase in VPD resulted in a more than three-fold increase of E_L rates between 9 and 11 am; the E_L response to increases in R_g, on the other hand, was conservative, i.e. E_L was still marginal at 8 am, when R_g had already reached 25% of its daily maximum. E_L rates peaked earlier (11 am) than R_g (1 pm) and much earlier than VPD (3 pm); they subsequently declined consistently throughout the day, regardless of further rises in R_g and VPD levels. Considerable hysteresis effects were observed, particularly for VPD: at similar VPD levels (55% of daily maximum), E_L rates were 10-fold higher at the 11 am maximum than in the late afternoon. Large hysteresis in the water use response to VPD have also been shown in other tropical species, for eucalyptus (e.g., *Eucalyptus miniata* Cunn. Ex Schauer and *Eucalyptus tetrodonta* F.Muell.) (O'Grady et al. 1999, Zeppel et al. 2004). The early peak of E_L rates, however, seems unusual. In other investigated tropical species, peaks in water use and R_g tend to coincide, or R_g peaks first (e.g. Zeppel et al. 2004, Horna et al. 2011); this is also true for tree-based land use systems in the research region (A. Röll et al. unpublished data). The pronounced hysteresis in the E_L response of oil palm to VPD as well as the unusually early peak and the subsequent steady decline of E_L rates regardless of VPD and radiation patterns may point to internal trunk water storage mechanisms. As we measured sap flux density on the leaf petioles, i.e. above the trunk, the high E_L rates at relatively low VPD and R_g levels may be made possible by trunk water storage and/or root pressure mechanisms; likewise, the steady decline in E_L rates after the 11 am peak could be explained by depleted trunk water storage reservoirs. In general, it seems that oil palms may not be able to react to e.g. high R_g or VPD levels at noon or in the afternoon. This buffered behavior of oil palm transpiration on the intra-daily level may explain why oil palms do not seem to transpire past a certain threshold ("levelling-off") on the inter-daily scale: during many of the hours with potentially favorable environmental conditions, oil palms already transpire at substantially reduced rates due to yet unexplained factors.

3.5 Conclusions

New, oil-palm-petiole specific parameters for the original calibration equation were derived in laboratory experiments. They differ from the original parameters and may allow for a more precise estimation of sap flux density in oil palms using the TDP method.

In the field, the observed variation in individual leaf water use was high, but the underlying reasons remain unknown. An un-stratified analysis of potential estimation errors of stand transpiration associated with sample size suggests analytically derived "optimal" sample sizes of 13 leaves to determine average leaf water use and counting leaves on four palms to determine the average number of leaves per palm. The resulting relative standard error of the mean of stand transpiration was 14.2%.

Our stand transpiration estimate for oil palm (1.1 mm day^{-1}) seems relatively low in comparison to values reported from other studies for a variety of tropical land-use systems. An analysis of the environmental drivers of oil palm water use on the intra-daily scale suggests a strong difference to tropical tree species. In the morning, water use rates reacted very sensitively to increases in vapor pressure deficit; they increased rapidly and reached their maximum early in the day (11 am). However, water use rates started to decline consistently after this early peak, despite further rises in vapor pressure deficit and radiation levels. This may be responsible for the observed uncoupled day-to-day behavior of oil palm transpiration from fluctuations in vapor pressure deficit and radiation levels.

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Chapter 4

Transpiration in an oil palm landscape: effects of palm age

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Abstract Chapter 4

Oil palm (*Elaeis guineensis* Jacq.) plantations cover large and continuously increasing areas of humid tropical lowlands. Landscapes dominated by oil palms usually consist of a mosaic of mono-cultural, homogeneous stands of varying age, which may be heterogeneous in their water use characteristics. However, studies on the water use characteristics of oil palms are still at an early stage and there is a lack of knowledge on how oil palm expansion will affect the major components of the hydrological cycle. To provide first insights into hydrological landscape-level consequences of oil palm cultivation, we derived transpiration rates of oil palms in stands of varying age, estimated the contribution of palm transpiration to evapotranspiration, and analyzed the influence of fluctuations in environmental variables on oil palm water use. We studied 15 two- to 25-year old stands in the lowlands of Jambi, Indonesia. A sap flux technique with an oil palm specific calibration and sampling scheme was used to derive leaf-, palm- and stand-level water use rates in all stands under comparable environmental conditions. Additionally, in a two- and a 12-year old stand, eddy covariance measurements were conducted to derive evapotranspiration rates. Water use rates per leaf and palm increased 5-fold from an age of two years to a stand age of approx. 10 years and then remained relatively constant. A similar trend was visible, but less pronounced, for estimated stand transpiration rates of oil palms; they varied 12-fold, from 0.2 mm day^{-1} in a 2-year old to 2.5 mm day^{-1} in a 12-year old stand, showing particularly high variability in transpiration rates among medium-aged stands. Confronting sap flux and eddy-covariance derived water fluxes suggests that transpiration contributed 8% to evapotranspiration in the 2-year old stand and 53% in the 12-year old stand, indicating variable and substantial additional sources of evaporation, e.g. from the soil, the ground vegetation and from trunk epiphytes. Diurnally, oil palm transpiration rates were characterized by an early peak between 10 and 11 am; there was a pronounced hysteresis in the leaf water use response to changes in vapor pressure deficit for all palms of advanced age. On the day-to-day basis this resulted in a relatively low variability of oil palm water use regardless of fluctuations in vapor pressure deficit and radiation. We conclude, that oil palm dominated landscapes show some spatial variations in (evapo)transpiration rates, e.g. due to varying age-structures, but that the temporal variability of oil palm transpiration is rather low. Stand transpiration rates of some studied oil palm stands compared to or even exceed values reported for different tropical forests, indicating a high water use of oil palms under certain site or management conditions. Our study provides first insights into the eco-hydrological characteristics of oil palms as well as a first estimate of oil palm water use across a gradient of plantation age. It sheds first light on some of the hydrological consequences of the continuing expansion of oil palm plantations.

Key words: Chrono-sequence, evapotranspiration, eddy covariance, sap flux, Granier-type thermal dissipation probes

4.1 Introduction

Oil palm (*Elaeis guineensis* Jacq.) has become the most rapidly expanding crop in tropical countries over the past decades, particularly in South East Asia (FAO 2014). Asides from losses of biodiversity and associated ecosystem functioning (e.g. Barnes et al. 2014), potentially negative consequences of the expansion of oil palm cultivation on components of the hydrological cycle have been reported (e.g. Banabas et al. 2008). Only few studies have dealt with the water use characteristics of oil palms so far (Comte et al. 2012). Evapotranspiration estimates derived from micrometeorological or catchment-based approaches range from 1.3 to 6.5 mm day^{-1} for different tropical locations and climatic conditions (e.g. Radersma and Ridder 1996, Henson and Harun 2005). To our knowledge, influences of site or stand characteristics on oil palm water use have not yet been addressed.

Landscapes dominated by oil palms are not necessarily homogeneous in their water use characteristics. Oil palms are usually planted in mono-specific and even-aged stands; commonly, stands are cleared and replanted at an age of approx. 25 years due to difficulties in harvesting operations, potentially declining yields and the opportunity to plant higher yielding varieties of oil palm. This creates a mosaic of stands of varying age, and hence with possibly different hydrological characteristics.

Substantial differences in transpiration rates of dicot tree stands have been shown for stands of varying age in several studies (e.g. Jayasuriya et al. 1993, Roberts et al. 2001, Vertessy et al. 2001, Delzon and Loustau 2005); commonly, water use increases rapidly after stand establishment, reaching a peak after some decades (which is associated with high stand productivity and high stand densities) before declining more or less consistently with increasing age. This has e.g. been demonstrated for *Eucalyptus regnans* F. Muell. (Cornich and Vertessy 2001), *Eucalyptus sieberi* L. Johnson (Roberts et al. 2001) and *Pinus pinaster* Aiton (Delzon and Loustau 2005) for stands between 10 and 160 years old. Declines in transpiration rates in older stands were mainly explained by decreasing leaf and sapwood area with increasing stand age (Roberts et al. 2001, Vertessy et al. 2001, Delzon and Loustau 2005). This may not be the case in palms, as at least at the individual level, for two Amazonian palm species (*Iriartea deltoidea* Ruiz & Pav. and *Mauritia flexuosa* L.*)* linear increases of water use with increasing height, and hence age, have been demonstrated (Renniger et al. 2009, Renninger et al. 2010).

Water use patterns over a gradient of plantation age to our knowledge have not yet been studied for oil palms. Water use could both increase or decline with increasing stand age. Reasons for declining water use at a certain age include decreasing functionality of trunk xylem tissue with increasing age due to the absence of secondary growth in monocot species (Zimmermann 1973), a variety of other hydraulic limitations (see review of dicot tree studies in Ryan et al. 2006) and increased hydraulic resistance due to increased pathway length with increasing trunk height

(Yoder et al. 1994). However, for Mexican fan palms (*Washingtonia robusta* Linden ex André H Wendl.), no evidence of increasing hydraulic limitations with increasing palm height was found (Renninger et al. 2009). On the other hand, oil palm trunk height increases linearly with age (Henson and Dolmat 2003). With increasing trunk height and hence volume, internal water storages probably also increase, possibly enabling larger (i.e. older) oil palms to transpire at higher rates (Goldstein et al. 1998, Madurapperuma et al. 2009). Additionally, increased stand canopy height is expected to result in an enhanced turbulent energy exchange with the atmosphere, i.e. a closer coupling of transpiration to environmental drivers, which can facilitate higher transpiration rates under optimal environmental conditions (Hollinger et al. 1994, Vanclay 2009).

To investigate the water use characteristics of oil palm stands of varying age, we derived leaf-, palm- and stand-scale transpiration estimates from sap flux density measurements with thermal dissipation probes (TDP, Granier 1985) in 15 different stands (2–25 years old) in the lowlands of Jambi, Sumatra, Indonesia. We used the oil palm specific calibration equation and field measurement scheme recently proposed by Niu et al. (2015). Additionally, in two of these stands (two and 12 years old) we used the eddy covariance technique (Baldocchi 2003) to derive independent estimates of evapotranspiration rates. For comparative purposes, the measurements were conducted under similar environmental conditions and partly simultaneously. Our objectives were (1) to derive transpiration rates of oil palms in stands of varying age, (2) to estimate the contribution of palm transpiration to evapotranspiration, and (3) to analyze the influence of micro-meteorological drivers on oil palm water use. The study provides some first insights into the eco-hydrological characteristics of oil palms at varying spatial (i.e. from leaf to stand) and temporal (i.e. from hourly to daily) scales as well as first estimates of oil palm stand transpiration rates and their contribution to total evapotranspiration. It assesses potential hydrological consequences of large-scale oil palm expansion on main components of the water cycle.

4.2 Methods

4.2.1 Study sites

The field study was conducted in Jambi, Sumatra, Indonesia (**Figure 4.1**). Between 1991 and 2011, average annual temperature in the region was 26.7 ± 0.2 °C (1991–2011 mean ± SD), with little intra-annual variation. Annual precipitation was 2235 ± 385 mm, a dry season with less than 120 mm monthly precipitation usually occurred between June and September. However, the magnitude of dry season rainfall patterns varied highly between years (data from Airport Sultan Thaha in Jambi). Soil types in the research region are mainly sandy and clay Acrisols (Allen et al. 2015). We had research plots in a total of 15 different oil palm stands (**Table 4.1**), 13 of which were small holder plantations and two of which were properties of big companies. The stands were spread over two landscapes in the Jambi province (i.e. the Harapan and Bukit Duabelas regions, **Figure 4.1**), were all at similar altitude (60 m ± 15 m a.s.l.) and belonged to the larger experimental set-up of the CRC990 (www.uni-goettingen.de/crc990, Drescher et al. in preparation). Stand age ranged from 2 to 25 years. Management intensity and frequency (i.e. fertilizer and herbicide application, manual and chemical weeding of ground vegetation and clearing of trunk epiphytes) varied considerably among the examined oil palm stands, but both were generally higher in larger plantations, particularly in PTPN6.

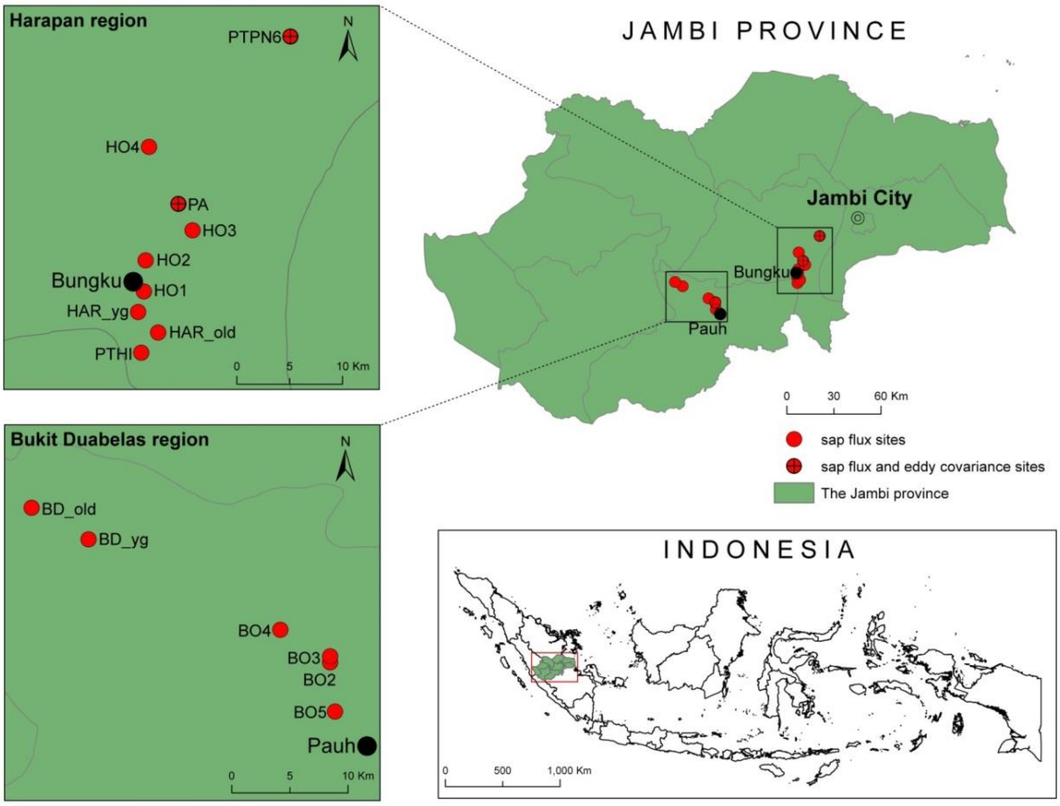

Figure 4.1. Locations of the studied oil palm stands in Jambi province, Sumatra, Indonesia.

4.2.2 Sap flux measurements and transpiration

Following a methodological approach for sap flux measurements on oil palms (Niu et al. 2015), we installed thermal dissipation probe (TDP) sensors in the leaf petioles of 16 leaves, four each on four different palms, for each of the 15 examined stands. Insulative materials and aluminum foil shielded the sensors to minimize temperature gradients and reflect radiation. Durable plastic foil was added for protection from rain. The sensors were connected to AM16/32 multiplexers connected to a CR1000 data logger (both Campbell Scientific Inc., Logan, USA). The signals from the sensors were recorded every 30 sec and averaged and stored every 10 min. The mV-data from the logger was converted to sap flux density (g cm^{-2} h^{-1}) with the empirically-derived calibration equation by Granier (1985), but with a set of equation parameters *a* and *b* that was specifically derived for TDP measurements on oil palm leaf petioles (Niu et al. 2015).

Individual leaf water use rates were calculated by multiplying respective sap flux densities (e.g. hourly averages, day sums) by the water conductive areas of the leaves; the water use values of all individual leaves measured simultaneously (min. 13 leaves) were averaged (kg day^{-1}). To scale up to average palm water use (kg day^{-1}), average leaf water use rates were multiplied by the average number of leaves per palm. Multiplying the average palm water use by the number of palms per unit of land (m^2) yielded stand transpiration rates (*T*, mm day^{-1}). This approach is associated with sample size related estimation errors of stand transpiration rates of 14% (described in detail in Niu et al. 2015).

The sap flux measurements were conducted between April 2013 and December 2014, for a minimum of 3 weeks per study plot (**Table 4.1**). Three of the plots (BO3, PA, and PTPN6) ran over several months, partly in parallel to other plots. Most measurements, however, were conducted successively and thus partly took place under varying weather conditions. Thus, to minimize day-to-day variability introduced by varying weather for the analysis of effects of stand age on water use at different spatial scales, we used the average of three comparably sunny and dry days from the measurement period of each stand. Exploratory analyses had shown than unexplained variability was lower on sunny days than e.g. on cloudy or intermediate days or when using the averages of the full respective measurement periods. We chose days with a daily integrated radiation of more than 17 MJ m^{-2} day^{-1} and an average daytime VPD of more than 1.1 kPa; respective averages of all days included in the analysis were 20.3 ± 2.6 MJ m^{-2} day^{-1} and 1.6 ± 0.3 kPa (also see **Table 4.1**).

4.2.3 Stand structural characteristics

For all sample leaves, the leaf petiole baseline length was measured between upper and lower probe of each TDP sensor installed in the field; this allowed calculating the water conductive area of each leaf (Niu et al. 2015). For each sample palm, trunk height (m) and diameter at breast height (cm) were measured and the number of leaves per palm was counted. Over time, new leaves emerged and old ones were pruned by the farmers; we assumed the number of leaves per palm to be constant over our measurement period. On the stand level, we counted the number of palms per hectare.

4.2.4 Eddy covariance measurements and evapotranspiration

The eddy covariance technique (Baldocchi 2003) was used to measure evapotranspiration (ET, mm day^{-1}) in two of the 15 oil palm stands, the 2-year-old (PA) and the 12-year-old (PTPN6) stand (**Table 4.1**). Towers of 7 m and 22 m in height, respectively, were equipped with a sonic anemometer (Metek uSonic-3 Scientific, Elmshorn, Germany) to measure the three components of the wind vector, and an open path carbon dioxide and water analyzer (Li-7500A, Licor Inc., Lincoln, USA) to derive evapotranspiration rates (Meijide et al. in preparation). Fluxes were calculated with the software EddyPro (Licor Inc), planar-fit coordinate rotated, corrected for air density fluctuation and quality controlled. Measurements were conducted between July 2013 and February 2014 in the 2-year old and from March to December 2014 in the 12-year old stand. For the analysis, we used the average of the same three sunny days that were selected for the sap flux analysis in the respective plots (see sap flux measurements and transpiration). Daytime (6am–7pm) evapotranspiration rates were used for the analyses and comparison to transpiration rates in order to avoid possible measurement errors as a consequence of low turbulent conditions during nighttime hours.

To estimate the contribution of stand transpiration to total evapotranspiration, we confronted sap flux derived transpiration rates with eddy covariance derived evapotranspiration rates. To derive transpiration rates, we followed a sap flux calibration and field measurement scheme specifically put forward for oil palms (Niu et al. 2015), which was reported to be associated with sample size related measurement errors of about 14%. To derive evapotranspiration rates we applied the eddy covariance technique in carefully-chosen and well-suited locations and focused on daytime observations only, when estimation uncertainties are commonly low (< 30%, Richardson et al. 2006). The observed differences between evapotranspiration and transpiration estimates presented in this study are thus likely largely due to natural rather than methodological reasons.

4.2.5 Environmental drivers of oil palm water use

A total of three micrometeorological stations were set up in proximity to the oil palm stands in both landscapes; for the analysis of the water use characteristics of the respective stands, we used the micrometeorological data from the closest available station, at a maximum distance of approx. 15 km and at similar altitude (60 m ± 15 m a.s.l.). The stations were placed in open terrains. Air temperature and relative humidity were measured at a height of 2 m with a Thermohygrometer (type 1.1025.55.000, Thies Clima, Göttingen, Germany) to calculate vapor pressure deficit (VPD, kPa). A short wave radiation sensor (CMP3 Pyranometer, spectral range 300–2800 nm, Kipp & Zonen, Delf, The Netherlands) was installed at a height of 3 m, the latter to measure global radiation (R_g, MJ m^{-2} day^{-1}, from here on referred to as “radiation”). Measurements were taken every 15 sec and averaged and stored on a DL16 Pro data logger (Thies Clima) every 10 min.

The eddy covariance towers (see eddy covariance measurements and evapotranspiration) were also equipped with micrometeorological sensors. Measurements were taken above the canopy, at respective heights of 6.7 and 22 m. Air temperature and humidity (Thermohygrometer, type

1.1025.55.000, Thies Clima), short wave radiation (BF5, Delta-T, Cambridge, United Kingdom) and net radiation (CNR4 Net radiometer, Kipp & Zonen) were measured every 15 sec and averaged and stored on a DL16 Pro data logger (Thies Clima) every 10 min.

Soil moisture was recorded in the center of eight of the 15 study plots and at the micrometeorological stations and eddy covariance towers. Soil moisture sensors (Trime-Pico 32, IMKO, Ettlingen, Germany) were placed 0.3 m under the soil surface and connected to a data logger (LogTrans16-GPRS, UIT, Dresden, Germany). Data were recorded every hour, for 16 months from June 2013 on. Exploratory analyses showed no significant effects of soil moisture on water use rates ($P > 0.1$). Soil moisture fluctuated only little at the respective locations and during the respective measurement periods and even on a yearly scale, e.g. between 32 ± 2% and 38 ± 2% between June 2013 and June 2014 (minimum and maximum daily values, mean ± SE between the three micrometeorological stations). Soil moisture did e.g. also not fall below 36% during the measurement period in the long-term monitoring (BO3) stand. It was non-limiting for plant water use. As it showed no significant relationship with water use rates, we omitted soil moisture from further analyses of influences of fluctuations in environmental variables on oil palm water use. We instead focused on the micrometeorological drivers VPD and radiation. For the diurnal analysis, we averaged the values of three comparably sunny days and normalized VPD and radiation by setting the highest observed hourly rates to one.

All statistical analyses and graphing were performed with R version 3.1.1 (R Core Development team, 2014) and Origin 8.5 (Origin Lab, Northampton, MA, USA).

4.3 Results

4.3.1 Stand characteristics

The number of palms per unit of land linearly decreased with increasing stand age ($R^2 = 0.29$, $P = 0.04$; **Figure 4.2a**). The number of leaves per palm remained constant and varied little (32–40 leaves per palm) over stand age (**Figure 4.2b**). The trunk height of oil palms (**Figure 4.2c**) increased linearly with increasing age ($R^2 = 0.91$, $P < 0.01$), from about 2 m at an age of six to about 9 m at an age of 25 years. The average baseline length of leaf petioles at the location of sensor installation increased linearly with stand age ($R^2 = 0.65$, $P < 0.01$). As the number of leaves was constant in mature stands, the increasing baseline lengths of leaf petioles resulted in a significant linear increase of the water conductive area per palm with increasing stand age ($R^2 = 0.53$, $P < 0.01$). In consequence, the stand-level water conductive area also linearly increased with stand age ($R^2 = 0.26$, $P = 0.05$; **Figure 4.2d**).

4.3.2 Transpiration and evapotranspiration

Maximum sap flux densities on three sunny days as measured in the leaf petioles of oil palms were variable but did not show a significant trend over age among the examined stands (**Figure 4.3a**). Converted to leaf water use, a clear non-linear trend over stand age became apparent (R^2adj = 0.61, $P < 0.01$ for the Hill function, fit not shown) (**Figure 4.3b**): Leaf water use increased 5-fold from a 2-yr-old stand to a plot age of about 10 years; it then remained relatively constant with further increasing age. At the palm level (**Figure 4.3c**), water use rates closely resemble the relationship of leaf water use and stand age. At the stand level, oil palm transpiration was very low (0.2 mm day^{-1}) in the 2-year old stand and increased almost 8-fold until a stand age of 5 years. It then remained relatively constant with increasing age at around 1.3 mm day^{-1} (**Figure 4.3d**). However, three medium-aged stands (PTPN6, BO5, and HO2) that showed increased sap flux densities and leaf and palm water use rates also had higher stand transpiration rates, between 2.0 and 2.5 mm day^{-1}. Potentially, this could be related to differences in radiation on the respective three sunny days that were chosen for the analysis; however, there was no significant relationship between water use and radiation for the 15 stands. A further analysis of the water use rates of eight medium-aged stands with highly variable transpiration rates also gave no indications of variability being induced by differences in radiation. As for the leaf- and palm-level water use rates, a Hill function explained the relationship between stand transpiration and stand age (R^2adj = 0.45, $P < 0.01$), but the observed scatter was high. The transpiration rates of the two oldest examined stands (BD_old, 22 years and HAR_old, 25 years) possibly indicate a slight decline of transpiration rates at advanced stand age. Overall, stand transpiration rates increased linearly with increasing stand water conductive area ($R^2 = 0.42$, $P = 0.01$). On the palm level, there was a linear relationship between water use and trunk height ($R^2 = 0.32$, $P = 0.03$), but stand transpiration did not have a linear relationship with average stand trunk height due to decreasing stand densities with increasing stand age; instead, as for transpirations vs. stand age, a Hill function explained the relationship between transpiration and stand trunk height best (R^2adj = 0.44, $P < 0.01$).

Evapotranspiration rates derived from the eddy covariance technique for the two year-old stand (PA) were 2.8 mm day^{-1} (average of three sunny days); the contribution of sap flux derived transpiration was 8%. For the 12 year-old stand (PTPN6), the evapotranspiration estimate was 4.7 mm day^{-1}; transpiration amounted to about 53%.

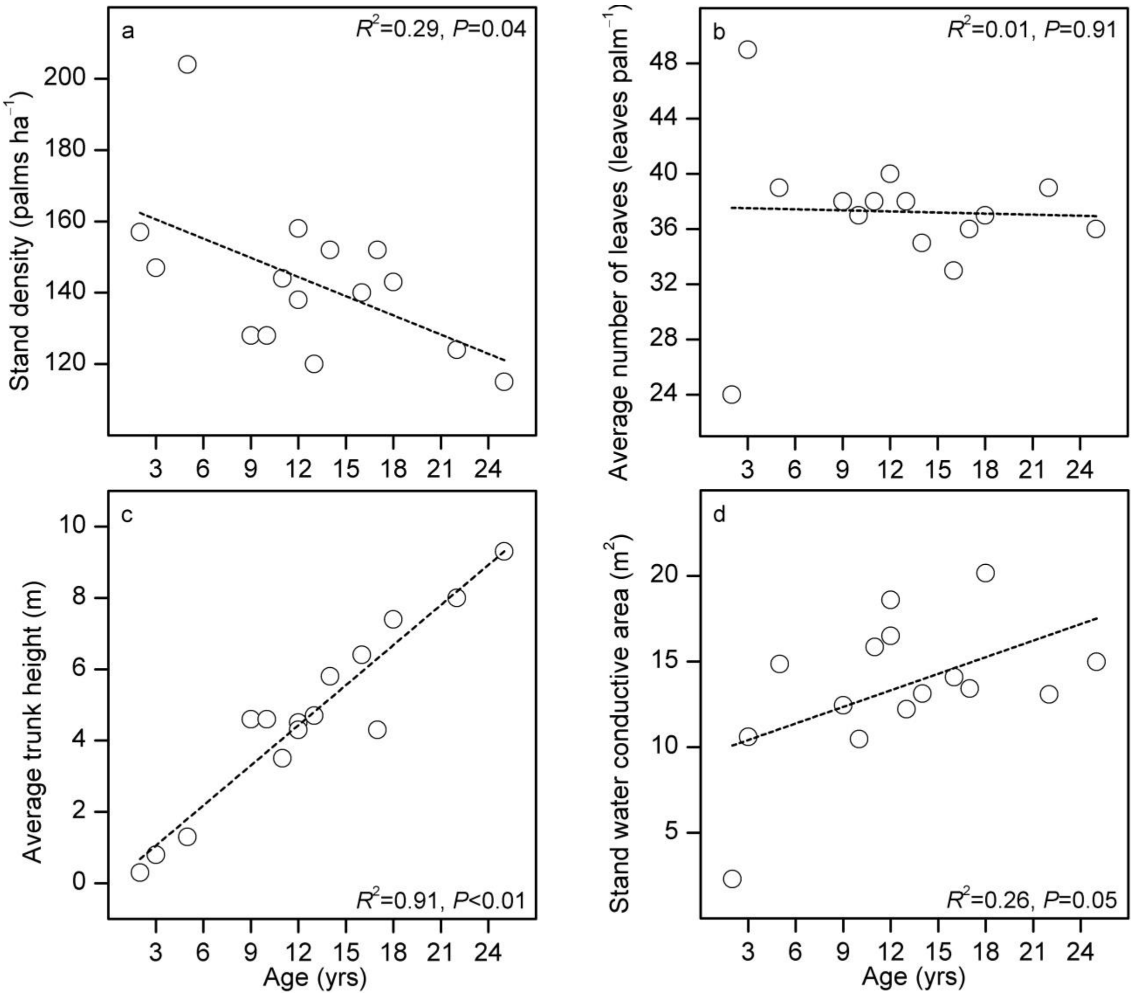

Figure 4.2. The change of stand density (a), average number of leaves per palm (b), average trunk height (c), and stand water conductive area (d) over age in the 15 studied oil palm stands.

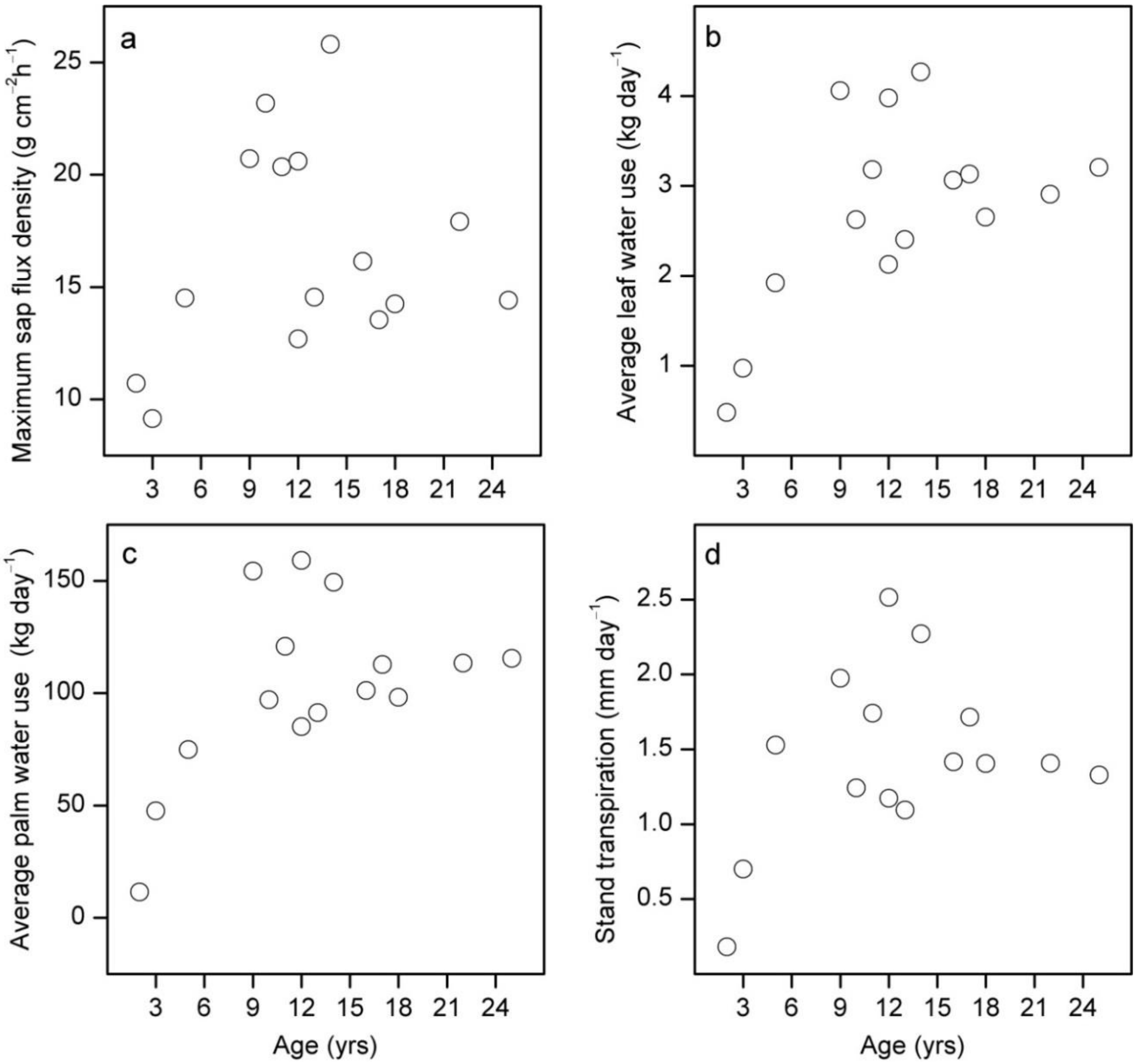

Figure 4.3. The change of maximum hourly sap flux density (a), average leaf water use (b), average palm water use (c) and stand transpiration (d) over stand age. Data of the different levels derived from simultaneous sap flux measurements on at least 13 leaves per stand; values of three sunny days averaged.

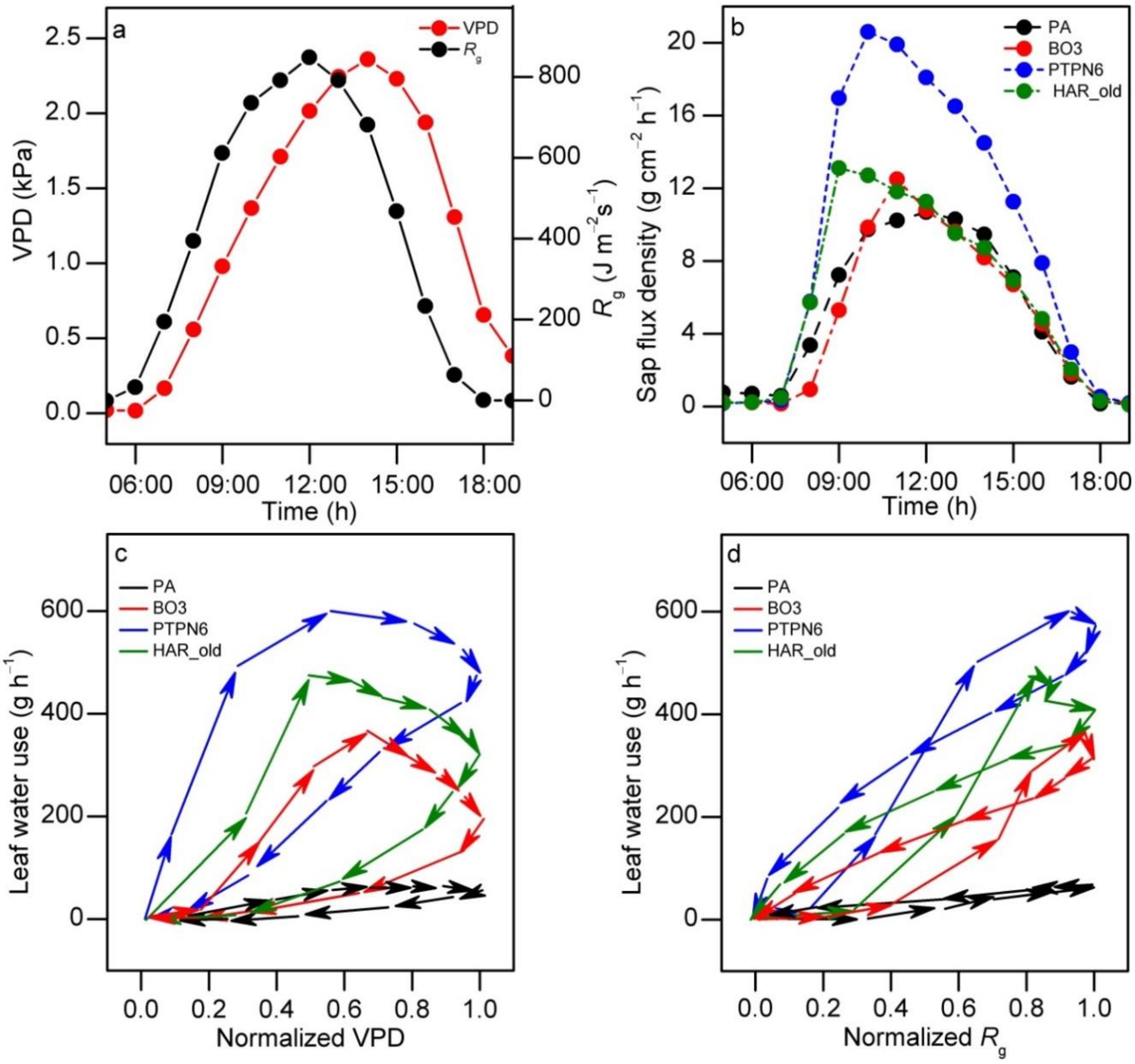

Figure 4.4. Diurnal course of vapor pressure deficit (VPD) and radiation (R_g) (a) and of sap flux density in four oil palm stands (b). Leaf water use plotted against hourly averages of normalized VPD (c) and Rg (d). Average water use estimates based on at least 13 leaves measured simultaneously; average water use rates, VPD and radiation of three sunny days, each point represents one hourly observation. Data are from the locations PA (2 years old, black arrows), BO3 (12 years old, low water use, red arrows), PTPN6 (12 years old, high water use, blue arrows) and HAR_old (25 years old, green arrows). Data were normalized by setting the maximum to one.

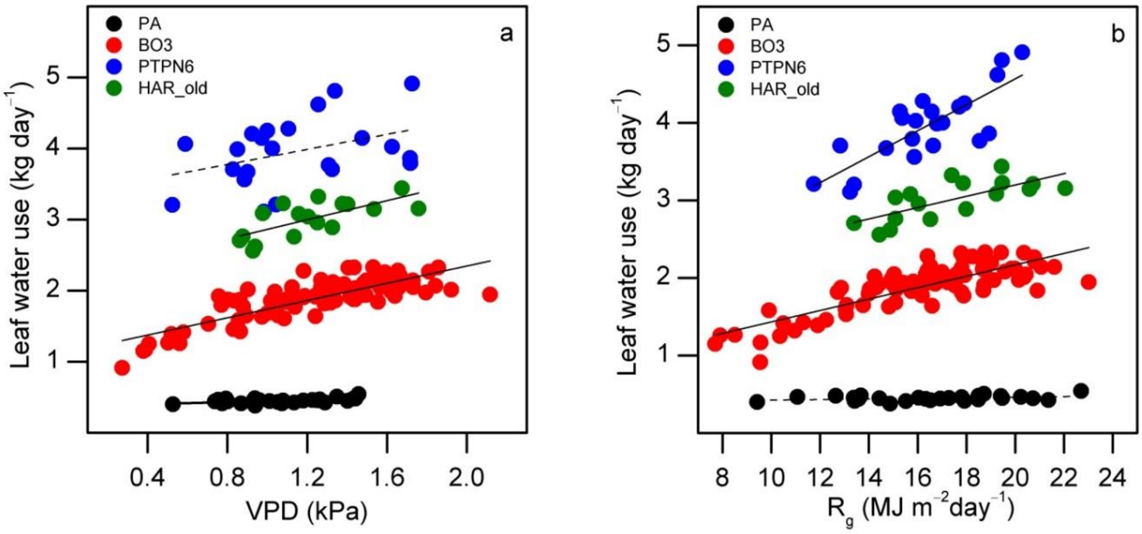

Figure 4.5. The day-to-day response of leaf water use rates in four different oil palm stands to changes in average daytime vapor pressure deficit (VPD) (a) and integrated daily radiation (R_g) (b) taken from the closest micrometeorological station from the respective plots. Data of at least 20 days per plot, each point represents one day. Leaf water use rates are from the locations PA (2 years old, black circles), BO3 (12 years old, low water use, red circles), PTPN6 (12 years old, high water use, blue circles) and HAR_old (25 years old, green circles). Significant linear relationships are indicated with solid ($P < 0.05$) and dotted ($P < 0.1$) lines.

4.3.3 Drivers of oil palm water use

Radiation peaked between 12 and 1 pm while vapor pressure deficit peaked at around 3 pm; the diurnal course of sap flux densities on three sunny days except for the 2-yr-old stand (PA) showed an early peak of sap flux density (10 to 11 am), which then decreased throughout the rest of the day (**Figure 4.4a and 4.4b**, respectively).Thus, there was a varying and partly pronounced hysteresis in the leaf-level response of transpiration to VPD (**Figure 4.4c**). It was small in the 2-year old stand (PA). In contrast, it was very pronounced in the 12-year old PTPN6 stand (high water use, commercial plantation), where a very sensitive increase of water use rates with increasing VPD during the morning hours was observed, reaching a peak in water use rates at only about 60% of maximum daily VPD. After that, water use rates declined relatively consistently throughout the day, despite further rises in VPD. The same pattern was observed in most of the stands; we present values for the oldest stand (HAR_old, 25 years) and another 12-year old stand (BO3, low water use, smallholder plantation) as further examples. The hysteresis in the transpiration response to radiation (**Figure 4.4d**) was generally less pronounced than for VPD. The day-to-day behavior of oil palm leaf water use rates to environmental drivers (i.e. VPD, radiation) seemed buffered, i.e. already relatively low VPD and radiation lead to relatively high water use rates (except for in the 2-yr-old stand), while even strong increases in VPD and radiation only induced rather small further increases in water use rates (**Figure 4.5**). For the 2-year-old stand (PA), leaf water use rates over time were almost constant (about 0.4 kg day^{-1}), regardless of daily environmental conditions. Likewise, the water use rates of the remaining stands were relatively insensitive to increases in VPD, i.e. two-fold increases in VPD only led to 1.1- to 1.2-fold increases in water use rates (**Figure 4.5**). A similarly buffered water use response to radiation was observed for the 12-year old small-holder stand (BO3) and the 25-year old stand (HAR_old), i.e. 1.5- and 1.3-fold increases, respectively, for two-fold increases in radiation. The water use response to fluctuations in radiation of the 12-year old commercial stand (PTPN6) was more sensitive, i.e. two-fold increases in radiation induced 1.8-fold increases in water use rates (**Figure 4.5**). The PTPN6 stand also had the highest absolute water use rates among the studied stands.

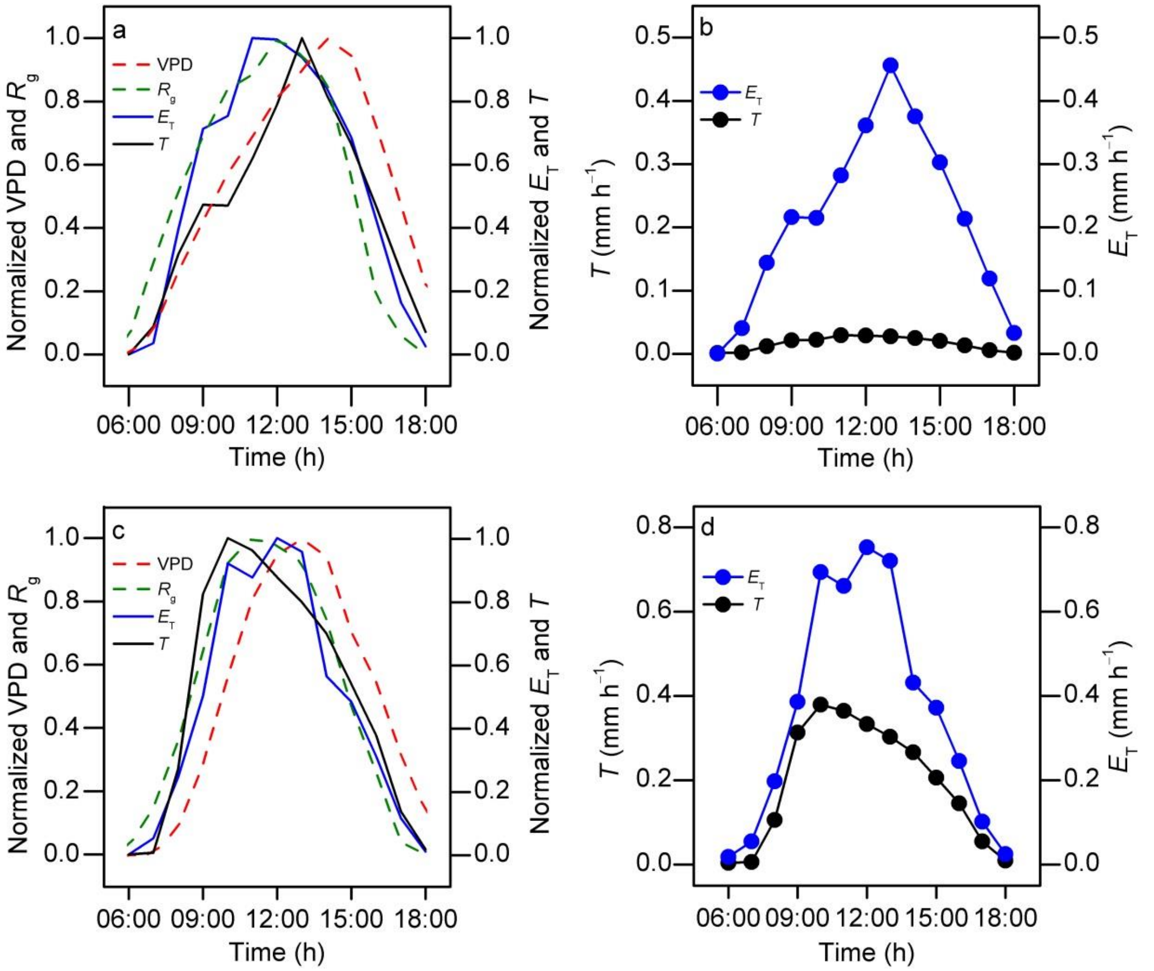

Figure 4.6. Normalized diurnal pattern of vapor pressure deficit (VPD), radiation (R_g), transpiration (T) and evapotranspiration (E_T) in a 2-year-old (PA) (a) and a 12-year-old (PTPN6) (c) oil palm stand; absolute hourly values of E_T and T in PA (b) and PTPN6 (d). Eddy covariance and sap flux density measurements were conducted in parallel to derive evapotranspiration and transpiration rates, respectively. Values of three sunny days averaged.

4.4 Discussion

4.4.1 Oil palm transpiration over age

Among 13 studied productive oil palm stands (i.e. > 4 years old) stand transpiration rates varied more than two-fold. The observed range (1.1–2.5 mm day^{-1}) compares to transpiration rates derived with similar techniques in a variety of tree-based tropical land-use systems, e.g. *Acacia mangium* plantations on Borneo (2.3–3.9 mm day^{-1} for stands of varying density, Cienciala et al. 2000), cacao monocultures and agroforests with varying shade tree cover on Sulawesi (0.5–2.2 mm day^{-1}, Köhler et al. 2009, 2013) and reforestation and agroforestry stands on the Philippines and in Panama (0.6–2.5 mm day^{-1}, Dierick and Hölscher 2009, Dierick et al. 2010). The highest observed values for oil palm stands (2.0–2.5 mm day^{-1}, PTPN6, BO5, and HO2 stands) compare to or even exceed values reported for tropical forests (1.3–2.6 mm day^{-1}, Calder et al. 1986, Becker 1996, McJannet et al. 2007), suggesting that oil palms can transpire at substantial rates under certain, yet unexplained site or management conditions despite e.g. a much lower biomass per hectare than in natural forests (Kotowska et al. 2015).

In the studied oil palm stands, stand-level transpiration rates increased almost 8-fold from an age of two years to a stand age of five years; they then remained relatively constant with further increasing age, but were highly variable among medium-aged plantations. The contradictory results found in previous studies for dicot tree mono-cultural stands of varying age, i.e., after a relatively early peak, lower stand transpiration rates with increasing stand age (Jayasuriya et al. 1993, Roberts et al. 2001, Vertessy et al. 2001, Delzon and Loustau 2005), could be explained by two reasons: firstly, the studied time-scales were much larger (e.g. comparison of 10- and 91-year old stands in Delzon and Loustau 2005) than in our oil palm study (stand age 2–25 years); secondly, oil palms are commonly planted in a fixed, relatively large grid, which results in a less pronounced reduction of stand density with increasing stand age than in dicot tree stands, which are often established at higher stand densities and consequently show higher density-dependent mortality rates.

On comparably sunny days, the stand-level transpiration among the 15 oil palm stands varied 12-fold, from 0.2 mm day^{-1} in a 2-year old to 2.5 mm day^{-1} in a 12-year old stand. A large part of this spatial variability could be explained by stand age (45%), and thus also by variables that were correlated to stand age, i.e. by average stand trunk height (44%) and by stand water conductive area (42%). Much of the remaining variability in stand transpiration rates could be explained by varying stand densities (variations of up to 30% between stands of similar age). Thus, when shifting from the stand level to the palm level, up to 60% of the spatial variability in palm water use rates could be explained by age and correlated variables. Much of the variability that remains on the palm level is induced by three stands where palm water use was much higher (> 150 kg day^{-1}) than in the other 12 stands (< 125 kg day^{-1}); excluding these three stands from the analysis, 87% of the spatial variability in palm water use rates could be explained by age (Hill function). The remaining unexplained variability as well as the high water use rates in the three mentioned stands could be related to differences in site and soil characteristics. However, all studied stands were located in comparable landscape positions (i.e. upland sites of little or medium inclination) and on similar mineral soils, i.e. loam or clay Acrisols of generally comparable characteristics (Allen et al. in review, Guillaume et al. 2015). Differences in management intensity could also contribute to the remaining unexplained variability of stand transpiration rates over age. The highest observed transpiration value in our study came from a stand in an intensively and regularly fertilized, high yielding commercial plantation. Thus, there may be a trade-off between management intensity, and hence yield, on the one hand, and water use of oil palms on the other hand.

4.4.2 Oil palm transpiration vs. evapotranspiration

Evapotranspiration rates under sunny conditions derived from eddy covariance measurements were 2.8 mm day^{-1} at PA (2-years old) and 4.7 mm day^{-1} at PTPN6 (12-years old). Sap-flux derived transpiration estimates for the same days were 0.2 mm day^{-1} at PA and 2.5 mm day^{-1} at PTPN6; the differences between evapotranspiration and transpiration estimates, 2.6 and 2.2 mm day^{-1}, respectively, were substantial. The contribution of palm transpiration to total evapotranspiration was very low (8%) in the 2-year old PA stand (**Figure 4.6**). Thus, the majority of water fluxes to the atmosphere came from evaporation (e.g. from the soil, interception) and transpiration by other plants. The spaces between palms (planting distance approx. 8 × 8 m) were covered by a dense, up to 50 cm high grass layer at the time of study (approx. 60% ground cover); transpiration rates from grasslands can exceed those of forests (e.g. review in McNaughton and Jarvis 1983, Kelliher et al. 1992) and could well account for 1–2 mm day^{-1} to (partly) explain the observed difference of 2.6 mm day^{-1} between evapotranspiration and transpiration estimates in the PA stand. The 2-year old oil palms were still very small (average trunk height 0.3 m, overall height 1.8 m) and had a low average number of leaves (24 as opposed to an average of 37 ± 1 between the 15 studied stands); further, leaves were much smaller than in mature stands. Leaf area index (LAI) of 2-year old oil palm stands was reported be at least 5-fold lower (LAI < 1) than in mature stands of similar planting density as our study plots (Henson and Dolmat 2003). The very low observed water use of the oil palms in PA (12 kg day^{-1} per palm compared to approx. 100 kg day^{-1} per palm in mature stands) and the consequent very low contribution of palm transpiration to evapotranspiration thus do not seem contradictory.

At PTPN6 (12 years old) transpiration rates (2.5 mm day^{-1}) as well as the contribution of transpiration to evapotranspiration (53%) were much higher than in the 2-year old stand (PA);

also, total evapotranspiration was almost 70% higher (4.7 mm day^{-1}). The sum of evaporation (e.g. from the soil) and transpiration by other plants was of similar magnitude (2.2 mm day^{-1}, i.e. 15% lower) as in PA. Due to the intense management, there was very little ground vegetation in inter-rows present in the PTPN6 stand. However, the abundant trunk epiphytes in butts of pruned leaf petioles that remain on the trunks of mature oil palms may contribute significantly to non-palm transpirational water fluxes. Additionally, oil palm trunks were reported to have a large potential external water storage capacity (up to 6 mm, Merten et al. submitted) for stemflow water after precipitation events; the mentioned butts of pruned leaf petioles constitute 'chambers' filled with humus, water and epiphytes, which can remain moist for several days following rainfall events. On dry, sunny days of high evaporative demand, the (partial) drying out of these micro-reservoirs may significantly contribute to water fluxes from evaporation. This is supported by the diurnal course of all water fluxes except oil palm transpiration at PTPN6 (calculated by subtracting hourly transpiration from evapotranspiration rates), which closely followed VPD until its 3 pm peak, but then declined rapidly, suggesting significant other water fluxes to the atmosphere (e.g. from evaporation) that are still marginal during the morning hours, reach their peak at the time VPD peaks and are extremely sensitive to decreasing VPD in the afternoon.

Our eddy-covariance derived evapotranspiration estimates of 2.8 and 4.7 mm day^{-1} (on sunny days, in 2- and 12-year old stands, respectively) compare very well to the range reported for oil palms in other studies: For 3–4 year old stands in Malaysia, eddy-covariance derived values of 1.3 mm day^{-1} and 3.3–3.6 mm day^{-1} were reported for the dry and rainy season, respectively (Henson and Harun 2005). For mature stands, a value of 3.8 mm day^{-1} was given, derived by the same technique (Henson 1999). Micrometerologically-derived values for 4–5 year old stands in Peninsular India were 2.0–5.5 mm day^{-1} during the dry season (Kallarackal et al. 2004). A catchment-based approach suggested values of 3.3–3.6 mm day^{-1} for stands in Malaysia between 2 and 9 years old (Yusop et al. 2008); evapotranspiration rates derived from the Penman-Monteith equation and published data for various stands were 1.3–2.5 mm day^{-1} in the dry season and 3.3–6.5 mm day^{-1} in the rainy season (Radersma and Ridder 1996). None of these studies contradict our eddy-covariance derived evapotranspiration rates for the PA and PTPN6 stands; the values reported from most studies as well as our values overlap in a corridor from about 3 mm day^{-1} to about 5 mm day^{-1}. This range compares to evapotranspiration rates reported for rainforests in South East Asia (e.g. Tani et al. 2003a, Kumagai et al. 2005). Considering that oil palm stands e.g. have much lower stand densities and biomass per hectare than natural forests (Kotowska et al. 2015), this indicates a quite high evapotranspiration from oil palms at both the individual and the stand level. In our study, transpiration amounted to 53% of evapotranspiration in the 12 year-old oil palm stand, which is lower than values reported e.g. for mature coconut stands (68%, Roupsard et al. 2006) and rainforests in Malaysia (81–86%, Tani et al. 2003b). The low relative contribution of palm transpiration to total evapotranspiration in oil palm stands could be due to relatively high water fluxes from evaporation, e.g. after rainfall interception. Interception was reported to be substantially higher in oil palm stands in the study region (28%, Merten et al. in review) than e.g. in rainforests in Malaysia (12–16%, Tani et al. 2003b) and Borneo (18%, Dykes 1997). The high water losses from interception paired with relatively high water use of oil palms under certain conditions could contribute to reduced water availability at the landscape level in oil palm dominated areas (Merten et al. in review).

4.4.3 Micro-meteorological drivers of oil palm water use

We examined the relationship between water use rates and VPD and radiation on the intra-daily scale (hourly averages of three sunny days, **Figure 4.4**): In all examined oil palm stands except the very young stand (PA, 2 years old), under comparable sunny conditions, the intra-daily transpiration response to the mentioned environmental drivers was characterized by an early peak (10am–11am), before radiation (12am–1pm) and VPD (2pm–3pm) peaked; after this early peak of water use rates, however, they subsequently declined consistently throughout the day, regardless of further increases of radiation and VPD (**Figure 4.4**). For most thus far examined dicot tree species, peaks in water use rates coincide with peaks in radiation (e.g. Zeppel et al. 2004, Köhler et al. 2009, Dierick et al. 2010, Horna et al. 2011); however, a similar behavior as in oil palms, i.e. early peaks of transpiration followed by consistent declines, has been reported, but not yet explained, for *Acer rubrum* L. (Johnson et al. 2011) and some tropical bamboo species (Mei et al. in preparation). Due to the early peaks, considerable hysteresis in the oil palm transpiration response to VPD was observed in all examined stands except for PA (2 years old). Similar findings have been reported for some tropical tree species, e.g. for eucalyptus trees in Australia during the dry season in connection with high stand water use rates (O'Grady et al. 1999, Zeppel et al. 2004); during the rainy season, hysteresis was much smaller. Likewise, large hysteresis was found for *Nothofagus fusca* Hook. f. on clear, but not on cloudy days (Meinzer et al. 1997). This was discussed in the context of the development of water stress (Kelliher et al. 1992) and potentially decreasing leaf stomatal conductance and assimilation rates over the course of a day (Eamus and Cole 1997). Stomatal sensitivity to VPD may increase in the afternoon, resulting in stomata closure and hence lower water use rates (Zeppel et al. 2004); this may potentially be due to changes in leaf water potential, soil moisture content or xylem sap abscistic acid content (Prior et al. 1997, Thomas et al. 2000, Thomas and Easmus 2002) or a decline in soil-to-canopy resistance (Williams et al. 1998, Zeppel et al. 2004); also, the contribution of stem water storage to transpiration in the morning may play a role (Waring and Running 1978, Waring et al. 1979, Goldstein et al. 1998). The latter may explain the pronounced hysteresis in the water use response of oil palms to VPD as well as the unusually early peak followed by a steady decline regardless of VPD and radiation patterns, which could be the result of depleted trunk water storage reservoirs. Other (palm) species were reported to have substantial internal trunk water storage capacities (e.g. Holbrook and Sinclair 1992, Madurapperuma et al. 2009), which can sustain relatively high transpiration rates despite limiting environmental conditions (e.g. Vanclay 2009).

In all 15 oil palm stands, the day-to-day response of water use rates to changes in VPD seemed buffered, i.e. near-maximum daily water use rates were reached at relatively low VPD, but better environmental conditions for transpiration (i.e. higher VPD) did not induce strong increases in water use rates (i.e. 1.2-fold increase in water use for a two-fold increase in VPD). For tropical tree and bamboo species, more sensitive responses to fluctuations in VPD, i.e. 1.4- to 1.7-fold increases and more than two-fold increases, respectively, have been reported (Köhler et al. 2009, Komatsu et al. 2010). However, a similar 'levelling-off' effect of water use rates at higher VPD, as observed for the oil palm stands in our study, has been reported for Moso bamboo stands in Japan (in contrast to coniferous forests in the same region, where water use had a linear relationship with VPD, Komatsu et al. 2010). Likewise, a sigmoid relationship between sap flux densities and an environmental index basing on temperature, humidity, radiation and wind speed, i.e. no further increases of sap flux densities past a certain threshold in environmental conditions, were reported for 10 tropical forest tree species in Costa Rica (O'Brien et al. 2004). For both photosynthesis rates (Dufrene and Saugier 1993) and water use rates (Niu et al. 2015) of oil palm leaves, linear increases with increasing VPD were reported at relatively low VPD, until a certain threshold (1.5–1.8 kPa) was reached, after which no further increases in photosynthesis and water use rates, respectively, occurred. The hydraulic limitations buffering the day-to-day oil palm water use response to VPD are yet to be explained. As soil moisture was non-limiting, they are likely of micrometeorological or eco-physiological nature. The early peaks of water use rates and the consequent strong hysteresis to VPD on the intra-daily level, which may point to a depletion of internal trunk water storage reservoirs early in the day as a possible reason for substantially reduced oil palm water use rates at the time of diurnally optimal environmental conditions, give some first indications of the direction that further studies could take.

As to VPD, the day-to-day water use response to fluctuations in radiation of the studied oil palm stands seemed buffered, i.e. two-fold increases in radiation resulted in less than 1.5-fold increases in water use. The only exception among the 15 studied stands was the commercial, high water use PTPN6 stand, where increases in radiation induced almost 1:1 linear increases in water use, which is similar to the day-to-day behavior reported for several tropical tree species and a bamboo species (Köhler et al. 2009, Dierick et al. 2010).

4.5 Conclusions

The study provides first insights into eco-hydrological characteristics of oil palms at varying spatial and temporal scales and first estimates of oil palm stand transpiration rates across an age gradient. The contribution of transpiration to total evapotranspiration was also assessed. We found that water use rates per leaf and palm increased five-fold from an age of two years to a stand age of approx. 10 years and then remained relatively constant. Likewise, stand transpiration rates increased almost eight-fold from an age of two years to a stand age of five years and then remained constant with further increasing age, but were highly variable among medium-aged plantations. Across all studied stands, oil palm transpiration varied 12-fold. Other water fluxes besides transpiration, e.g. from the soil, grasses and epiphytes, contributed substantially and variably to evapotranspiration, reducing the large difference between the stands transpiring at the lowest and highest rates, respectively, to a less than two-fold difference in evapotranspiration. In the diurnal course, most oil palms showed a strong hysteresis between water use and VPD. On the day-to-day basis this results in a relatively low variability of oil palm water use regardless of fluctuations in VPD and radiation. In conclusion, oil palm dominated landscapes show some spatial variations in (evapo)transpiration rates, e.g. due to varying age-structures and stand densities, but the temporal variability of oil palm transpiration is rather low. Stand transpiration rates of some oil palm stands compare to or even exceed values reported for tropical forests, indicating high water use of oil palms under certain site or management conditions. For a comprehensive understanding of landscape-level hydrological consequences of the continuing oil palm expansion, this will have to be addressed further.

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Table 4.1. Stand locations, characteristics and study periods

Plot code	Location/Village name (Jambi province, Indonesia)	Age (yrs)	Study region (H = Harapan, B = Bukit Duabelas)	Latitude (S)	Longitude (E)	Altitude (m)	Stand type (S = small holding, C = company)	Study period	Average radiation/VPD of three selected days (MJ m^{-2} day^{-1}/kPa)	Additional comments
PA	Pompa Air	2	H	01°50'7.62"	103°17'44.22"	75	S	15 October 2013–14 January 2014	21.6/1.4	eddy covariance measurements
HAR_yg	Bungku	3	H	01°55′38.5″	103°15′40.4″	63	S	28 September 2013–24. October 2013	21.8/1.6	
BD_yg	Pematang Kabau	5	B	01°58′50.0″	102°36′18.4″	55	S	09 July 2013–03 August 2013	17.4/1.5	
BO5	Lubuk Kepayang	9	B	02°06'48.9"	102°47'44.5"	65	S	01 September 2013–22 September 2013	20.4/1.6	
HO4	Pompa Air	10	B	01°47'12.7"	103°16'14.0"	48	S	18 July 2013–05 August 2013	19.9/1.4	
BO4	Dusun Baru	11	B	02°03'01.5"	102°45'12.1"	34	S	06 August 2013–26 August 2013	22.9/1.8	
BO3	Lubuk Kepayang	12	B	02°04'15.2"	102°47'30.6"	71	S	03 July 2013–30 September 2013	21.8/1.8	
PTPN6	PT. Perkebunan Nusantara 6	12	H	01°41'34.8"	103°23'27.6"	70	C	19 July 2014–20 December 2014	19.7/1.4	eddy covariance measurements

Table 4.1 continued

Plot code	Location/Village name (Jambi province, Indonesia)	Age (yrs)	Study region (H = Harapan, B = Bukit Duabelas)	Latitude (S)	Longitude (E)	Altitude (m)	Stand type (S = small holding, C = company)	Study period	Average radiation/VPD of three selected days (MJ m^{-2} day^{-1}/kPa)	Additional comments
BO2	Lubuk Kepayang	13	H	02°04'32.0"	102°47'30.7"	84	S	10 June 2013–04 July 2013	24.9/2.1	
HO2	Bungku	14	H	01°53'00.7"	103°16'03.6"	55	S	25 September 2013–19 November 2013	21.3/1.5	
HO1	Bungku	16	H	01°54'35.6"	103°15'58.3"	81	S	09 August 2013–30 August 2013	22.31.9	
HO3	Pompa Air	17	H	01°51'28.4"	103°18'27.4"	64	S	07 December 2013–19 January 2014	16.7/1.0	
PTHI	PT.Humusindo	18	H	01°57′43.2″	103°15′50.3″	59	C	15 November 2013–04 December 2013	17.5/1.1	
BD_old	Pematang Kabau	22	B	01°57′22.4″	102°33′39.9″	73	S	14 July 2013–30 July 2013	15.1/1.4	
HAR_old	Bungku	25	H	01°56′41.5″	103°16′41.9″	43	S	30 September 2013– 01 November 2013	21.1/1.6	

Chapter 5

Transpiration changes by transforming tropical rainforest to rubber and oil palm plantations

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Complete draft version.

5.1 Hydrological consequences of rainforest transformation

Rainforest transformation to monocultures alters ecosystem water cycles with consequences at least at regional scales and including e.g. shifts in precipitation and streamflow patterns or periodical water scarcity. For the ‘Maritime Continent’ of Indonesia, a current deforestation hotspot, eco-hydrological consequences of rainforest transformation to the prevalent production systems rubber and oil palm remain unknown. We assessed transpiration rates at 32 sites in forests and rubber and oil palm land use types based on a sap flux method. Stand transpiration was highest in forest, intermediate in ‘jungle rubber’ agroforests and oil palm plantations and much lower in rubber plantations. Oil palm transpiration was ‘buffered’ at the day-to-day scale due to a distinct diurnal response to micrometeorological fluctuations. Pronounced eco-hydrological differences between rubber and oil palm point to increased susceptibility of oil palm dominated landscapes for periodical water scarcity and thus to potentially severe and neglected hydrological consequences of the continuing transformation of tropical rainforests.

Rainforest transformation to agricultural systems alters ecosystem water cycles with consequences at least at regional scales (Aragao 2012). Transpiration, i.e. water use by plants, is central to the hydrological cycle and is an important biosphere-atmosphere feedback mechanism (Jasechko et al. 2013). In Amazonia, e.g., reductions in land-atmosphere water fluxes after large-scale rainforest transformation to pasture substantially altered regional precipitation patterns (e.g. Zhang et al. 2001, Brown et al. 2005, Sampaio et al. 2007, Aragao 2012). Currently, a hot spot of rainforest transformation is the ‘Maritime Continent’ of Indonesia (e.g. Hansen et al. 2013, FAO 2015); it has been postulated that latent atmosphere heating substantial over ‘maritime’ regions and that global climate is affected more by ‘maritime’ than by ‘continental’ land use change (van der Molen et al. 2006). In contrast to the transformation of Amazonian rainforests to pasture or soy-bean (e.g. Barona et al. 2010, Sampaio et al. 2007), Indonesian (lowland) rainforests are largely being transformed to rubber tree (*Hevea brasiliensis* Müll.) and oil palm (*Elaeis guineensis* Jacq.) monocultures (Koh and Wilcove 2008, Carlson et al. 2014, FAO 2015). Scattered in between these highly productive agricultural systems, some traditional agroforestry systems remain in the landscape (e.g. ‘jungle rubber’). They are considered a glimmer of hope in the context of balancing economics and ecosystem services (Wibawa et al. 2005, Shibu 2009).

In contrast to pasture in Amazonia, the mentioned ‘maritime’ rubber and oil palm transformation systems have a ‘forest-like’ stand structure. As prominently put forward by Roberts (1983) for European broadleaved forest stands, transpiration is assumed to be a rather conservative process, i.e. stand transpiration rates are relatively homogeneous despite highly heterogeneous stand structures.

This may also be valid for forest and ‘tree’-based transformation systems in the tropics. Estimates for oil palm plantations in South East Asia suggest a similar magnitude of land-atmosphere water fluxes as e.g. reported for tropical rainforests in the region (Tani et al. 2003, Henson and Harun 2005, Kumagai et al. 2005, Yusop et al. 2008). On the other hand, severe changes in hydrological functioning after rainforest transformation (e.g. periodic water scarcity) were recently reported for oil palm landscapes (Obidzinski et al. 2012, Larsen et al. 2014). Reported land-atmosphere water fluxes from rubber plantations on the Asian mainland even exceed those of natural forests (Tan et al. 2011), which can potentially result in severe negative impacts on essential hydrological ecosystem services (Ziegler et al. 2009), e.g. (periodically) reduced streamflow and ground water discharge (Bruijnzeel 1989, 2004). However, for the ‘Maritime Continent’ eco-hydrological consequences of rainforest transformation to the prevalent agricultural systems (i.e. oil palm and rubber monocultures) yet remain to be assessed comprehensively. Available studies encompass a variety of methodological approaches and (continental) climatic regimes, and deriving over-arching scientific findings is further hindered by a lack of sufficient spatial replication and reference systems.

To assess changes in the magnitude of the central water flux of stand transpiration as well as in its spatial and temporal variation after rainforest transformation, we studied rainforest, jungle rubber, rubber and oil palm in the lowlands of Jambi Province on Sumatra, Indonesia with a sap flux approach. 32 study sites were equally distributed over the four land use types (**Supp. Figure 5.4**). The region is an agricultural post-deforestation landscape and resembles the Indonesian rainforest transformation process to ‘productive’ land use types. Between 1985 and 2007, 71% of lowland forests were cleared in Jambi; today, monoculture rubber and oil palm plantations dominate the landscape (Laumonier et al. 2010, FAO 2015). For each land use type, we estimated stand transpiration, identified controls of spatial (i.e. stand-to-stand) variation of transpiration and analyzed the coupling of transpiration to environmental variables at varying temporal scales. Our results shed light on changes in transpiration associated with the rapidly continuing rainforest transformation to agricultural monocultures such as oil palm plantations on the ‘Maritime Continent’. They point to substantial differences in eco-hydrological functioning between trees and (oil) palms.

5.2 Substantial changes in spatial and temporal transpiration patterns after rainforest transformation

We found pronounced differences in the magnitude of transpirational water fluxes among forests, jungle rubber agroforests and rubber and oil palm plantations. Sap-flux derived transpiration rates of eight replicates per land use type (medians) on sunny days were lowest in rubber (1.0 mm day^{-1}), intermediate in oil palm (1.4 mm day^{-1}) and jungle rubber (1.6 mm day^{-1}) and highest in the forest

(1.8 mm day^{-1}, **Figure 5.1**). Estimated yearly averages of transpiration for the respective 32 stands were generally 15-25% lower than the presented sap-flux derived transpiration rates on sunny days; respective yearly sums of stand transpiration were 320 mm year^{-1} (rubber), 414 mm year^{-1} (oil palm), 527 mm year^{-1} (jungle rubber) and 558 mm year^{-1} (forest).

Spatial variation (quantified by the inter quartile range normalized by the median, nIQR) on sunny days was very small among (fully-leaved) rubber plantations (14% nIQR), intermediate in forest (25%) and jungle rubber (28%) and highest in oil palm (37%). On cloudy days, stand-to-stand variation in tree based land use types (i.e. forest, jungle rubber and rubber) was 1.2- to 2.4-fold larger than on sunny days, i.e. differences in stand transpiration among sites became more pronounced under limiting micrometeorological conditions. We observed the opposite for oil palm, i.e. a 20% reduction in spatial variation of transpiration on cloudy days. This indicates buffering mechanisms in the oil palm transpiration response to fluctuating environmental conditions compared to tree based land use types. At the yearly scale, 65%-89% of the substantial observed spatial variation of transpiration among stands of the same land use type was explained by differences in stand structure (i.e. stand density, average trunk diameter, stand water conductive area) and site characteristics (i.e. annual averages and ranges of soil moisture and below-canopy air temperature, respectively) ($P<0.05$, multiple linear regression, **Supp. Table 5.5**).

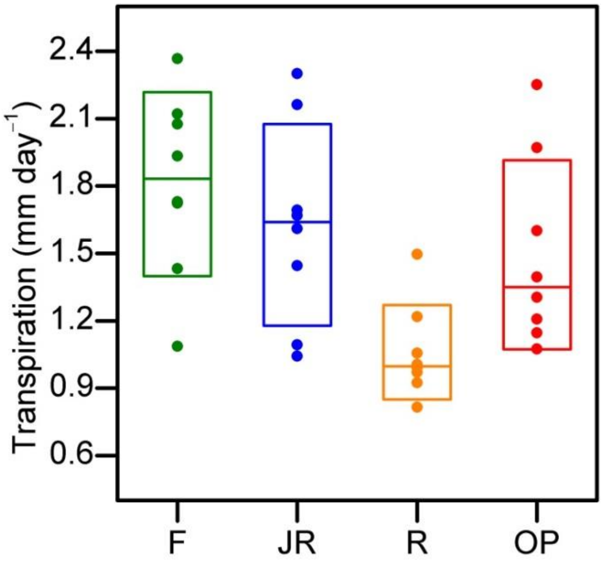

Figure 5.1. Spatial, plot-to-plot variation of sap flux derived transpiration in the four land use types forest (F), jungle rubber (JR), rubber (R) and oil palm (OP) on three sunny days. Data from 32 plots, rubber transpiration rates derived from fully-leaved conditions. Horizontal lines indicate medians, boxes represent the inter quartile range.

Indications of buffered transpirational behavior of oil palm were strengthened by analyses of long-term monitoring sap flux data from four stands (one in each land use type, 110 days of simultaneous measurements), i.e. the temporal, day-to-day variation of oil palm transpiration was substantially reduced ('buffered') compared to tree based land use types (**Figure 5.2**). The nIQR of normalized day-to-day transpiration rates was 1.4-fold larger in forest and jungle rubber than in oil palm. In rubber plantations, (partial) leaf shedding associated with pronounced reductions in transpiration during prolonged dry periods resulted in a two-fold larger overall day-to-day variation of transpiration than in oil palm plantations. In all four land use types, day-to-day transpiration rates were mainly driven by the micrometeorological variables VPD ($R^2adj= 0.35-0.60$, $P<0.05$, Hill function, **Supp. Figure 5.6**) and radiation ($R^2adj= 0.46-0.67$, $P<0.05$, Hill function, **Supp. Figure 5.7**). Combining these two variables in a Jarvis-type model explained 82-95 % of the observed day-to-day variation of transpiration in the studied land use types (**Supp. Table 5.2**). Adding e.g. soil moisture or temperature (or an array of further recorded micrometeorological variables) did not significantly improve the precision of predicting day-to-day transpiration. We consequently assume that the reasons for the observed buffered day-to-day transpiration response of oil palms compared to tree based land use types are not environmentally limiting conditions alone, but are rather strongly influenced by hydro-physiologically distinct mechanism in oil palms. Buffered day-to-day transpirational behavior compared to forests has e.g. also been reported for another monocot species (i.e. Moso bamboo, Komatsu et al. 2010).

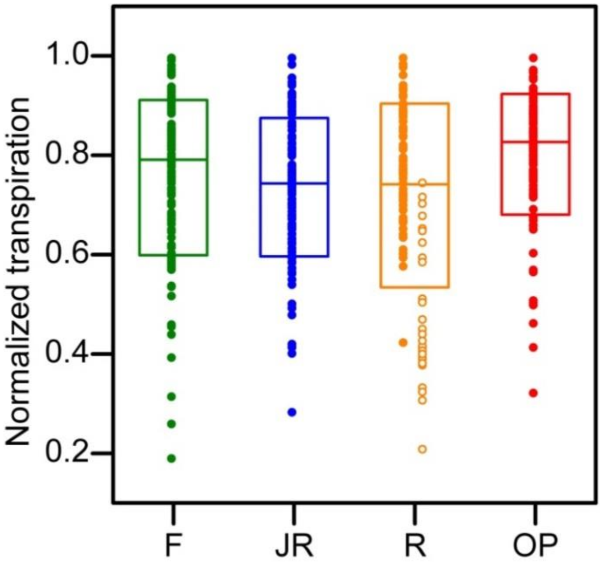

Figure 5.2. Temporal, day-to-day variation of normalized sap flux derived transpiration in forest (F), jungle rubber (JR), rubber (R) and OP. Data from four long-term sap flux monitoring plots (110 days of simultaneous measurements). Data normalized by setting the observed daily maximum within each

land use type to one. Hollow points for rubber indicate transpiration rates during leaf shedding period; rubber statistics are provided for the full measurement period, i.e. including both the fully-leaved state and times of (partial) leaf shedding. Horizontal lines indicate medians, the boxes represent the inter quartile range.

We analyzed diurnal coupling of transpiration to micrometeorological drivers (i.e. VPD and radiation) in the four land use types under sunny and cloudy conditions by examining occurrence and magnitude of hysteresis (i.e. integrated diurnal difference between micrometeorological ‘input’ and transpirational ‘output’), ‘transpirational surplus’ and ‘deficit’ (i.e. the respective hysteresis areas above and below the 1:1 line, **Figure 5.3**) and ‘transpirational net effect’ (i.e. deficits subtracted from surpluses, **Supp. Table 5.4**). The diurnal response of transpiration to VPD and radiation (values normalized by setting highest observed hourly values to one) was distinct for oil palms, but very similar among the three tree-based land use types (i.e. forest, jungle rubber and rubber), which were thus combined for the analysis (referred to as ‘trees’).

On sunny days, trees optimized their transpirational behavior via a close pre-noon coupling to radiation and a close afternoon coupling to VPD. This resulted in a strong positive transpirational net effect in trees to both VPD and radiation, and thus a strong positive ‘combined transpirational effect’ (**Supp. Table 5.4)**. Oil palm transpiration, on the other hand, remained relatively coupled to radiation throughout the day (small total hysteresis area, zero net effect). Its diurnal pattern was completely decoupled from VPD (**Figure 5.3)**, i.e. oil palm transpiration peaked early in the day (11am) when VPD was at only 50% of its daily maximum, but then consistently declined throughout the rest of the day despite substantially further increasing VPD. At the VPD peak (3pm), oil palm transpiration was reduced to 60% of its daily maximum, while tree transpiration was still near maximum (>80%). The pre-noon transpirational surplus to VPD in oil palm due to high transpiration rates early in the day was outbalanced by a large afternoon deficit, i.e. unlike for the studied trees the net effect to VPD in oil palms was negative under sunny conditions. As opposed to trees, this points to an inability (i.e. a ‘buffering effect’) of oil palms to make full use of favorable conditions for transpiration (particularly in the afternoon), which was e.g. reflected in a 20% reduced range between maximum and median of transpiration at the day-to-day scale in oil palms as compared to trees (**Figure 5.2).**

Likewise, we found evidence of buffering mechanisms of oil palm transpiration on cloudy days, i.e. in oil palms limiting micrometeorological conditions resulted in relatively less pronounced reductions in transpirational surplus than in trees. Tree transpiration on cloudy days was closely coupled to VPD (**Figure 5.3**). This resulted in a strong decoupling from radiation (**Supp. Fig. 5.8**), i.e. large pre-noon transpirational deficits and equally large afternoon surpluses to radiation (zero net effect, **Supp. Table 5.4**). The strong positive transpirational net effects to VPD and radiation observed in trees on sunny days were thus both substantially reduced on cloudy days, which results in pronounced reductions of tree transpiration on days with limiting micrometeorological conditions. In contrast, in oil palms reductions in transpirational net effect between sunny and cloudy conditions were much less pronounced, as oil palm transpiration remained closely coupled to radiation on cloudy days (zero net effect) and oil palm was able to sustain relatively higher afternoon transpiration rates than under sunny conditions (**Figure 5.3**). Limiting environmental conditions thus induced relatively less pronounced reductions of transpiration in oil palms than in trees. This was e.g. reflected in the slightly higher median and the substantially lower nIQR of oil palm compared to trees at the day-to-day scale (**Figure 5.2**).

Generally, oil palm transpiration increased much quicker in the morning hours and diurnally peaked earlier than tree transpiration (particularly on sunny days); after its early peak, however, oil palm transpiration consistently declined, which was not observed in trees. This behavior may point to influences of internal water storage mechanisms in oil palms, as demonstrated for the palm species *Sabal palmetto* Walt. (Holbrook and Sinclair 1992) and *Syagrus romanzoffiana* Cham. (Madurapperuma et al. 2009). Internal water storage contribution to pre-noon transpiration could explain the early peaks, while their eventual depletion could explain the much lower afternoon transpiration rates as compared to trees.

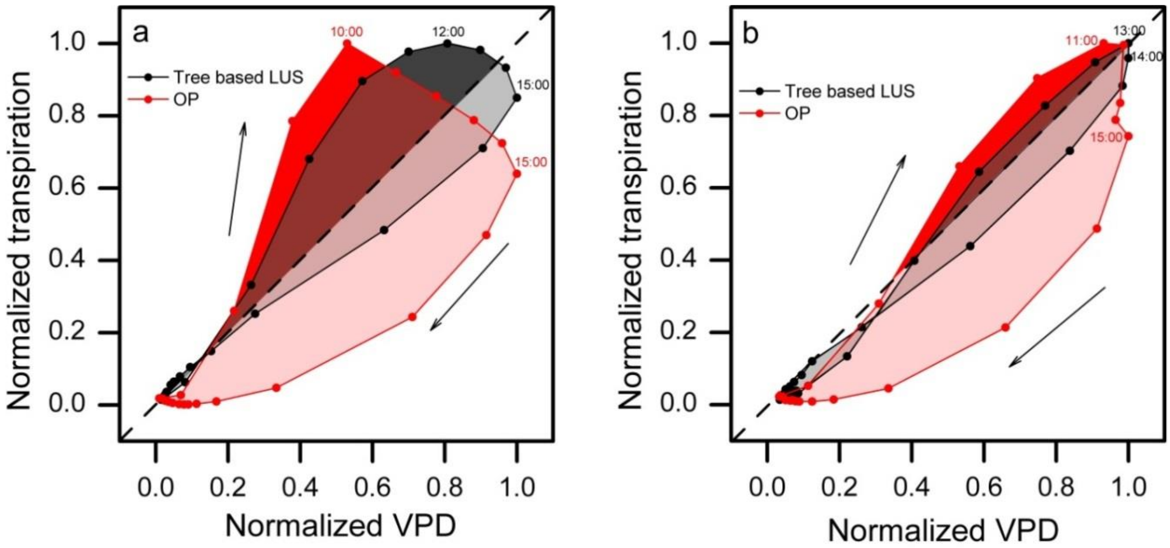

Figure 5.3. Diurnal response of normalized transpiration in tree based land use types (forest, jungle rubber and rubber combined) and in oil palms, respectively, to changes in normalized vapor pressure deficit under sunny (a) and cloudy (b) conditions, respectively. Data from 32 plots averaged. Respective hysteresis areas above and below the 1:1-relationship represent ‘transpirational surplus’ (darker colors) and ‘deficit’ (lighter colors). Subtracting deficits from surpluses yields ‘transpirational net effects’.

5.3 Impacts of rainforest transformation on the water cycle

Sap-flux derived transpiration rates for 32 sites in four lowland land use types in Jambi, Indonesia pointed to substantial changes in the magnitude of the 'central' ecosystem water flux of transpiration after rainforest transformation. We found relatively high stand transpiration rates among eight productive oil palm plantations. Evapotranspiration from oil palm plantations was also reported to be relatively high (also see Röll et al. 2015). The magnitude of water fluxes from productive oil palm plantations can thus be substantial (i.e. similar to rainforests), which can partially be explained by very high, management-intensity-dependent productivity of oil palm plantations despite relatively low biomass per hectare (Kotowska et al. 2015). Stand transpiration rates of rubber plantations, on the other hand, were much lower than those of rainforests, jungle rubber agroforests and oil palm plantations, partly due to (partial) leaf shedding during pronounced dry periods.

These insights were derived from eco-hydrological research in a tropical lowland post-deforestation landscape in a 'maritime' environment, in contrast to e.g. the continental conditions of the Amazon Basin or the Asian mainland. However, our results can likely be applied to other tropical lowland regions e.g. in the African and American tropics, where particularly oil palms area also wide spread (FAO 2015). Our estimate of potential evapotranspiration (ET_{pot}, mm yr^{-1}) derived from micrometeorological measurements (Allen et al. 1998) for our study region was 1026±80 mm yr^{-1} (mean ± SE between four stations), which falls into the range of ET_{pot} values provided for the humid tropics in general (927-1076 mm yr^{-1}, Schlesinger et al. 2014). For tropical rainforests, 70±14% of ET_{pot} are typically accounted for by plant transpiration (Schlesinger et al. 2014), which yields a corridor of 519 to 904 mm yr^{-1} for stand transpiration of tropical rainforests including primary forests. Our transpiration estimate for partly logged lowland rainforest remnants on Sumatra (543±49 mm yr^{-1}) falls into the lower end of this range and is e.g. slightly lower than values reported for pristine tropical lowland forest in Australia (587-596 mm yr^{-1}, McJannet et al. 2007, Wallace et al. 2010) and e.g. slightly higher than an estimate for Dipterocarp forests (excluding trees DBH < 20cm) on Borneo (516 mm yr^{-1}, Becker 1996). For 'jungle rubber' agroforests, no transpiration rates are available yet for comparison; our estimate (yearly average 1.4±0.2 mm day^{-1}) is centered within the range provided for a variety of tropical tree based agroforestry and reforestation systems (0.5-2.5 mm day^{-1}, Dierick and Hölscher 2009, Köhler et al. 2009, Dierick et al. 2010, Komatsu et al. 2010, Kunert et al. 2010, Köhler et al. 2013). Our transpiration estimate for rubber plantations was low (310±15 mm yr^{-1}); transpiration varied highly between fully-leaved conditions (1.0±0.1 mm day^{-1}) and periods of partial leaf shedding (0.6±0.1 mm day^{-1}). Using rubber-specific ET_{pot}/transpiration ratios of about 3:1 (fully-leaved) and 5:1 (leaf shedding, Kobayashi et al. 2014) and the ET_{pot} estimate for our study region (1026±80 mm yr^{-1}) yields (almost identical) transpiration rates of 0.9 (fully-leaved) and 0.6 mm day^{-1}

(leaf shedding). Several studies report similarly pronounced reductions in rubber transpiration rates during dry periods (e.g. Ayutthaya et al. 2010, Guardiola-Claramonte et al. 2010, Kunjet et al. 2013, Kobayashi et al. 2014). However, stand transpiration rates of productive, fully-leafed rubber plantations on the Asian mainland are reported to be substantially higher than the estimates for our 'maritime' lowland study region (median 1.0 mm day^{-1} on sunny days). E.g., maximum transpiration rates of up to 2.2 mm day^{-1} in Cambodia (Kobayashi et al. 2014) and between 1.6 and 2.3 mm day^{-1} in Thailand (Ayutthaya et al. 2010, Ayutthaya et al. 2011, Boithias et al. 2012) were reported. However, these studies were conducted under regimes of generally much lower and very seasonal rainfall, while VPD in these 'continental' regions is generally higher than in our 'maritime' study region. This results in seasonally highly variable and annually up to over 70% higher potential evapotranspiration than in our study region (e.g. Zhou et al. 2006, 2008, see **Supp. Figure 5.5** for relatively constant ET_{pot} pattern in our study region).

The above review suggests, that the statement by Roberts (1983), that stand transpiration among European broadleaved forests is a rather conservative process, also seems applicable to the tropics; transformation of rainforests to 'tree'-based tropical land use types do not seem to induce drastic changes in the magnitude of transpirational and evapotranspirational water fluxes in the majority of cited studies. Our research confirms this for a 'maritime' lowland landscape regarding the transformation to rubber agroforests and oil palm plantations; rubber plantations, however, had much lower (annual) stand transpiration rates. We also conclude that (evapo)transpirational water fluxes from oil palm plantations can be substantial under certain site or management conditions.

Asides from substantial changes the magnitude of transpirational water fluxes after rainforest transformation, we also found pronounced differences in the transpirational day-to-day behavior among the studied land use types, i.e. between tree based land use types (forest, jungle rubber, rubber) and oil palms. The day-to-day response of oil palms was 'buffered' compared to tree based land use types, i.e. even pronounced fluctuations in micrometeorological conditions resulted in relatively low temporal variation of oil palm transpiration rates, which we explained by a distinct response to diurnal fluctuations in micrometeorological conditions in oil palms. The pronounced differences in transpirational characteristics that we observed between rubber and oil palm were found to play a key role in explaining periodically occurring local water scarcity in oil palm dominated landscapes, as it was recently reported in social studies in Indonesia (Obidzinski et al. 2012, Larsen et al. 2014, Merten et al. 2015). Rubber expansion, which has been on-going in Indonesia much longer than the relatively recent oil palm boom (e.g. Sunderlin et al. 2001, Koh and Wilcove 2008), to our knowledge has not been associated with phenomena of water scarcity in the humid 'maritime' tropics.

The ability of rainforests to soak up and store precipitated water in a heterogeneous complex of organic litter and soil layers and highly root-penetrated mineral topsoils with a high organic carbon content (e.g. Lal 1996, Franzluebbers 2002, Bronick and Lal 2005, Yimer et al. 2008) is lost after transformation to both oil palm and rubber plantations due to severe erosion (Guillaume et al. 2015). In contrast to rubber, however, oil palms have relatively high water use rates and transpire relatively constantly despite fluctuating environmental conditions. Paired with the erosion-induced low soil water storage capacity, this behavior can enhance or induce periodical water scarcity in oil palm dominated landscapes, i.e. low streamflow and groundwater levels, which have been reported to be a potential consequence of forest transformation in various studies (e.g. Bruijnzeel 1989, Lal 1996, Bruijnzeel 2004, Krishnaswamy 2013). Our work points to substantial eco-hydrological differences between tree- and palm-based transformation systems as well as to potentially severe and thus far neglected landscape-scale hydrological consequences of ('maritime') rainforest transformation to monoculture plantations, particularly in the case of transformation to oil palm.

5.4 Methods

The study was conducted in Jambi Province on Sumatra, Indonesia (**Supp. Figure 5.4**). From 1991-2011, annual temperature was 26.7 ± 0.2 °C (mean ± SD), with little intra-annual variation. Annual precipitation was 2235 ± 385 mm; a dry season with less than 120 mm monthly precipitation usually occurred between June and September, but the magnitude of dry season rainfall patterns varied highly between years (data from Airport Sultan Thaha in Jambi). We had 32 study sites that were evenly distributed over four land use types in Jambi (forest, 'jungle rubber' agroforest, monoculture rubber and oil palm plantations). They were located at similar altitude and in similar landscape positions (i.e. upland sites with usually moderate slopes) and were part of the larger experimental set-up of the CRC990 (www.uni-goettingen.de/crc990); the monoculture plantations were of similar age (8-16 yrs). They were small-holder plantations under similar management. Soil types were clay and loam Acrisols; soil conditions within each land use type in each landscape were relatively homogeneous (Allen et al. 2015, Guillaume et al. 2015). A variety of stand structural characteristics were recorded in each study plot (Kotowska et al. 2015).

In the 32 study plots (**Supp. Table 5.1**), we measured sap flux density with the thermal dissipation probe (TPD, Granier 1985) method in leaf petioles of oil palms and in trunks of trees to derive transpiration rates. To derive sap flux densities for oil palm, we used an oil palm specific calibration and experimental design (Niu et al. 2015). For TDP measurements on trees, we confirmed the original TDP calibration equation (Granier 1985) in laboratory calibration experiments. Four of the 32 study plots were long-term monitoring plots (> 1 year), one in each land use type; they were equipped with a relatively large amount of sensors, i.e. 56 for oil palm and 20 for forest, jungle rubber and rubber. In the remaining 28 plots, sap flux was measured for reduced periods of time (min. three weeks), and with a reduced number of sensors, i.e. 16 in oil palm, jungle rubber and forest and 12 in rubber.

To upscale from sap flux point measurements to stand transpiration, water conductive areas had to be derived for each stand; for oil palm, we used a recently established specific approach. To derive DBH-dependent water conductive areas for dicot trees in forest, jungle rubber and rubber plots, we measured radial patterns of sap flux density with increasing depth into the xylem with heat field deformation sensors (Nadezhdina et al. 2012) in parallel to TDP measurements and derived radial SFD patterns. Using inventory data (Kotowska et al. 2015) subsequently allowed calculating stand water conductive areas. To derive stand-scale transpiration rates, the average sap flux densities (hourly, daily) of all sensors running simultaneously in a certain plot were multiplied by the respective stand water conductive area. For the analysis, only days with a minimum of 13 (oil palm), 10 (rubber) and 14 (jungle rubber and forest sites) sensors running in parallel, respectively, were included. Estimates with these sample sizes are associated with 13% for oil palm (Niu et al. 2015), <10% for rubber (Kobayashi et al. 2014) and up to 35% for forest and jungle rubber plots (e.g. Granier et al. 1996). As not all sap flux measurements could be conducted in parallel, we used the respective averages of the three most sunny and most cloudy days within each measurement period, as to minimize day-to-day variability induced by weather, e.g. for an analysis of spatial variation of transpiration. For day-to-day analyses, the full data sets were used (min. 3 weeks per site).

For analyses of environmental drivers of transpiration, micrometeorological data were recorded at four stations set up near the 32 study sites. They were located at similar altitude (60 m ± 15 m a.s.l.) in open terrains; a variety of micrometeorological variables were recorded. Potential evapotranspiration was calculated with the Penman–Monteith equation (Allen et al. 1998) from micrometeorological variables. Environmental and sap flux measurements were conducted from March 2013 to April 2014. Exploratory analyses showed no influence of fluctuations in soil moisture on day-to-day transpiration rates ($P>0.5$). We thus focused on the classic micrometeorological drivers vapor pressure deficit (VPD) and radiation.

Diurnally, we plotted normalized transpiration rates (hourly maximum set to one) against normalized VPD and normalized radiation, respectively, to examine occurrence of hysteresis. On the day-to-day level, we plotted normalized transpiration rates (daily maximum within each respective measurement period set to one) against absolute values of VPD and radiation to examine the transpiration response over a broad range of micrometeorological conditions.

To model day-to-day transpiration rates, we used a Jarvis-type model (after O'Brien et al. 2004). We used 50 days of daily VPD and radiation values and derived parameters *b*, *c* and *d* from the four long-term monitoring plots for each land use type (**Supp. Table 5.2**). Parameter *a* was derived for all 32 plots by using the maximum observed daily transpiration rate from each measurement period (min. 3 weeks) and multiplying it by land use specific factors derived from exploratory analysis (**Supp. Table 5.3**). Using the derived stand and land use type specific model parameters and micrometerological data (i.e. average daily VPD and integrated daily radiation) from the stations in the vicinity of the study sites, annual transpiration rates could be calculated for all 32 studied stands.

All statistical analyses and graphing were performed with R version 3.1.1 (R Core Development team, 2014) and Origin 8.5 (Origin Lab, Northampton, MA, USA). More detailed information on all applied methods is provided as Supplementary Information.

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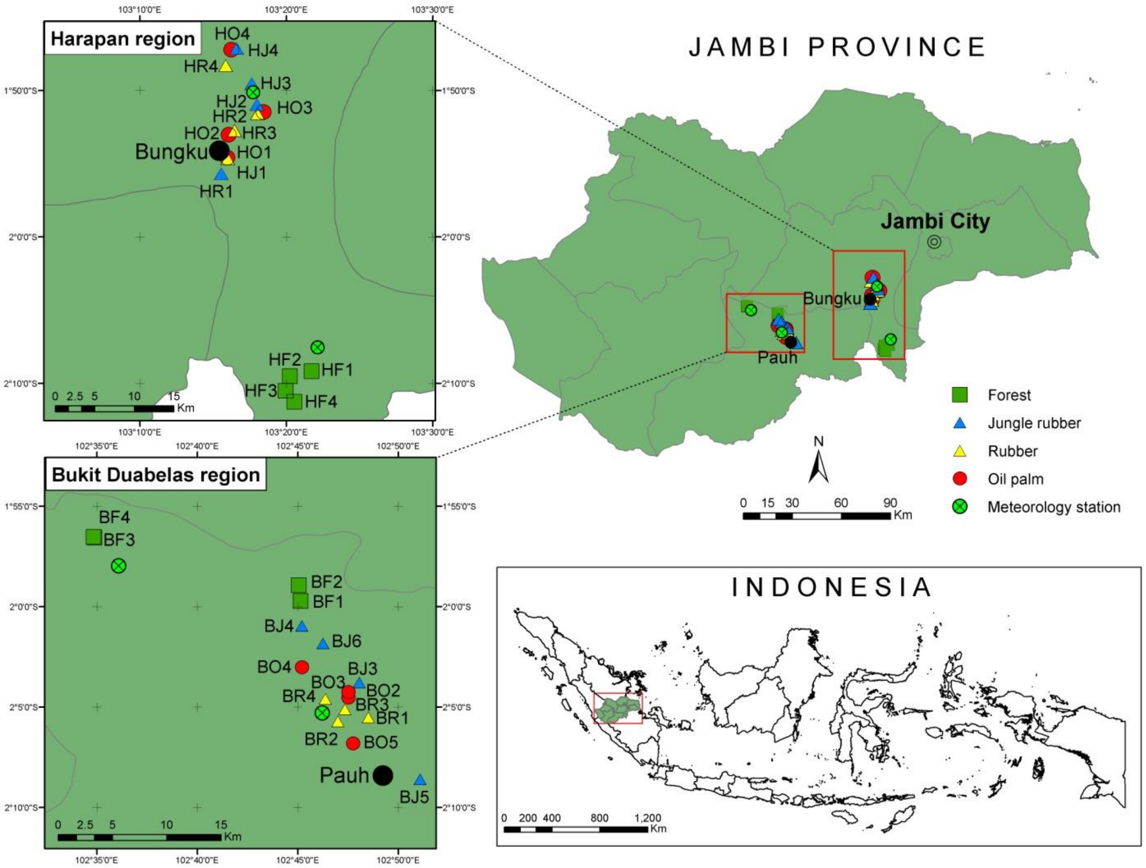
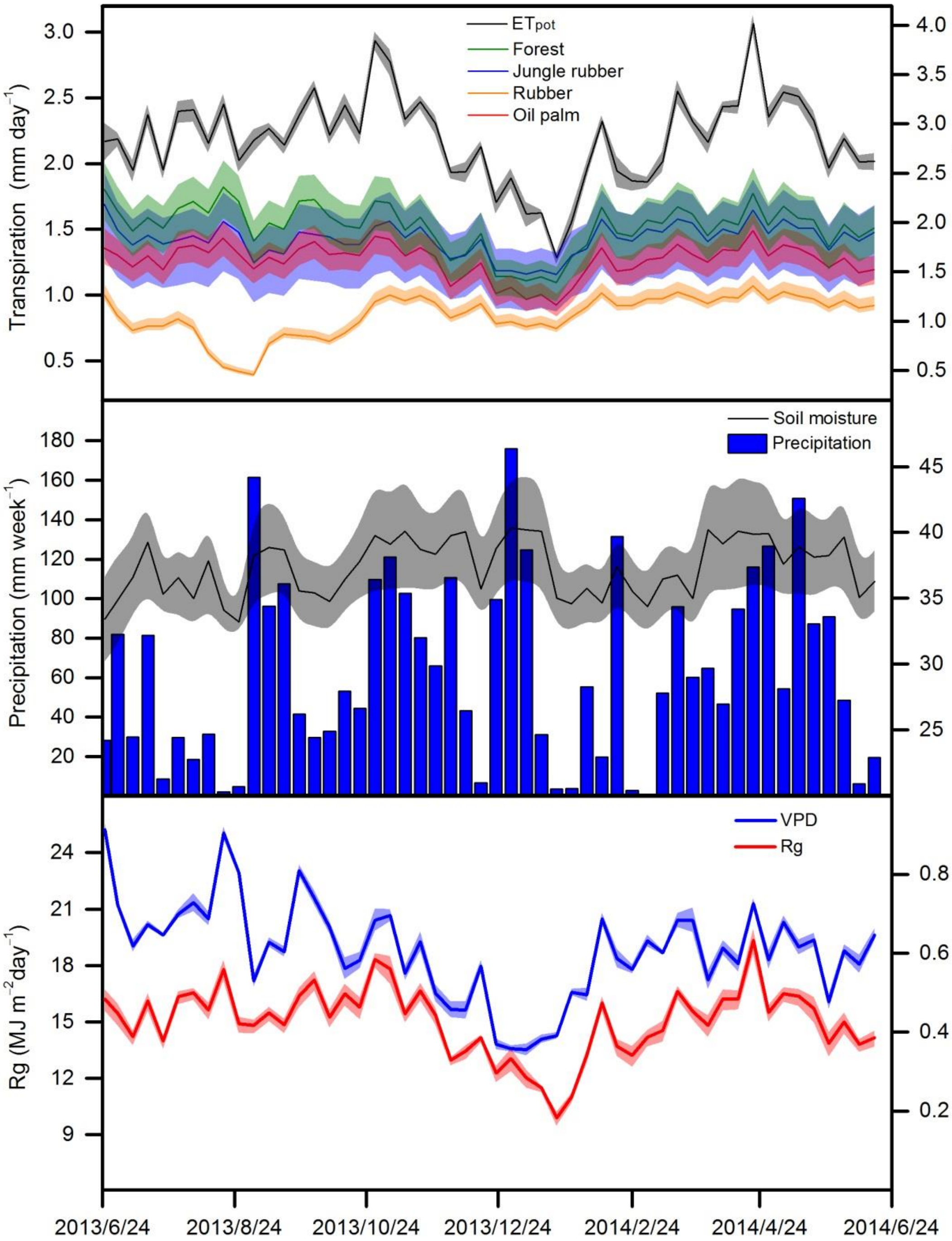
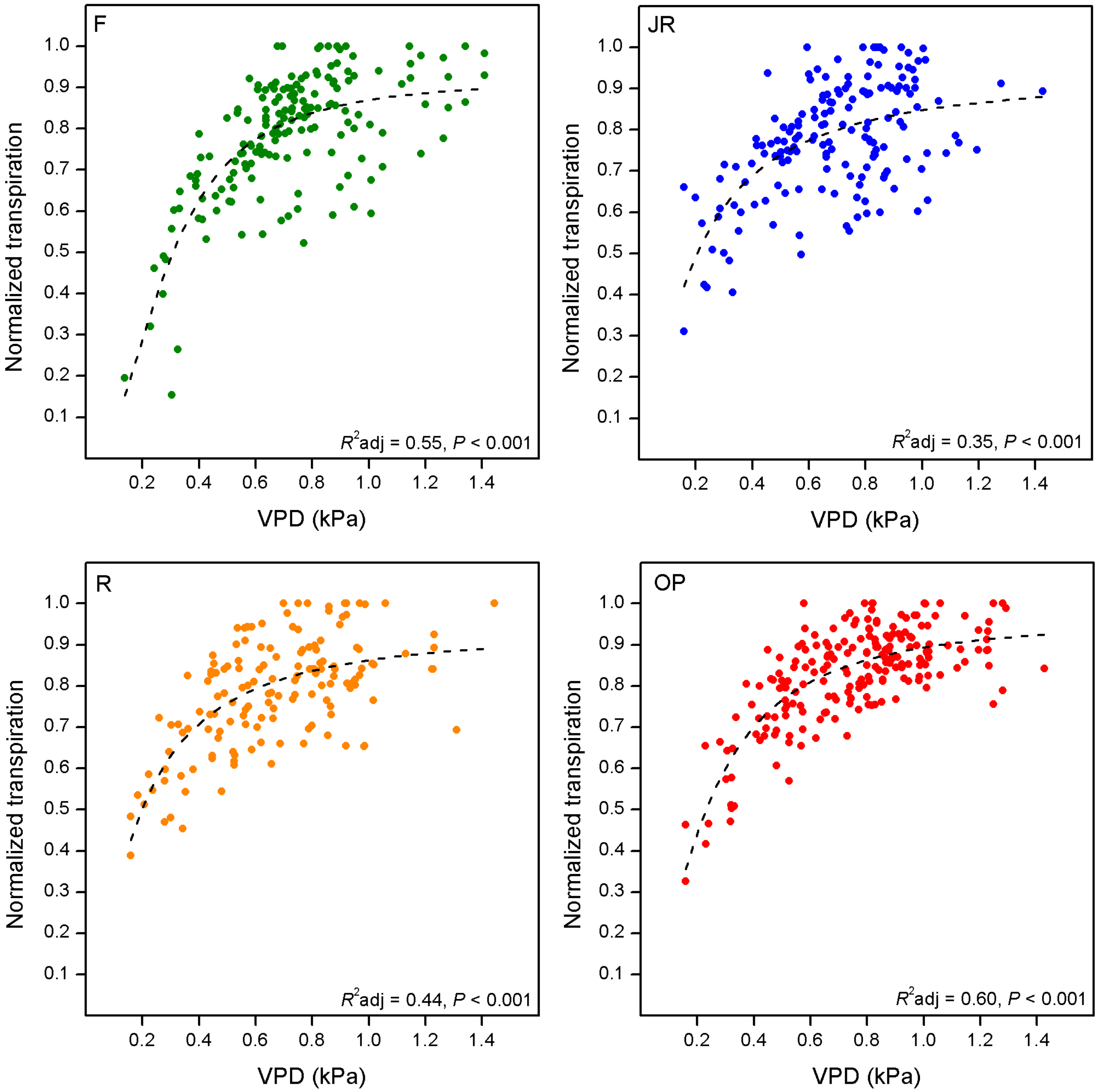
5.6 Supplementary Information Chapter 5



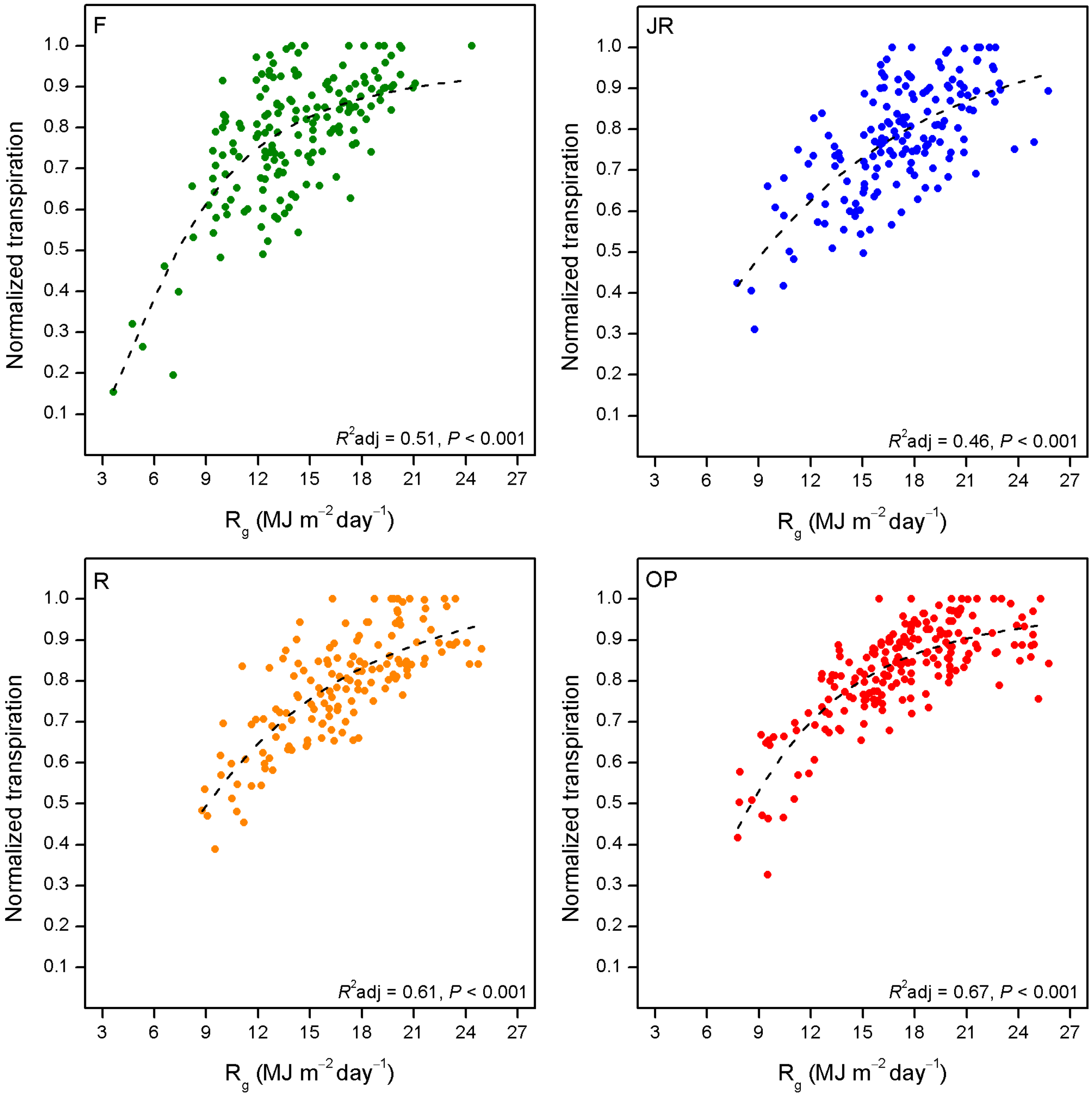
Supp. Figure 5.4: Location of the study sites in the land use types forest, 'jungle rubber' agroforest and oil palm and rubber monoculture plantations in Jambi province, Sumatra



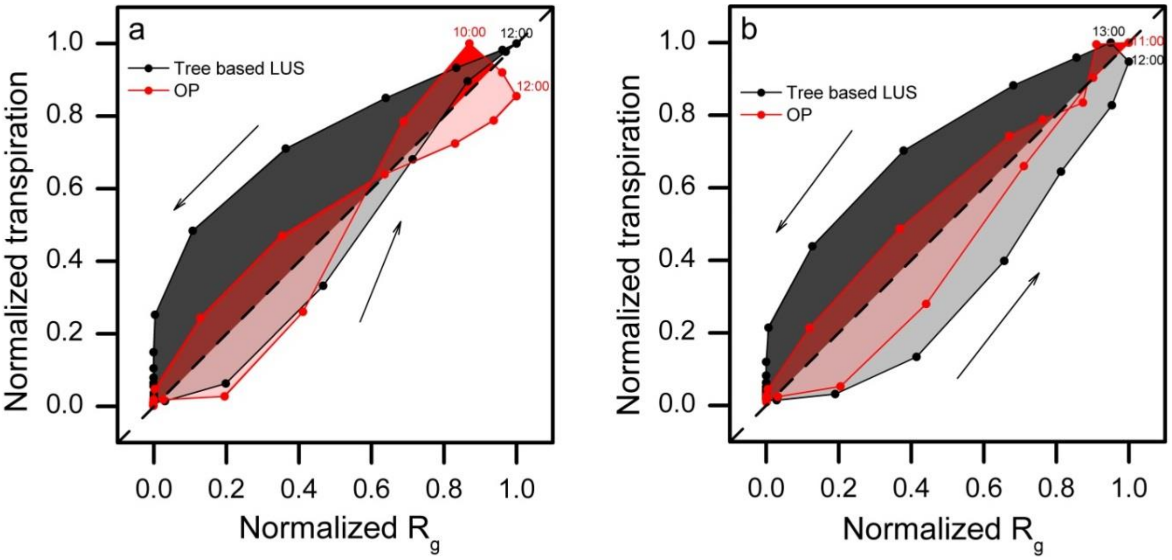
Supp. Figure 5.5: Weekly values of transpiration in forest, jungle rubber, rubber and oil palm and of potential evapotranspiration (ET_{pot}) in the study region (a). Soil moisture and precipitation (b), and radiation (R_g) and vapor pressure deficit (VPD) (c). Values provided for June 2013-June 2014 for the Bukit Duabelas landscape in Jambi, Sumatra, Indonesia, based on sap flux measurements in32 plots and micrometeorological measurements by four stations. Lines are respective medians, transparent corridors represent the inter quartile range.



Supp. Figure 5.6. Normalized daily transpiration rates plotted against VPD for each of the four land use types forest (F), jungle rubber (JR), rubber (R) and oil palm (OP). Transpiration values from all 32 study plots (eight per land use type) normalized by setting the highest observed daily value of each plot to one.



Supp. Figure 5.7. Normalized daily transpiration rates plotted against radiation for each of the four land use types forest (F), jungle rubber (JR), rubber (R) and oil palm (OP). Transpiration values from all 32 study plots (eight per land use type) normalized by setting the highest observed daily value of each plot to one.



Supp Figure 5.8. Diurnal response of normalized transpiration in tree based land use types (forest, jungle rubber and rubber combined) and in oil palms, respectively, to changes in radiation under sunny (a) and cloudy (b) conditions, respectively. Data from 32 plots averaged. Respective hysteresis areas above and below the 1:1-relationship represent ‘transpirational surplus’ (darker colors) and ‘deficit’ (lighter colors). Subtracting deficits from surpluses yields ‘transpirational net effects’.

Supp. Table 5.1. Plot, stand and measurement period characteristics of the 32 study plots.

Plot code †	**Landscape †**	**LUT †**	**Latitude (S) †**	**Longitude (E) †**	**Altitude (m) †**	**Stand density (ha^{-1}) ***	**Avg. stand height (m) ***	**Avg. Stand DBH (cm) ***	**Stand sapwood area (m^{2} ha^{-1})**	**C-stock_total (Mg C ha^{-1}) ***	**NPP_total (Mg C ha^{-1} yr^{-1}) ***	**canopy_cover (%) ***	**Loam (l) or clay (c) Acrisol ^**	**Additional comments**
BF1	BD	F	S 01°59' 42.5"	E 102°45 '08.1"	83	500	16.5	23.3	3.6	132	9	90	l	
BF2	BD	F	S 01° 58'55.1 "	E 102°45 '02.7"	77	400	16.8	23.7	3.2	166	12	90	l	
BF3	BD	F	S 01°56’ 33.9"	E 102°34 ’52.7"	87	452	16.6	22.3	3.6	183	15	93	l	long term monitoring
BF4	BD	F	S 01°56’ 31.0"	E 102°34 ’50.3"	87	560	18.3	23.2	4.3	232	13	92	l	
BJ3	BD	JR	S 02°03' 46.7"	E 102°48 '03.5"	89	1088	14.2	16.2	3.6	83	9	89	l	
BJ4	BD	JR	S 02°00' 57.3"	E 102°45 '12.3"	60	756	13.7	16.6	3.2	78	11	86	l	
BJ5	BD	JR	S 02°08' 35.6"	E 102°51 '04.7"	51	692	14.5	17.8	2.7	86	8	88	l	long term monitoring
BJ6	BD	JR	S 02°01’ 49.3"	E 102°46 ’15.0"	76	532	15.0	18.8	3.4	84	10	83	l	
BR1	BD	R	S 02°05' 30.7"	E 102°48 '30.7"	71	552	13.4	17.0	1.9	48	7	85	l	
BR2	BD	R	S 02°05' 06.8"	E 102°47 '20.7"	95	556	13.5	14.0	1.4	27	10	80	l	
BR3	BD	R	S 02°05' 43.0"	E 102°46 '59.6"	90	464	13.2	14.5	1.2	25	9	85	l	long term monitoring
BR4	BD	R	S 02°04' 36.1"	E 102°46 '22.3"	51	484	13.7	15.4	1.4	31	8	88	l	
BO2	BD	OP	02°04' 32.0"	102°47 '30.7"	84	120	4.7	73.2	12.2	23	12	70	l	
BO3	BD	OP	02°04' 15.2"	102°47 '30.6"	71	138	4.5	81.0	15.8	26	18	77	l	long term monitoring
BO4	BD	OP	02°03' 01.5"	102°45 '12.1"	34	144	3.5	85.1	15.9	23	13	76	l	
BO5	BD	OP	02°06' 48.9"	102°47 '44.5"	65	128	4.6	77.7	12.5	23	18	76	l	
HF1	HAR	F	S 02°09' 09.9"	E 103°21 '43.2"	76	664	19.6	20.9	4.4	209	11	92	c	
HF2	HAR	F	S 02°09' 29.4"	E 103°20 '01.5"	75	728	18.4	19.5	4.6	181	11	92	c	
HF3	HAR	F	S 02°10' 30.1"	E 103°19 '57.8"	58	632	21.1	21.4	4.3	215	11	93	c	
HF4	HAR	F	S 02°11' 15.2"	E 103°20 '33.4"	77	616	21.0	22.0	4.3	243	10	94	c	
HJ1	HAR	JR	S 01°55' 40.0"	E 103°15 '33.8"	51	572	14.7	18.2	2.2	88	11	89	c	
HJ2	HAR	JR	S 01°49' 31.9"	E 103°17 '39.2"	84	684	13.7	16.4	2.6	63	10	88	c	
HJ3	HAR	JR	S 01°50' 56.9"	E 103°17 '59.9"	95	672	14.0	16.7	2.4	72	10	90	c	

Plot code †	Lands-Cape †	LUT †	Latitude (S) †	Longitude (E) †	Alti-tude (m) †	Stand density (ha^{-1}) *	Avg. stand height (m) *	Avg. Stand DBH (cm) *	Stand sap-wood area (m^2 ha^{-1})	C-stock_total (Mg C ha^{-1}) *	NPP_total (Mg C ha^{-1} yr^{-1}) *	canopy_cover (%) *	Loam (l) or clay (c) Acri-sol ^	Additional comments
HJ4	HAR	JR	S 01°47' 07.3"	E 103°16 '36.9"	57	720	13.7	15.9	2.8	68	8	88	c	
HR1	HAR	R	S 01°54' 39.5"	E 103°16 '00.1"	77	372	14.4	20.5	1.7	45	7	89	c	
HR2	HAR	R	S 01°52' 44.5"	E 103°16 '28.4"	59	300	13.9	18.5	1.2	31	7	85	c	
HR3	HAR	R	S 01°51' 34.8"	E 103°18 '02.1"	90	448	13.0	17.6	1.6	42	8	87	c	
HR4	HAR	R	S 01°48' 18.2"	E103° 15'52.0"	71	820	12.4	14.5	2.2	57	7	87	c	
HO1	HAR	OP	01°54' 35.6"	103°15 '58.3"	81	140	6.4	76.4	14.1	37	19	78	c	
HO2	HAR	OP	01°53' 00.7"	103°16 '03.6"	55	152	5.8	82.3	13.1	36	16	79	c	
HO3	HAR	OP	01°51' 28.4"	103°18 '27.4"	64	152	4.3	79.4	20.8	30	18	79	c	
HO4	HAR	OP	01°47' 12.7"	103°16 '14.0"	48	128	4.6	71.9	10.5	26	16	79	c	

† CRC990: www.uni-goettingen.de/crc990 * Kotowska et al. 2015 ^ Allen et al. 2015

Suppl. Table 5.2. Adjustment of Jarvis model for modeling yearly transpiration values and model validation. Parameter fitting on data from four long-term monitoring plots, one in each land use type (forest, jungle rubber, rubber, oil palm); adjusted parameters *a*, *b*, *c* and *d* and R² and RSME for adjustment period (*n* = 45 days each). Model validation on *n* days; model performance indicated by R² and RSME of the full period as well as by a comparison of modeled and measured mean transpiration and range of transpiration over the validation period.

Plot	Model adjustment (n = 45 days)						Model validation (n = 95-126 days)						
	a	b	c	d	R²	RSME	n	R²	RSME	average T	avg model T/real T	range T	range T model/real
	mm day^{-1}	*MJ day^{-1} m^{-2}*	*kPa*	*kPa*		*mm day^{-1}*	*days*		*mm day^{-1}*	*mm day^{-1}*	*%*	*mm day^{-1}*	*%*
BF3	2.25	4.74	0.23	0.22	0.97	0.05	126	0.95	0.07	1.42	99.1	1.36	95.4
BJ5	1.95	2.53	0.16	0.35	0.86	0.07	102	0.84	0.07	1.35	100.4	0.9	97.1
BR3	1.38	5.26	0.11	0.16	0.86	0.05	102	0.86	0.08	0.9	104.4	0.93	94
BO3	2.17	15.44	0.16	0.09	0.95	0.05	95	0.82	0.07	1.1	100.4	0.94	98.8

Supp. Table 5.3. Adjustment of the Jarvis model for yearly modelling of transpiration rates for 31 plots in the four land use types forest (F), jungle rubber (JR), rubber (R) and oil palm (OP) (jungle rubber plot HJ4 excluded due to insufficient data for modelling). Adjustment period *t* (days), maximum modeled daily transpiration rates (Jarvis parameter *a*), R² and nRSME (round square mean error normalized by mean, %) as indicators of model quality during the adjustment period as well as modelled yearly (T_{year}, mm yr^{-1}) and daily (T_{day}, mm day^{-1}) transpiration rates derived from the presented *a* parameters and land use type specific *b*, *c* and *d* parameters (see Supp. Table 2). For each variable, medians and the inter quartile range (IQR) are provided by land use type.

Land use type	**Study plot**	***t*** *days*	**Jarvis Parameter *a*** *mm day^{-1}*	**R²adj**	**nRSME** *%*	**T_{year}** *mm day^{-1}*	**T_{day}** *mm year^{-1}*
F	BF1	12	2.21	0.73	5.82	502	1.38
F	BF2	12	1.34	0.78	4.80	304	0.83
F	BF3	48	2.25	0.97	3.57	511	1.40
F	BF4	19	2.66	0.92	8.46	604	1.66
F	HF1	12	2.85	0.95	9.02	647	1.77
F	HF2	14	3.33	0.92	5.79	757	2.07
F	HF3	12	2.69	0.76	10.15	611	1.67
F	HF4	12	1.93	0.86	8.32	438	1.20
F	***Median***	***12***	***2.46***	***0.89***	***7.07***	***558***	***1.53***
F	***IQR***	***3***	***0.59***	***0.15***	***3.06***	***134***	***0.37***
JR	BJ3	13	3.14	0.79	10.37	739	2.03
JR	BJ4	18	2.24	0.89	2.08	527	1.44
JR	BJ5	30	1.95	0.86	5.57	459	1.26
JR	BJ6	12	2.81	0.77	5.52	662	1.81
JR	HJ1	13	1.45	0.88	4.28	341	0.94
JR	HJ2	14	2.31	0.82	6.04	544	1.49
JR	HJ3	11	1.44	0.77	9.69	339	0.93
JR	***Median***	***13***	***2.24***	***0.82***	***5.57***	***527***	***1.44***
JR	***IQR***	***4***	***0.86***	***0.09***	***2.97***	***202***	***0.55***
R	BR1	13	1.29	0.91	6.16	296	0.81
R	BR2	14	1.61	0.82	8.89	370	1.01
R	BR3	35	1.38	0.86	5.76	317	0.87
R	BR4	15	1.47	0.83	9.74	337	0.92
R	HR1	12	1.05	0.82	7.57	241	0.66
R	HR2	11	1.41	0.75	11.28	324	0.89
R	HR3	13	1.36	0.94	10.52	312	0.86
R	HR4	12	1.65	0.80	11.56	379	1.04
R	***Median***	***13***	***1.40***	***0.83***	***9.31***	***320***	***0.88***
R	***IQR***	***2***	***0.16***	***0.06***	***3.49***	***37***	***0.10***
OP	BO2	15	1.93	0.76	5.49	332	0.91
OP	BO3	45	2.17	0.95	4.89	373	1.02
OP	BO4	12	2.78	0.83	6.87	478	1.31
OP	BO5	15	3.73	0.88	6.82	642	1.76
OP	HO1	12	2.47	0.78	4.29	425	1.16
OP	HO2	22	3.78	0.85	3.93	651	1.78
OP	HO3	13	2.33	0.87	7.28	401	1.10
OP	HO4	11	2.34	0.83	9.97	403	1.10
OP	***Median***	***14***	***2.41***	***0.84***	***6.16***	***414***	***1.13***
OP	***IQR***	***5***	***0.73***	***0.06***	***2.23***	***125***	***0.34***

Supp. Table 5.4. Area of total hysteresis and of 'transpirational surplus' and 'deficit' as well as 'transpirational net effect' of oil palm and tree transpiration to VPD and radiation, respectively. Values are provided for sunny days, cloudy days and as the difference between the two, i.e. the 'sensitivity' of the transpiration response to varying weather conditions. Transpiration, VPD and radiation values were previously normalized by setting the respective diurnal maxima to one (see Fig. 3); derived areas are thus merely in 'area units'. Further, for a more simple interpretation, the values in the table were again normalized: in the upper half of the table, the value of the total hysteresis of trees to VPD on sunny days was set to 100% (absolute value: 0.239 area units); in the lower half, the combined surplus area of trees (i.e. the sum of surplus areas to VPD and Rg) on sunny days was set to 100% (absolute value: 0.387 area units). The diurnal values for sunny and cloudy days (respective average values of three comparable days) were derived by averaging the values of all eight oil palm and all 24 tree study sites, i.e. the values of forest, jungle rubber and rubber plantations were averaged for the analysis.

		Sunny days			**Cloudy days**			**Changes between sunny and cloudy days ('sensitivity')**		
Land use type	**Area Type**	**to VPD**	**to Rg**	**to VPD and Rg combined**	**to VPD**	**to Rg**	**to VPD and Rg combined**	**to VPD**	**to Rg**	**to VPD and Rg combined**
Trees (T)	Total hysteresis	**100**	130	-30	45	174	-129	-55	44	-99
Oil palm (OP)	Total hysteresis	194	74	120	149	65	85	-44	-9	-36
Difference T-OP	Total hysteresis	-94	56	-150	-105	109	-214	-11	53	-64
Trees (T)	Surplus (S)	39	61	**100**	9	61	70	-29	0	-30
	Deficit (D)	23	19	42	18	47	65	-5	28	23
	Net effect (S-D)	16	42	58	-9	14	5	-25	-28	-53
Oil palm (OP)	Surplus (S)	45	22	67	17	19	35	-28	-3	-31
	Deficit (D)	75	24	98	75	21	97	1	-2	-2
	Net effect (S-D)	-30	-2	-32	-59	-3	-61	-29	-1	-30
Difference T-OP	Surplus (S)	-6	40	33	-7	42	35	-1	3	1
	Deficit (D)	-52	-5	-56	-57	25	-32	-6	30	24
	Net effect (S-D)	45	44	90	50	17	67	4	-27	-23

Supp. Table 5.5. Stand structural and site-related drivers of spatial variation of stand transpiration between eight plots per land use type (forest, jungle rubber, rubber and oil palm). Results of multiple linear regression: variable estimates and standard errors (SE), t-values and p-values (Pr>t) as well as statistical significance. Adjusted R^2 and significance level of the multiple linear regressions for each land use type. Stand structural variables (from Kotowska et al. 2015) that had a significant influence were average stand diameter at breast height (DBH, cm), stand sapwood area (SWA, cm^2) and stand density (N, ha^{-1}). Respective measured site-related variables with a significant influence were the range of annual soil moisture fluctuations (SM range, Vol.%), the range of annual air temperature fluctuations under the canopy (AT range, °C) and the annual near-minimum (5-percentile) temperature under the canopy (AT min, °C).

Land Use Typ	**Variable**	**Estimate**	**SE**	**t value**	**Pr>t**	**Sig.**
Forest	Intercept	1888.97	422.36	4.472	0.00656	**
	DBH	-70.2	18.12	-3.875	0.0117	*
	SM range	26.56	10.35	2.567	0.05025	.
	R2 adj	0.78			0.01023	*
Jungle rubber	Intercept	-1041.00	363.50	-2.865	0.0352	*
	SWA	0.0296	0.0039	7.596	0.000628	***
	AT range	84.43	35.74	2.362	0.064562	.
	R2 adj	0.89			0.001736	**
Rubber	Intercept	582.043	70.158	8.296	0.000166	***
	DBH	-15.779	4.221	-3.738	0.009646	**
	R2 adj	0.65			0.009646	**
Oil palm	Intercept	-9152.332	3666.41	-2.496	0.0547	.
	N	-5.15	1.559	-3.305	0.0214	*
	AT min	474.635	169.569	2.799	0.038	*
	R2adj	0.67			0.02636	*

Supplementary detailed method description

Study sites

The field study was conducted in the lowlands of Jambi, Sumatra, Indonesia (**Supp. Figure 5.4**). Between 1991 and 2011, average annual temperature in the region was 26.7 ± 0.2 °C (1991-2011 mean ± SD), with little intra-annual variation. Annual precipitation was 2235 ± 385 mm, a dry season with less than 120 mm monthly precipitation usually occurred between June and September. However, the magnitude of dry season rainfall patterns varied highly between years (data from Airport Sultan Thaha in Jambi). We had 32 study plots (50 x 50m) that were evenly spread over two landscapes in the Jambi province (i.e. the Harapan and Bukit Duabelas regions, **Supp. Figure 5.4**), were all at similar altitude (60 m ± 15 m a.s.l., **Supp. Table 5.1**) and belonged to the larger experimental set-up of the CRC990 (www.uni-goettingen.de/crc990). Within each region, four different land use types (forest, 'jungle rubber' agroforest, monoculture rubber and oil palm plantations) were studied with four spatial replicates each, adding up to a total of 32 study plots. They were located in similar landscape positions (i.e. upland sites with usually moderate slopes); the monoculture plantations were of similar age (8-16 yrs) and were all small-holder plantations under similar management. Soil types in the BD region are mainly clay Acrisols, in the HAR region loam Acrisols; soil conditions within each land use type in each landscape were relatively homogeneous (Allen et al. 2015, Guillaume et al. 2015).

Stand structural characteristics

For oil palms, on all sample leaves the leaf petiole baseline length was measured between upper and lower probe of each TDP sensor installed in the field (see Niu et al. 2015 for details). For each palm within a respective plot, trunk height (m) and diameter at breast height (cm) were recorded; on sap-flux sample palms, the number of leaves per palm was counted additionally. Over time, new leaves emerged and old ones were pruned by the farmers; we assumed the number of leaves per palm to be constant over the respective measurement periods. On the stand level, we counted the number of palms per hectare.

In forest, jungle rubber and rubber plots diameters at breast height (DBH) and tree heights were recorded for all trees within the respective plots; on some trees diameters were recorded at heights up to 3 m due to the occurrence of buttress roots or management-induced damages at breast height (e.g. on rubber trees). Stand gap fraction was estimated (Kotowska et al. 2015). In addition, on the sap flux sample trees bark thickness was measured with a small caliper at the location of sensor installation. On the stand level, we counted the number of trees with a DBH > 10 cm per hectare.

Environmental measurements

A total of four micrometeorological stations were set up in open terrain in proximity to the study sites in both landscapes; for the analysis of the water use characteristics of the respective stands, we used the micrometeorological data from the closest available station, at a maximum distance of approx. 10 km (jungle rubber, oil palm and rubber plantations) and 20 km (forest reference sites), respectively. The stations were located at similar altitude (60 m ± 15 m a.s.l.). Air temperature and relative humidity were measured at a height of 2 m with a Thermohygrometer (type 1.1025.55.000, Thies Clima, Göttingen, Germany) to calculate vapor pressure deficit (VPD, kPa). Wind speed was measured with a three cup anemometer (Thies Clima) at a height of 4 m. A net radiation sensor (NR Lite2, spectral range 200−100,000 nm, Kipp & Zonnen, The Netherlands) and a short wave radiation sensor (CMP3 Pyranometer, spectral range 300−2800 nm, Kipp & Zonnen) were installed at a height of 3 m, the latter to measure global radiation (R_g, MJ m^{-2} day^{-1}, from here on referred to as 'radiation'). Measurements were taken every 15 sec and averaged and stored on a DL16 Pro data logger (Thies Clima) every 10 min. All data were recorded for our full sap flux measurement campaign (March 2013 to April 2014), partly much longer.

Potential evapotranspiration (ET_{pot}, mm day^{-1}) was calculated with the FAO Penman–Monteith equation (FAO 56: Allen et al. 1998) based on the previously described micrometeorological input variables.

Transpiration rates derived from sap flux measurements

Laboratory calibration of sap flux method

In the field, we used the thermal dissipation probe (TPD, Granier 1985, 1987, 1996) method to measure sap flux in leaf petioles of oil palms and in the trunks of dicot trees. Species-specific calibration is recommended when working with previously unstudied species (e.g. Sperling et al. 2012, Sun et al. 2012). We performed laboratory calibration experiments (e.g. Bush et al. 2010, Renninger et al. 2010) to confirm or if necessary derive new parameters for the standard sap flux equation by Granier (1985). For oil palm, we used the specific, newly-calibrated equation by Niu et al. (2015) and strictly followed their experimental design (i.e. use of identical sensors and measurement scheme). Also, in analogy to their work, we performed calibration experiments for several studied dicot tree species. Pooling the data of five rubber tree segments confirmed the original equation by Granier (1985), i.e. there was a strong linear, almost-1:1 relationship between TDP-derived and gravimetric reference measurements ($J_s = 0.98* J_g$; $R^2=0.95$; $p<0.001$). For forest trees, we pooled the data of seven segments of three commonly occurring species; as for rubber, the original Granier equation was confirmed ($J_s=0.94*J_g$; $R^2=0.92$; $P<0.001$). This is in line with reports that the original equation yields reliable estimates when studying diffuse-porous dicot tree species and strictly following the original design (Granier 1985, Lu et al. 2004).

Field measurement scheme and sensor installation

Four of 32 study plots (see **Supp. Figure 5.4**) were equipped with TDP sensors as extensive, long-term monitoring plots (measurement period > 1 year), one in each land use type (BF3, BJ5, BR3, BO3, see **Supp. Figure 5.4**). For oil palm, 56 TDP sensors (1.25 cm length) were installed on the underside of oil palm leaf petioles on 10 palms of varying height (see Niu et al. 2015 for details). For forest, jungle rubber and rubber plots, two sensors were installed into the outer xylem (0-2.5 cm) of 10 dicot tree trunks per plot, at breast height in the North and South of the trunk, respectively. We chose dominant and co-dominant individuals, as they account for the major part of stand water use; within the dominant and co-dominant sociological classes, we evenly chose individuals of relatively larger, medium and smaller diameter (min. DBH: 10 cm). In the jungle rubber plot, five rubber trees and five non-rubber dicot trees were chosen.

In the remaining 28 plots, sap flux was measured for reduced periods of time (min. three weeks), and with a reduced number of sensors, i.e. in the leaf petioles of 16 leaves (four each on four different palms) for oil palm plots (following the scheme by Niu et al. 2015), in the trunks of six rubber trees and in the trunks of eight dicot trees in forest and jungle rubber plots (with two sensors per trunk). Individuals were chosen by the same criteria as in the long-term monitoring plots. In jungle rubber plots, at least three of the eight sap-flux sample trees were selected to be rubber trees.

After sensor installation, insulative materials and aluminum foil were added to minimize temperature gradients and reflect radiation. Durable plastic foil was added for protection from rain. The sensors were connected to AM16/32 multiplexers connected to a CR1000 data logger (both Campbell Scientific Inc., Logan, USA). The signals from the sensors were recorded every 30 sec and averaged and stored every 10 min. The mV-data from the logger were converted to sap flux density (SFD, g cm^{-2} h^{-1}) with the empirically-derived calibration equation by Granier (1985) for rubber and other dicot tree species after confirmation in laboratory experiments. For oil palm, species-specific equation parameters were used (Niu et al. 2015).

Establishing water conductive areas

To upscale from sap-flux point-measurements to stand transpiration, water conductive areas had to be established for each stand. For oil palm leaf petioles at the location of sensor installation, we used a linear regression between leaf baseline length and leaf conductive area, which was derived by Niu et al. (2015) for oil palms in the same study region based on laboratory staining experiments. Multiplying with the average number of leaves per palm and the number of palms per hectare, respectively, yielded palm- and stand-level water conductive areas.

To derive water conductive areas for dicot trees in forest, jungle rubber and rubber plots, we measured radial patterns of sap flux density with increasing depth into the xylem (0-8 cm, 1 cm resolution) with heat field deformation (HFD, Nadezhdina, 2012) sensors (ICT International, Armidale, Australia) in the 10 individuals from the long-term monitoring plots (BR3, BJ5, BF3). The measurements were conducted in parallel to TDP measurements (0-2.5 cm depth into xylem) on these individuals. Radial SFD patterns obtained by HFD measurements were normalized to a depth of 1.25 cm (center of TDP sensors) for the extrapolation of the single-point TDP measurements to whole-tree water use rates (e.g. following Oishi et al. 2008).

'Effective sapwood area' (SWA_{eff}), i.e. the conductive area of each individual normalized for the SFD at the standard TPD measurement depth, was linearly related to DBH for rubber trees for the DBH-range observed in our study (10-35 cm, $SWA_{eff} = 12.691*(DBH-0.66/2) - 72.672$, $R^2=0.69$, $p<0.05$). The DBH-SWA_{eff} relationship for rubber trees in jungle rubber plots was also linear ($SWA_{eff} = 8.2008* (DBH-0.66/2) - 37.997$, $R^2=0.65$, $P<0.05$) for the observed DBH-range of 10-40 cm. For non-rubber trees in both forest and jungle rubber plots, the relationship between DBH and SWA_{eff} was log-linear: it was $\log(SWA_{eff})=4.9194+0.0284*DBH$ ($R^2=0.88$, $p<0.00001$) for trees in forest plots and $\log(SWA_{eff})= 3.499 +0.0826*DBH$ ($R^2=0.65$, $p<0.05$) in jungle rubber, valid for respective DBH-ranges of 10-120 cm and 10-50 cm, respectively.

Transpiration rates and error margins

To derive stand-scale transpiration rates, the average SFD (hourly, daily values) of all sensors running simultaneously in a respective plot were multiplied by the previously derived stand water conductive areas. For the analysis, only days with a minimum of 13 (oil palm), 10 (rubber) and 14 (jungle rubber and forest sites) sensors running in parallel, respectively, were included.

Estimates with these sample sizes have been reported to be associated with estimation errors of stand transpiration rates of 14% for oil palm (described in detail in Niu et al., 2015). Analogous exploratory analyses with data from the long term monitoring plots showed that the respective minimum sample sizes were associated with estimation errors in stand transpiration rates of <10% for rubber monocultures (Kobayashi et al. 2014), while they have been estimated to be as high as 35% for heterogeneous stands (e.g. forest, jungle rubber) (Granier et al. 1996).

Analyzing the drivers of transpiration

Environmental and sap flux measurements were conducted from March 2013 to April 2014. Exploratory analyses showed no influence of the rather small annual fluctuations of soil moisture on transpiration rates (P>0.5). Where data was available, soil moisture appeared to be non-limiting in all studied plots during the respective measurement periods. We thus focused the analysis on the classic micrometeorological drivers vapor pressure deficit (VPD) and radiation.

Diurnally, we plotted normalized transpiration rates (hourly maximum set to one) against normalized VPD and normalized radiation, respectively, to examine occurrence of hysteresis. Data from all measurements within the eight plots of each land use type (i.e. forest, jungle rubber, rubber and oil palm) were averaged for these analyses. On the day-to-day level, we plotted normalized transpiration rates (daily maximum within each respective measurement period set to one) against absolute values of VPD and radiation to examine the transpiration response over a broad range of micrometeorological conditions.

As not all sap flux measurements could be conducted in parallel, we used the respective averages of the three most sunny/dry and most cloudy days within each measurement period (min. 3 weeks), as to minimize day-to-day variation induced by weather e.g. for an analysis of spatial variation. We chose days with a daily integrated radiation of more than 15 MJ m^{-2} day^{-1} and an average daytime VPD of more than 0.8 kPa for 'sunny' and with < 13 MJ m^{-2} day^{-1} and <0.6 kPa for 'cloudy' days. For other analyses, the full data sets were used (min. 3 weeks).

Modelling yearly transpiration rates

We used a Jarvis-type model previously mainly applied to explain sap flux responses of tropical tree species to environmental drivers (O'Brien et al. 2004, applied e.g. in Dierick and Hölscher 2008, Köhler et al. 2009) to model long-term, i.e. yearly transpiration rates. We adjusted it to our purpose in the sense of using daily values instead of hourly values.

$$T_{model} = a \times \frac{R_g}{b+R_g} \times \frac{1}{1+exp^{\frac{c-VPD}{d}}} \tag{5.1}$$

Where T_{model} is the modeled transpiration in mm day^{-1}, $R_g$the integrated daily radiation [MJ day^{-1} m^{-2}], VPD the average daily vapor pressure deficit [kPa] and a, b, c and d the equation parameters to be fitted for each plot. Parameter a (mm day^{-1}) represents the maximum modeled daily transpiration rate of each plot, b (MJ day^{-1} m^{-2}) describes the response to radiation (R_g) and c and d (kPa) the response to VPD.

We derived parameters *b*, *c* and *d* from the four long-term monitoring plots for each land use type. 50 days of data were used to adjust the parameters; they were then confronted with 110 days of measured data from the monitoring plots. The derived parameters performed very well for all land use types ($R^2>0.8$, $P<0.0001$), monthly model values did not diverge from measured values by more than 5%. The respective parameters were thus believed to be appropriate for deriving yearly transpiration rates of the four land use types.

Parameter a was derived for all 32 plots by using the maximum observed daily transpiration rate from each measurement period and multiplying it by land use specific factors derived from exploratory analysis with monitoring plot data (1.40 for rubber, jungle rubber and forest, 1.65 for oil palm). Thus, using the land use specific parameters *b, c* and *d*, (daily, yearly) transpiration rates could be modeled for all 32 plots.

All statistical analyses and graphing were performed with R version 3.1.1 (R Core Development team, 2014) and Origin 8.5 (Origin Lab, Northampton, MA, USA).

5.7 References of Supplementary Information Chapter 5

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Chapter 6

Water scarcity and oil palm expansion: social views and environmental processes

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Abstract Chapter 6

Transformations of natural ecosystems e.g. from rainforests to intensively managed plantations result in significant changes in the hydrological cycle including periodic scarcity of clean water for human consumption. In Indonesia, large areas of natural forest have been lost and extensive oil palm plantations have been established over the last decades. We conducted a combined social and environmental study in such a region of recent transformation, the Jambi province on Sumatra. The objective was to derive complementary lines of arguments to provide balanced insights into social perceptions and eco-hydrological processes accompanying environmental transformations. Interviews in local villages highlighted the concerns of people regarding decreasing water levels in wells during dry periods and increasing fluctuations in streamflow between rainy and dry periods. Sap flux measurements on forest trees and oil palms indicate that oil palm plantations use about as much water as forests for transpiration. Eddy covariance analyses of evapotranspiration over oil palm pointed to substantial additional sources of evaporation such as the soil and epiphytes. Stream base flow from a catchment predominantly covered by oil palm plantations was lower than from a catchment dominated by rubber plantations; both showed high peaks after rainfall. An estimate of erosion indicated approximately 30 cm of topsoil loss after forest conversion. Analyses of climatic variables measured over the last 20 years as well as of a standardized precipitation evapotranspiration index for the last century suggest that droughts are recurrent in the area, but that their frequency and intensity has not increased. Consequently, we assume that conversions of natural rainforest ecosystems to oil palm plantations lead to a redistribution of precipitated water mainly by run-off, which leads to the reported periodic water scarcity. Our combined social and environmental approach thus points to significant and thus far neglected eco-hydrological consequences of oil palm expansion.

Key words: Eco-hydrology; erosion; evapotranspiration; forest; human perception; land use change; rubber plantation; run-off; streamflow; transpiration.

‘When there was still a lot of forest around Bungku even during a drought of two months we still had water in our wells. But now there is no forest anymore, there is oil palm.’

- farmer from Bungku, Jambi, Indonesia; personal communication to J. Merten, June 2013.

6.1 Introduction

Large-scale environmental transformations such as the current oil palm expansion in Indonesia are characterized by the interaction of social, economic, and ecological processes. It is increasingly recognized that such transformations require research that includes both human and environmental dimensions (Bodin and Tenggö 2013), which has led to the development of social-ecological system frameworks (e.g. Ostrom 2009). Within social-ecological systems, human land use decisions such as large-scale oil palm expansion affect the supply of food, energy, and drinking water that ecosystems can provide (Berkes and Folke 2002). Generally, scientific research can benefit from local knowledge and perceptions of the environment, as e.g. expemplified in the above statement by a farmer from Jambi (Sumatra, Indonesia). Local knowledge and perceptions have successfully been integrated into some conceptual frameworks investigating the reciprocity of social-ecological relations (Ostrom 2009, Pahl-Wostl et al. 2010, Scholz et al. 2011, as cited in Binder et al. 2013). Applied environmental research, however, often fails to adequately integrate social aspects (Wandersee et al. 2012, Tàbara and Chabay 2013, Reyers et al. 2014, Orenstein and Groner 2014). We see a need for applied studies that give credit to the embeddedness of eco-hydrological processes in socio-cultural processes (Bourdieu 1976) by confronting local environmental perceptions with measurements of environmental processes.

Indonesia currently undergoes large-scale transformations characterized by natural ecosystems declining and monoculture plantations increasing in area, thereby creating substantial changes in the socio-ecological system. Oil palm plantations have rapidly expanded in Indonesia over the past decades, from a total of less than one million ha in 1990 to over 7 million ha in 2013; today, Indonesia is the global leader in crude palm oil production (FAO 2015). Oil palm often replaces other cash or subsistence crops (e.g. rubber plantations), but has also been identified as a driver of large-scale deforestation (Koh and Wilcove 2008, Carlson et al. 2012). Such large-scale environmental transformation towards intensive agricultural systems may cause severe changes in the hydrological cycle (Bruijnzeel 1989, 2004, Krishnaswamy et al. 2013). In our research area, the expansion of oil palm plantations has made water scarcity an issue in the human perception as e.g. expressed in the introductory quote. Such socio-hydrological consequences and linkages of forest transformation have not yet been adequately studied (Lele 2009).

Available scientific as well as popular studies linking oil palm plantations to the water cycle mainly focus on water quality (e.g. Wakker 2005, Friends of the Earth et al. 2008, Babel et al. 2011, Colchester and Chao 2011, Buschmann et al. 2012, Gharibreza et al. 2013). The few social science studies examining effects on water quantity do not explain the underlying reasons of declining water availability (e.g. Obidzinski et al. 2011, Larsen et al. 2014). From the natural sciences perspective, water-related studies on oil palm thus far are scarce and often examine single components of the hydrological cycle (also see Comte 2012).

In this study, we aim at integrating social and natural science approaches to analyze the social- and eco-hydrological consequences of oil palm expansion. The starting point for our interdisciplinary, problem-oriented research was the environmental perception of changes in the water cycle by residents of Bungku, a local village in Jambi. We then investigated if and how these perceptions can be explained by empirically-derived environmental variables that were measured in the vicinity of the mentioned village. For this purpose, we analyzed micrometeorological, ecohydrological and pedological measurements in oil palm and rubber plantations as well as on reference forest sites. This allowed for an assessment of the consequences of forest transformation to monoculture plantations. We also analyzed long-term climatic data to evaluate potential climatic changes in the Jambi region. Our objectives were (1) to asses human perceptions of changes in the local water cycle in an oil palm dominated region, (2) to confront the perceived changes with empirically derived environmental data, and (3) to identify and separate environmental processes leading to changes in the water cycle. More generally, we want to derive different complementary lines of argument in order to provide more balanced insights into social perceptions and eco-hydrological processes accompanying environmental transformation.

6.2 Methods

6.2.1 Study region

Our study sites are located near Bungku village in the South of Jambi Province, Indonesia, in the eastern lowlands of Sumatra (**Figure 6.1**). Climate is tropical humid (26.5 °C, 2235 mm year-1, based on data from the meteorological station at the airport Sulthan Thaha, Jambi) with a dry season from June to September characterized by monthly precipitation frequently falling below 100 mm. Between 1985 and 2007, 1.7 million ha of forest were cleared in the lowland areas (< 150 m elevation) of the Jambi province, which corresponds to 71 % of the 1985 forest area (Laumonier et al. 2010). Today mono-culture rubber and oil palm plantations dominate the landscape. Rubber has been cultivated in Jambi since Dutch colonial time; oil palm business started in the mid-1980s and has been expanding to over 700,000 ha plantation area in 2013 (Hauser-Schäublin and Steinebach 2014). Large-scale private and state-owned oil palm plantations now shape the landscape; smallholder plantations are also increasing continuously, accounting for almost half of the plantation area in Indonesia (Indonesian Ministry of Agriculture 2011, cited after Obidzinski 2012). Unclear land ownership, large-scale land use concessions and uneven possibilities of participation in the lucrative oil palm business have resulted in land use conflicts, at times of violent nature (Colchester et al. 2011, Hein 2013, Steinebach 2013, Beckert et al. 2014, Hauser-Schäublin and Steinebach 2014, Hein and Faust 2014).

The environmental study plots were located on upland mineral soils; soil type is loam Acrisol (K. Allen et al. unpublished data), which is characterized by a clay accumulation horizon in some decimeter of depth. Measurements were taken on four plots each in oil palm monocultures (HO1 – HO4), in rubber monocultures (HR1 – HR4), and at forest reference sites (HF1 – HF4, **Figure 6.1**). Each of these 12 plots was 50 m × 50 m in size. The oil palm and rubber plots were located in the vicinity of the village of Bungku, Jambi. Plantation ages ranged from seven to 16 years; the plantations were smallholder properties under similar management. The forest reference plots were located in the Harapan Rainforest, 30 km from Bungku, which had been partially severely logged until approximately 2003. The area became a conservation and restoration area in 2010. Additional measurements were taken in a 12 year-old large-scale plantation 25 km from Bungku (PTPN6, **Figure 6.1**).

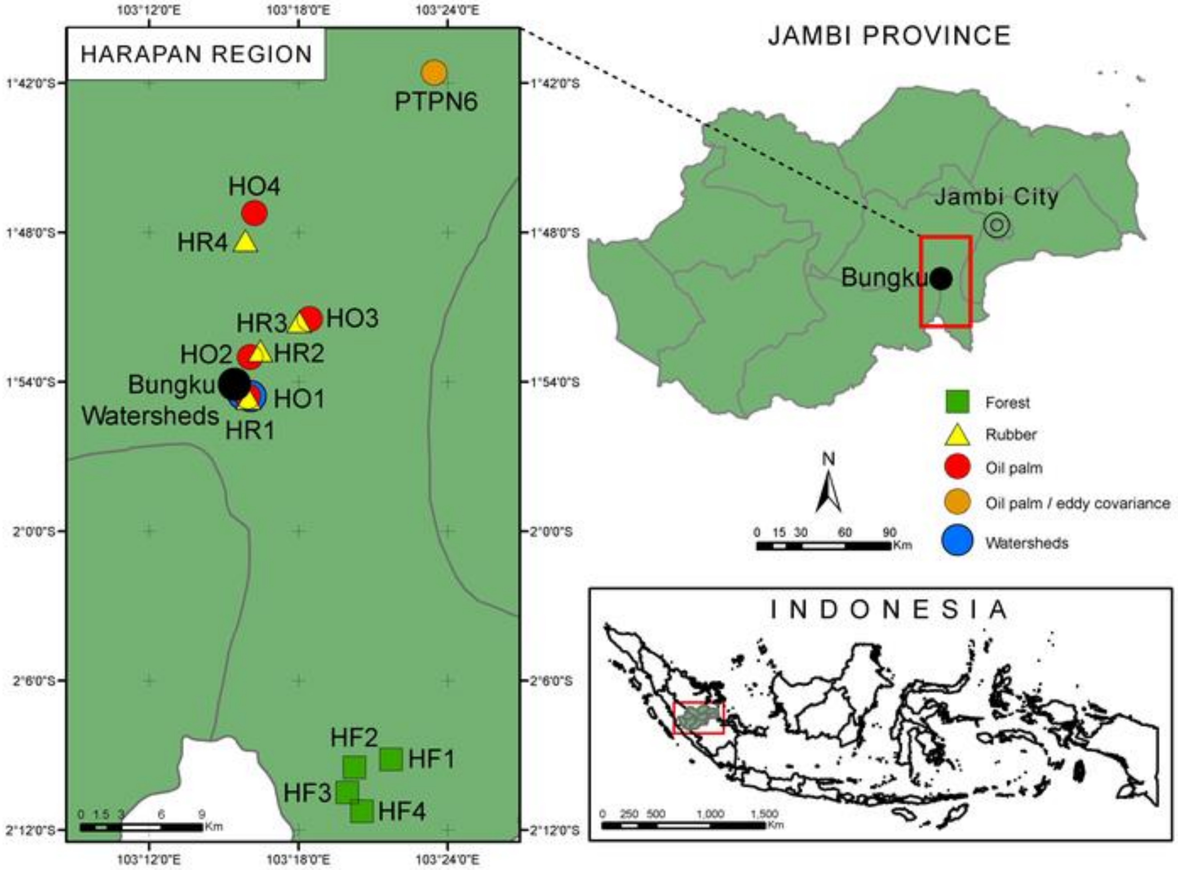

Figure 6.1. Locations of the study sites in Jambi province, Sumatra, Indonesia.

6.2.2 Social dimension

An inductive case study using qualitative methods was conducted in two hamlets in the northern part of the village of Bungku, Jambi (**Figure 6.1**). We investigated perceptions and interpretations of changes in the local water cycle over the last 25 years by local residents. Problem-centered, semi-structured household interviews (after Mayring 2002) (n = 30) were triangulated with participatory observation, focus group discussions and Participatory Rural Appraisal tools (timeline interviews, resource mapping) (after Kumar 2002). Participants were chosen according to the snowball sampling methods (Schnell et al. 2013), trying to reflect the social structure of the village. Supplementary information was obtained through nine key informant interviews with representatives of the private sector, civil society organizations and public authorities on the regional level.

6.2.3 Environmental patterns and processes

6.2.3.1 Land use change

In the PTPN6 large-scale oil palm plantation (**Figure 6.1**), the eddy covariance technique (Baldocchi 2003) was used to measure evapotranspiration; the three components of the wind vector (METEK USA-1, Elmshorn, Germany) as well as water fluxes (LICOR 7500, Lincoln, USA) were measured. For the analysis and to facilitate comparison to the other plots, we used data from three sunny days during October and November 2014 as to minimize day-to-day variability induced by weather.

Transpiration rates, soil erosion, air temperature under the canopy and soil moisture fluctuations were studied on oil palm, rubber, and forest plots (HO1 – HO4, HR1 – HR4, and HF1 – HF4, **Figure 6.1**). To estimate stand transpiration rates we measured sap flux densities with thermal dissipation probes (Granier 1985, 1996) in these 12 plots as well as at the PTPN6 site. For measurements in oil palm leaf petioles, we used the calibration and sampling scheme as proposed by Niu et al. (2015). The standard equation (Granier 1985) was used for trees in rubber and forest plots. For trees, radial profiles of changes in sap flux density with xylem depth were established. To extrapolate from trees and palms to stand transpiration, inventory data were used (Kotowska et al. 2015). As measurements were partly not conducted simultaneously, we also averaged the values of three sunny days for the analysis in order to minimize variability induced by weather. More details on these and all other applied methods can be found in the Appendix.

On the 12 forest and plantation plots, the soil carbon content in the Ah horizon (down to max. 10 cm depth) was measured (Guillaume et al. 2015) and soil erosion was estimated by assessing the soil carbon isotopic composition (δ13C) with depth. The δ13C profiles in the plantations were compared with the forest reference plots, where erosion was assumed to be zero. This was necessary to estimate the thickness of the surface layer lost by erosion after forest conversion. To assess fluctuations in microclimate (air temperature, air humidity and soil moisture), weather stations equipped with thermohygrometers (Galltec Mella, Bondorf, Germany) and soil moisture sensors (IMKO Trime-PICO, Ettlingen, Germany) were installed on the 12 study plots.

Within two small catchments partly encompassing the oil palm and rubber plantations (plots HO1-4, HR1-4, **Figure 6.1**), we recorded streamflow and measured rainfall interception for four months. One catchment (extension of 14.2 ha) was dominated by 10-14 year-old oil palm plantations (90% of the area). The other catchment (4.9 ha) consisted of different rubber stands: eight year-old (19% of the area) and 30 year-old (56% of the area) monoculture rubber plantations and jungle rubber (25 % of the area), a mix of rubber trees and naturally established dicot tree species. We selected a two-week period (7 to 20 Nov 2013) of the recorded hydrographs encompassing both dry and rainy conditions. Rainfall interception of the oil palm and rubber monocultures in the respective catchments was assessed by measuring throughfall and stemflow, and subtracting them from incident rainfall.

6.2.3.2 Climate change

For the period from 1991-2011, we analyzed air temperature and rainfall data from the meteorological station located at Airport Sultan Thaha, Jambi, property of the Indonesian meteorological service (BMKG). Our aim was to assess whether there have been climatic changes in Jambi over the last 20 years. Mean, maximum and minimum temperature as well as rainfall data were separated into their time components to detect trends in these variables over the last years. For an analysis of climatic trends on a greater temporal scale, we calculated the Standardized Precipitation Evapotranspiration Index (SPEI) from the Global SPEI Database (SPEIbase, Vicente-Serrano et al. 2010) for the Bungku region from 1901-2011. The SPEI is a multi-scalar drought index that takes into account precipitation and potential evapotranspiration to determine drought conditions; a strong drought is reflected by a high negative value.

6.3 Results

6.3.1 Social perspectives on changes in water availability

6.3.1.1 Perceptions of changes in local water resources

Over the last 25 years, the villagers of Bungku perceived pronounced changes of local water resources. Among the most frequently mentioned perceptions were a faster depletion of groundwater reservoirs during dry periods, a higher fluctuation of river levels with particularly low levels during dry seasons, and an increased pollution of surface waters (also see **Table 6.1**). The fast depletion of groundwater levels during dry seasons was of particular importance to the villagers as their water supply was mainly ensured by household wells. Wells that dried up in past decades have also been reported. However, the consensus among Bungku villagers was that the scarcity of well water has started to occur much faster and more frequently during dry periods since the early 2000s. Today, in times of prolonged dry periods many wells in the village fall dry.

In addition to the fast groundwater depletion, streamflow levels were reported to decrease much faster during dry seasons than it had been the case ten years ago; several smaller rivers stopped flowing after only a few weeks without rain. Swampy areas are generally numerous along streams and rivers in the research region. However, over the past years, many of them reportedly started to decrease in extent and depth, or dried out completely. During the rainy season, very high river levels with quick declines after rainfall events were observed in recent years.

Alterations in water quality were another frequent concern amongst the villagers of Bungku. The perception of surface water quality changed from "clean" and "pure" in past decades to "turbid" and "muddy" today. Water quality was described to be particularly bad in times of water scarcity. As a lot of wells in Bungku ran dry, many villagers relied on surface waters for their personal hygiene. This generated a further pollution of shallow or stagnant water bodies.

As a consequence of water scarcity during prolonged dry seasons the majority of the households were forced to access different, more abundant water resources. These were often at a distance of up to ten kilometers from the village. Alternatively, they relied on bottled water, both of which go along with economic and logistic challenges. Depending on their financial situation, households may be forced to continue using the polluted water to a certain degree, which may lead to diseases, e.g. of the skin. According to statistics of the community health center in Bungku, skin diseases and allergies were reported to be the second most common disease (after upper respiratory tract infections) in Bungku at the time of investigation.

The challenge in accessing clean water was also recognized by an official village document (Desa Bungku 2010). "Difficult access to clean water" was ranked among the four most urgent issues for all village hamlets (extending over an area of 600 km^2). An additional factor possibly interconnecting to seasonal water scarcity in Bungku was the observation of increasing air temperature. Villagers felt it had become significantly hotter since oil palm plantations started to dominate large parts of the landscape surrounding the village.

Table 6.1. Core statements by local villagers regarding perceived changes in local water resources. Interviews were conducted in the village of Bungku, Jambi, from May to July 2013. Quotes are personal translations by J. Merten.

Perceptions of changes in the water cycle	Core interpretations among the villagers	Excerpts from interviews
Drying of surface and subsurface waters	Oil palm expansion and deforestation cause a faster depletion of surface and subsurface waters.	‘Before, when people didn’t open the forest yet, it was better. The water started to get less since the people opened the forest.’ ‘When there was still a lot of forest around Bungku even during a drought of two months we still had water in our wells. But now there is no forest anymore, there is oil palm.’
	Oil palm plantations exert more pressure on local water resources than rubber cultivations or forested areas.	‘Before there were not so many oil palms. That’s why we still had enough water. Because oil palm needs a lot of water, while rubber can keep the water.’ ‘The negative thing about oil palm is that it's a plant that needs a lot of water. That’s why, if we plant oil palm near swamp areas, after some time the swamps will fall dry.’
Increasing pollution of local waters resources	Water quality has decreased as a consequence of high sediment loads in surface waters.	‘Did you observe any changes in the water quality?’ ‘Yes, it changed. A lot! Before the water was not that dark, but now it looks like it contains mud. Before there was not that much mud in the water.’ ‘After rainfall the water in the well becomes turbid. But after some days without rain the water quality is getting better again.’
	Water quality has decreased since more and more villagers have to rely on surface waters for their personal hygiene.	‘The people now have a problem with the water. The water quality of the river is not good anymore. But they still use it for washing and shower since there is no clean water anymore.’
Increasing local temperatures	Temperature has increased since oil palm plantations have extended over vast parts of the landscape.	‘When I came to Bungku in 1991 the temperature was different. There was still a lot of forest and the temperature was not as hot as today.’

6.3.1.2 Local interpretations of increasing seasonal water scarcity

The explanations by the villagers for the observed changes in local water supply were manifold but all directly or indirectly related to the ongoing land-use change in the Bungku region. The most frequent explanations given for decreasing groundwater and streamflow levels during dry seasons were deforestation and the expansion of oil palm cultivation. Water availability reportedly decreased notably after oil palms had become the dominant element in the landscape. Prevalent stories in the village included an allegedly high water use by oil palms, which causes adjacent swamp areas, rivers and wells to run dry. Rubber plantations, on the other hand, were believed to rather "conserve" or "store" water in the soil. Some villagers reported that wells they built in oil palm plantations ran dry after only a few weeks without rainfall, while wells inside rubber plantations provided water even during prolonged dry periods. Further explanations given for the low streamflow of local rivers included landscape-shaping activities of oil palm companies, e.g. draining of swamps, channelization of rivers or inadequate canalization in road construction.

Increasing pollution of surface waters was mostly related to the behavior of the villagers themselves. The main issues mentioned by the interviewees were the lack of waste (water) management, the use of surface waters for personal hygiene and the use of fish poison. With respect to oil palm cultivation, individual villagers blamed the lack of environmental management and the absence of buffer zones along rivers for increases in the sediment load of local rivers over the last years. Herbicide and pesticide leaching were reported to be significant further source of pollution in other studies (e.g. Banabas et al. 2008, Comte 2012, Obidzinski et al. 2012, Kløcker Larsen et al. 2014), but were only mentioned by few villagers in our study.

These interpretations reflect the opinion of most interviewees in Bungku, including both rubber and oil palm farmers. Two small groups of interviewees, however, presented different interpretations of local developments: some indigenous farmers and long-time residents emphasized that oil palms per se cause most environmental degradations occurring in the area and are e.g. also particularly "water-greedy". In contrast to this, individual more prosperous oil palm farmers, company representatives and local politicians negated any negative environmental impacts of oil palm expansion, rather stressing the economic benefits. These contradictory opinions are likely embedded in local contestations over access to land and natural resources. The actor groups that vigorously advocate the advantages of oil palm business are commonly among the winners of the ongoing land use transformations (Beckert et al. 2014).

6.3.2 Environmental patterns and processes

6.3.2.1 Land use change

Evapotranspiration rates derived from the eddy covariance technique in a 12-year old oil palm plantation in Jambi (PTPN6) were 4.7±0.1 mm day^{-1} (three sunny days, mean±SE) (**Table 6.2**). On the same days (and in the same plantation), transpiration by the oil palms as derived from sap flux measurements was estimated to be 2.5±0.1 mm day^{-1}; the remaining 47% of evapotranspiration are likely the sum of transpiration by other plants (e.g. ground vegetation, trunk epiphytes) and evaporation (e.g. from the soil).

Average transpiration rates of the five oil palm plots (HO 1-4, PTPN6) on sunny days were 1.8±0.3 mm day^{-1} (three sunny days averaged for each plot; mean±SE represent spatial variability among the five locations), 11% lower than the average of the four reference forest plots (HF1-4, 2.0±0.2 mm day^{-1}). However, such a small difference lies within the uncertainties associated with the used approaches (see e.g. Niu et al. 2015 for oil palm). The rubber plantations (HR1-4, 1.1±0.1 mm day^{-1}) had 85% lower average transpiration rates than forests and 63% lower than oil palm plantations. Additionally, rubber trees (partially) shed their leaves during the dry season, which effectively further reduced transpiration (by up to 70% at the peak of leaf shedding).

Rainfall interception in the catchment areas was 28% of incident rainfall in oil palm plantations, whereas it was 17% in rubber plantations. The observed difference is probably related to the high external trunk water storage capacity of oil palms, which we estimated to be 6 mm in a mature plantation in the oil palm dominated catchment. Butts of pruned petioles remain on the trunk over several years, forming chambers full of humus, water and epiphytes.

Streamflow data from two catchments confirmed differences between oil palm and rubber plantations: baseflow under dry conditions was lower in oil palm plantations (1.8 l s^{-1} per hectare catchment) than in rubber plantations (8.2 l s^{-1} ha^{-1}). After intense rainfall events (> 60 mm), recorded streamflow levels were strongly elevated in both catchments (up to 21.2 l s^{-1} ha^{-1} in the oil palm and 36.9 l s^{-1} ha^{-1} in the rubber catchment, respectively, **Figure 6.2**).

Soil erosion as derived from δ13C profiles as well as decreases in soil carbon content were similar in oil palm and rubber plantations, averaging 35±8 (mean±SE) cm of top soil loss and amounting to 70% of C content decrease since conversion in oil palm plantations, and 33± 10 cm and 62% in rubber plantations (**Table 6.2**, Guillaume et al. 2015). On forest sites, erosion was assumed to be zero (cf. Methods) and the C content in the Ah horizon was 6.8 ±0.8%.

The analysis of microclimatic conditions inside the plots showed no clear patterns in soil moisture. We think a possible reason is that the variability within the plots was higher than the variability within the land use systems and thus could not be assessed adequately by only one soil sensor per plot. However, differences were observed in air temperature under the canopy, which was higher in oil palm and rubber than in the forest (by 0.4 and 0.5°C respectively, **Table 6.2**) and showed 1.5-fold higher diurnal fluctuations in both plantation types than in the forest.

Table 6.2. Characteristics of the water cycle and connected variables of oil palm plantations, forest stands and rubber plantations as observed in the lowlands of Jambi, Indonesia (n.d. – not determined).

Variable	Method	Oil palm	Forest	Rubber
Evapotranspiration †	Eddy covariance	4.7 mm d-1	n.d.	n.d.
Transpiration †	Sap flux	1.8 mm d-1	similar	lower
Rainfall interception	Rain gauges	28 %	n.d.	lower
Soil carbon content	CN analyzer	2.1%	higher	similar
Stream base flow	Catchments	lower	n.d.	higher
Stream storm flow	Catchments	high peaks	n.d.	high peaks
Soil erosion ‡	d13C profiles	35 cm	n.d.	similar
Air temperature	Thermometers	25°C	lower	similar

† Average of three sunny days; ‡ soil erosion since forest conversion.

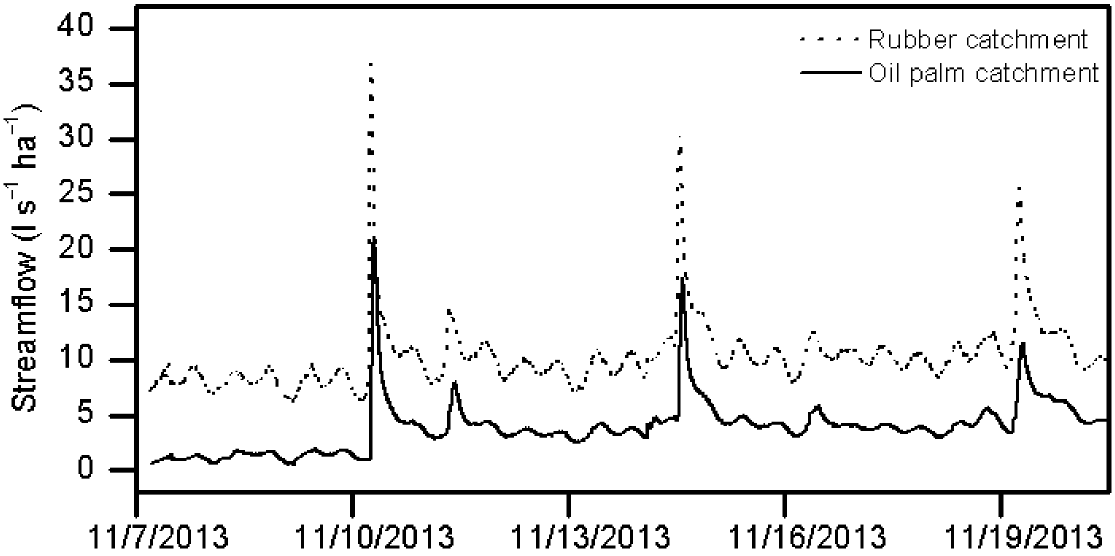

Figure 6.2. Streamflow patterns from oil palm dominated and rubber dominated catchments normalized by catchment area. Hydrographs from a two week period (7 to 20 Nov 2013) encompassing both dry and rainy conditions.

6.3.2.2 Climate change

The analysis of the SPEI indices over the past 100 years suggests that droughts are recurrent in Bungku area (**Figure 6.3**), and that their frequency and intensity has not increased over the last century. The most severe droughts, reflected by a high negative SPEI index value (i.e. -1.5), occurred in 1924, 1983 and 1998; they are associated with strong El Niño Southern Oscillation (ENSO) events. The evaluation of trends in air temperature and rainfall from 1991 to 2011 shows no significant changes in mean and maximum temperatures. However, the minimum temperature shows an increase of about 1°C in the period from 2004-2011 ($p<0.05$), indicating a small decrease in the range of annual temperature variation. Rainfall, for 21 years with complete data series, was 2235 ± 84 mm per year (mean±SE). Rainfall in Jambi is characterized by a dry season from June to September when monthly rainfall is below 120 mm. In some years such as 1993, 1994 or 2011, the dry season was more pronounced, with at least two consecutive months with monthly precipitation below 40 mm. Other years (e.g. 2005, 2010) were wetter and the dry season was not very pronounced, indicating high variability in the rainfall patterns between years. Based on the evaluated data, we conclude that there were no significant climatic changes in Jambi between1991 and 2011, and probably not over the last century either.

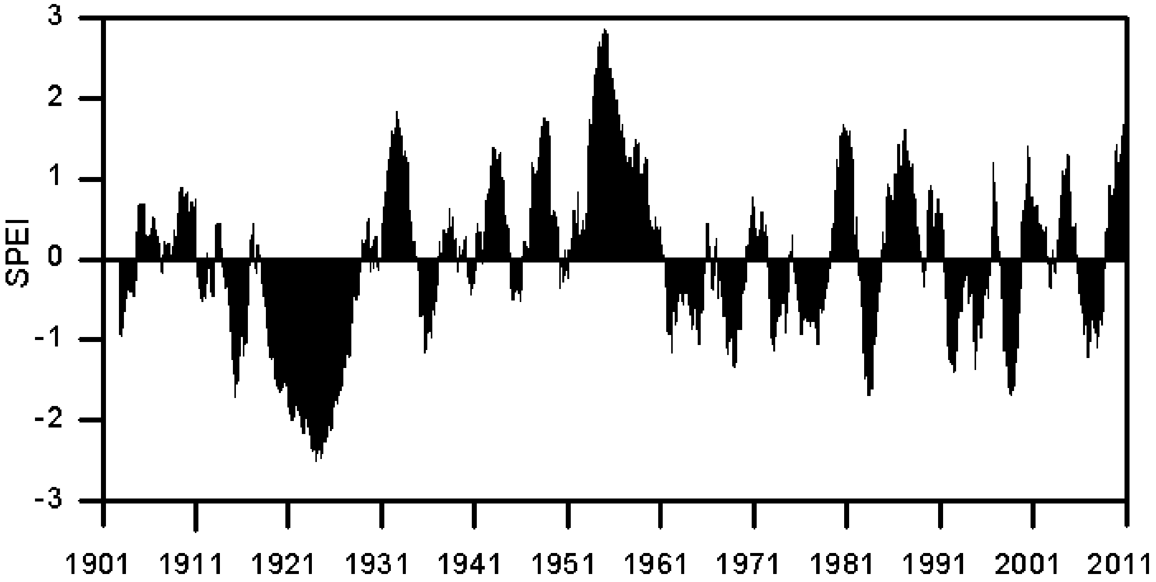

Figure 6.3. 24-month SPEI index (Standardized Precipitation Evapotranspiration Index), a multi-scalar drought index, from 1901 to 2011 in the Bungku region. Categorization of dryness by SPEI: Near normal (-1 to 1); Moderate dryness (-1.49 to -1); Severe dryness (-1.99 to -1.5); Extreme dryness (Less than -2). Same ranges for positive values indicate wetness.

6.4 Discussion

6.4.1 Social perceptions of changes in the local water cycle

Our study suggests that water availability during dry periods is an increasing problem for the local population in the oil palm dominated landscape of our research area. Among the interviewed villagers, the broad majority reported that significant changes in the hydrological cycle have occurred in the research region over the last 25 years. The main concern of the interviewed villagers was the decline of surface and subsurface waters which they attributed to the rapid local land use change from a landscape mosaic of forest and (jungle) rubber patches to an oil palm dominated land cover. Similar linkages between forest transformation and changes in local water supply have been reported, investigated and quantified in several studies, e.g. related to the development of Payment for Ecosystem Services schemes (Pattanayak 2001, 2004, Asquit et al. 2008, Muños-Piña et al. 2008, Lapeyre 2015). Such schemes are e.g. introduced to maintain watershed services from forest areas, including stable dry-season streamflow.

The villagers' perception in Bungku was that forest conversion to oil palm plantations impacted local water availability far more negatively than conversion to rubber monoculture plantations; during dry seasons oil palm plantations seem to use up a lot of the available water, in the opinion of the villagers.

These statements reflect the observation of most villagers, independent of their social background and including dedicated oil palm farmers. This is in line with findings from our household survey in Jambi (n= 700, Faust et al. 2013) that showed a high awareness of villagers towards environmental impacts by oil palm cultivation across all social groups in 45 studied villages in the Jambi province. Complaints about drying wells and surface waters specifically in the surroundings of oil palm plantations are consistent with studies by Obidzinski et al. (2011), Larsen et al. (2014), and an NGO report by Friends of the Earth et al. (2008).

Only two small groups of the interviewed villagers propagated different interpretations of local developments. Depending on their social background and their (non-)participation in the profitable oil palm business they overemphasized or completely neglected negative hydrological impacts by oil palm expansion. Thus, the local discourse on water supply is deeply embedded in a wider discourse on consequences of the regional land use change in general. Local water supply is being used as an argument to substantiate personal claims and viewpoints regarding the drastic expansion of monoculture oil palm plantations. As such, the discourse displays the dialectical societal relations to nature formed by the material-energetic flow of water as well as by social-cultural processes, i.e. the wider contestations and struggles related to the access of land and natural resources (Linton and Budds 2014, Becker and Jahn 2006, Görg 2003).

6.4.2 Confronting perceived changes with environmental measurements

Our results suggest that rainfall volume and seasonal patterns have not changed significantly since the beginning of oil palm expansion in the study region. Also, similar volumes of water are re-evaporated back into the atmosphere from oil palm plantations and forests, but the penetration of water into the soil is reduced in oil palm plantations. Thus, much precipitated water leaves the landscape as surface runoff, causing streamflow to be high during rainfall events; less water remains in the soil and in the landscape than in forested areas and groundwater recharge is decreased. In consequence, wells may dry out (earlier) during dry periods in oil palm dominated regions, as was reported by the majority of interviewed Bungku villagers. The perception of extremely high water use rates of oil palms as the main cause for increased seasonal water scarcity among some Bungku villagers does not match the results of our evapotranspiration and transpiration measurements. However, the people's perception that the regional oil palm expansion may be responsible for local water scarcity during dry periods is backed by several results from environmental measurements. We also have indications that there are significant differences between oil palm and rubber plantations as reported by several villagers.

6.4.3 Environmental processes leading to changes in the water cycle

Evapotranspiration rates derived from eddy covariance measurements for a 12-year old oil palm plantation under dry, sunny conditions were similar (4.7 mm day^{-1}) to values reported for lowland rainforests on Borneo (4.2 mm day^{-1} on annual average, Kumagai et al. 2005) and rainforests in Peninsular Malaysia (4.2 mm day^{-1} on annual average, Tani et al. 2003). The transpiration estimate derived from sap flux measurements for this oil palm plantation (2.5 mm day-1) was the highest among the five oil palm plantations assessed in this study, and also among 15 different oil palm plantations of varying age in the greater study region (A. Röll et al. unpublished data); it was similar to the highest transpiration rate among the four reference forest sites (2.4 mm day^{-1}). Our oil palm and forest transpiration estimates compare to transpiration rates reported for a variety of tropical forest sites (1.3–2.6 mm day$^{–1}$; Calder et al. 1986, Becker 1996, McJannet et al. 2007). This suggests that oil palms can transpire at substantial rates under certain conditions, despite e.g. their much lower biomass per hectare than on forest sites (Kotowska et al. 2015). Among all studied sites, the sap flux derived estimates for average forest and oil palm transpiration rates are similar, but rubber plantations transpire at more than 60% lower rates under similar conditions; also, rubber trees partially shed their leaves in pronounced dry periods, which further reduces transpiration by up to 70% explicitly in times of water scarcity. In addition to the much lower re-evaporation of water to the atmosphere, rainfall interception by rubber plantations is 1.7-fold lower than by oil palm plantations (28% of incident rainfall); our values for interception by oil palms compare to values reported for tropical forests in South East Asia (commonly 10-30%, e.g. Dietz et al. 2006, Dykes 1997, Kumagai et al. 2004). These differences in transpiration and interception can explain the lower baseflow from oil palm dominated catchments as compared to rubber dominated catchments that we observed.

Soil water infiltration capacities represented by Ks-values derived from ring infiltrometer experiments for different land use types in the research region were reported to decrease in the order from forest (47 cm hr^{-1}) to rubber (7 cm hr^{-1} on harvesting paths, 7.8 cm hr^{-1} between rubber trees) to oil palm plantations (3 cm hr^{-1} on harvesting paths and weeding circles) (Tarigan et al. unpublished data). The much lower infiltration capacities in plantations as compared to forest are consistent with the observed strong decline of soil quality after forest conversion; i.e. C content decrease and erosion (Guillaume et al. 2015). C content plays a key-role in soil aggregation (Franzluebbers 2002, Bronick and Lal 2005), while erosion brings deeper and denser soil layers to the soil surface. Thus, both are associated with lower soil permeability. Such soil degradation after forest conversion was e.g. also observed in similar land-use types in Malaysia (Gharibreza et al. 2013), China (de Blécourt et al. 2013) and Ghana (Chiti et al. 2014). Although the extent of soil degradation was similar between rubber and oil palm plantations, soil characteristics are more heterogeneous in oil palm plantations, i.e. soil organic carbon content is lower in inter-rows (Frazão et al. 2013) and frequent and intensive management and harvesting operations increase soil compaction, e.g. on harvesting paths. The surfaces with the most degraded soil in oil palm plantations correspond to the locations where rainfall interception is low due to the incomplete canopy cover between palms (>20% gap fraction, Kotowska et al. 2015). This may explain the higher run-off as reflected by two-fold higher relative peakflows (i.e. normalized by baseflow) in oil palm than in rubber plantations. In conjunction with the observed higher transpiration rates of oil palm as compared to rubber plantations, the increased run-off results in significantly less water being available for groundwater recharge after precipitation than in rubber plantations, and much less than in forested areas. Thus, groundwater recharge may be less efficient in oil palm dominated catchments than in rubber dominated ones, which may add to water scarcity during dry periods. Similar reductions in dry period baseflows and increases in post-precipitation peakflows after forest conversion have been reported in a variety of studies (e.g. Bruijnzeel 2004, Tiwari 2011, Elkaduwa and Sakthivadivel 1998, Sandström 1995, Bruijnzeel and Bremmer 1989, Fritsch 1993, Zhou et al. 2002, Zimmermann et al. 2010, Bonell et al. 2010).

Our findings are consistent with the ‘sponge and pump’ approach to hydrological effects of forest conversion (Bruijnzeel 2004, Peña Arancibia 2013). Forests may act as ‘sponges’ by enhancing infiltration rates and moisture retention due to the effects of organic matter and the root network on soil physical properties (cited after Peña Arancibia 2013). In our study, both land use types replacing the forest may have reduced the sponge effect. According to the ‘infiltration trade off hypothesis’ (Bruijnzeel 1986, 1989, 2004), the net effects of forest conversion on streamflow largely depend on the type of land cover replacing the forest. Baseflow (in dry periods) may be as high as in forested areas if losses in infiltration capacity are outbalanced by much lower (evapo)transpiration rates in the newly-established land use systems, which is often the case. In our study, the rubber plantations are such an example. The oil palm plantations, however, are different: we found soil degradation and thus low permeability as well as a high transfer of water vapor to the atmosphere. Combined, this can induce or enhance periodic water scarcity in oil palm dominated landscapes.

6.5 Conclusions

The broad majority of the interviewed local people reported that water shortages have occurred more often since oil palm cultivation has become the dominant land use. Several villagers strongly emphasized the viewpoint that oil palm is a major consumer of water and thus largely responsible for decreasing local water supplies. Analyses of environmental processes generally supported this perception and also confirmed differences between rubber and oil palm plantations. However, there is some added eco-hydrological complexity to the local interpretations. Our evapotranspiration data indicates that oil palm plantations use about as much water as forests for transpiration. Rather than to a high water use of oil palms per se, local water scarcity seems connected to the redistribution of water after precipitation at the landscape scale. In natural ecosystems, e.g. rainforest, the largest part of rainfall water is taken up by the soil and contributes to the transpiration of plants and groundwater recharge. Under oil palm plantations, however, precipitated water cannot well penetrate the eroded soil. Consequently, a significant amount of water leaves the landscape as run-off and less water is available for groundwater recharge. Large-scale conversion of natural forests to oil palm plantations thus induces or enhances periodic water scarcity.

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6.7 Appendix Chapter 6

6.7.1 Methodology of social study

The case study was an inductive study that aimed to investigate initial rumors of water shortages in the surrounding areas of oil palm plantations. The study site, the village Bungku in Jambi Province, was selected due to a dynamic land use history and reports of newly arising water scarcity. The core research questions were (1) if village residents had observed changes in local water resources (during the last 25 years), (2) how these possible changes could be explained according to the villagers' personal evaluations, and (3) how these changes impacted the water supply of the village.

The field research was conducted from May to July 2013. A combination of different qualitative methods was chosen to crosscheck interview results from different viewpoints. The range of methods applied included semi-structured, problem-centered household interviews (n = 30) (after Mayring 2002), participative observation, two focus group discussions and Participatory Rural Appraisal tools (one timeline interview, one resource mapping activity) (after Kumar 2002). Supplementary information was obtained through nine key informant interviews with representatives of the private sector, civil society organizations and public ministries on the regional level. All interview activities were conducted in Bahasa Indonesia with the help of an Indonesian research assistant.

Initial participants for household interviews were chosen based on their relevance for the research topic, e.g. length of time lived in Bungku. Subsequent interview partners were chosen by the snowball sampling method (Schnell et al. 2013), aiming to represent the social structure of the village. Focus group discussions were conducted with groups of six independent oil palm farmers to gain insight into local attitudes and concerns regarding oil palm cultivation. All interview activities were audio-recorded and written down in the form of detailed chronological protocols in English. Data processing and analysis followed the principles of a qualitative analysis of content (after Mayring 2002). Additional personal profiles of the interview partners allowed for an empirical typification (Kluge 2000) of the participants.

6.7.2 Methodology of climate change analysis

We used the Standardized Precipitation Evapotranspiration Index (SPEI), which takes into account precipitation and potential evapotranspiration, to determine drought conditions. Using the Global SPEI database (SPEIbase, Vicente-Serrano et al. 2010), which offers information about SPEI at the global scale with a 0.5 degrees resolution and monthly time resolution, we evaluated drought changes from 1900 until 2011 in Bungku area (E 103.25, S 1.25). The SPEIbase is based on monthly precipitation and potential evapotranspiration from the Climatic Research Unit of the University of East Anglia (CRUE TS 3.2 dataset).

Additionally, we analyzed air temperature and rainfall data from 1991 to 2011 from the meteorological station, property of the Indonesian meteorological service (BMKG), located at the Airport Sultan Thaha in Jambi. Rainfall was recorded daily, while temperature was manually recorded three times a day (7, 13 and 18h). Daily average temperature was calculated by double counting the measurement at 7am (to consider the lower temperatures during the night) and averaging it with the temperatures measured during the rest of the day. Daily minimum and maximum temperatures were also recorded. Data series were separated into its time components in order to detect possible changes in their trend over the period of study.

6.7.3 Methodology of environmental measurements

6.7.3.1 Evapotranspiration

The eddy covariance technique (Baldocchi et al. 2003) was used to measure evapotranspiration (ET) in a 12-year old oil palm plantation in Indonesia. In the oil palm plantation (S1.693 E 103.391, at approximately 25 km from Bungku, **Figure 6.1**), a 22 m high tower, equipped with a sonic anemometer (Metek uSonic-3 Scientific, Elmshorn, Germany) to measure the three components of the wind vector, and an open path carbon dioxide and water analyzer (Li-7500A, Licor_Inc, Lincoln, USA), was running from March 2014 until December 2014. Evapotranspiration fluxes were calculated using the software EddyPro, planar-fit coordinate rotated, corrected for air density fluctuation and quality controlled (Meijide et al., in preparation). For this analysis, ET was estimated using data from three sunny days during the period of July-August 2014, using daytime (6am-7pm) data, in order to avoid possible measurement errors as a consequence of low turbulent conditions during nighttime hours.

6.7.3.2 Transpiration

To derive transpiration rates, we used the thermal dissipation probe (TPD, Granier 1985, 1996) method to measure sap flux density (*SFD*) in leaf petioles of oil palms and in the trunks of dicot trees. For oil palm, 16 TDP sensors (1.25 cm length) were installed on the underside of oil palm leaf petioles on four palms of varying height per plot (see Niu et al. 2015 for details). For forest and rubber plots, two sensors were installed at breast height in the North and South, respectively, of six (rubber) or eight (forest) tree trunks per plot (2.5 cm sensor length). In the forest, we chose dominant and co-dominant individuals only, as they are expected to account for the major part of stand water use; within the dominant and co-dominant sociological classes, we evenly selected individuals of relatively larger, medium and smaller diameters (min. DBH: 10 cm).

After sensor installation, insulative materials and aluminum foil were added to minimize temperature gradients and reflect radiation. Durable plastic foil was added for protection from rain. The sensors were connected to AM16/32 multiplexers connected to a CR1000 data logger (both Campbell Scientific Inc., Logan, USA). The signals from the sensors were recorded every 30 sec and averaged and stored every 10 min. In each plot, *SFD* was measured for a minimum period of three weeks. For oil palm, the mV-data from the logger were converted to *SFD* (g cm^{-2} h^{-1}) with the equation by Granier (1985), but with an adjusted set of equation parameters *a* and *b* that was specifically derived for TDP measurements on oil palm leaf petioles (Niu et al. 2015). As for oil palm by Niu et al. (2015), the TDP method was tested against gravimetric measurements in the laboratory for rubber and forest trees. The gravimetric readings and the estimates using the original Granier equation were within the 95% confidence interval of a linear regression with a slope of 1. Thus, the original equation parameters (Granier 1985) were used for the analysis of rubber and forest trees.

To upscale from sap-flux point-measurements to water use rates per plant (kg day^{-1}) and ultimately to stand transpiration (mm day^{-1}), water conductive areas (cm^2) had to be established for each of the studied individuals and stands. For oil palm leaf petioles at the location of sensor installation, we used a linear regression between leaf baseline length and leaf conductive area, which was derived by Niu et al. (2015) for oil palms in the same study region based on laboratory staining experiments. To derive water conductive areas for dicot trees in forest and rubber plots, we measured the radial patterns of *SFD* with increasing depth (*d*, cm) into the xylem (0-8 cm, 1cm resolution) with heat field deformation sensors (HFD, Nadezhdina 2012, sensors from ICT International, Armidale, Australia) in 10 individuals per land use type. The measurements were conducted in parallel to TDP measurements (0-2.5cm depth) on these individuals; HFD sensors were installed in between TDP sensors (North and South), i.e. in the West, at a similar height on the tree. The radial *SFD* patterns obtained by the HFD measurements were normalized to a depth of 1.25 cm (center of TDP sensors) to allow for an extrapolation of the single-point TDP measurements in the outer xylem (0-2.5 cm) to whole-tree water use rates (following Oishi et al. 2008). To subsequently upscale to stand-scale transpiration rates inventory data were used.

The sap flux measurements were conducted between March 2013 and April 2014. As most measurements could not be conducted in parallel for logistical reasons, we used the respective averages of the three most sunny and dry days within each measurement period (min. 3 weeks) for the analysis of the spatial variability in transpiration rates between plots, as to minimize day-to-day variability induced by weather.

6.7.3.3 Soil characteristics and erosion

Soil samples were collected per horizon in one soil pit on each site. The subsoil under plantations was not affected by enhanced decomposition processes after forest conversion (Guillaume et al. 2015). Carbon content and C/N ratio below the Ah horizons were similar under forest and plantations. Therefore, we assess erosion by assuming C isotopic composition (δ13C values) in the plantation subsoil was similar to the values in the forest subsoil prior to conversion. Consequently, when an identical subsoil depth has a higher $\delta^{13}C$ in the plantation than the forest, we suggest that this layer experienced a vertical shift towards the soil surface after erosional loss of the upper layer.

A power function describing the increase of $\delta^{13}C$ with depth under forest was fitted in Statistica 10 using Equation 6.1.

$$\delta^{13}C_d = \delta^{13}C_{Ah} d^l \qquad (6.1)$$

where C(d), $\delta^{13}C(d)$, C(Ah) and $\delta^{13}C(Ah)$ are the C content and the $\delta^{13}C$ value estimated for the depth d and measured in the Ah horizon, respectively, d the depth in cm and l the fitted parameters of the function. Regressions were fitted using all samples below the Ah horizons in the four forest replicate sites.

Erosion was calculated using the power function describing the distribution of $\delta^{13}C$ with soil depth in the forest sites. Assuming that the shift in $\delta^{13}C$ in the plantation subsoil resulted from shift in the depth due to the erosion after conversion, we calculated the original depth before erosion for all samples under plantations by modifying Equation 6.2:

$$d_b = 10^{\frac{log_{10}(\delta 13C_d/\delta 13C_{Ah})}{-l}} \qquad (6.2)$$

where d_b is the estimated depth before the conversion to plantation, $\delta^{13}C_d$ is the $\delta^{13}C$ values of the samples under plantation at depth d, $\delta^{13}C_{Ah}$ is the mean $\delta^{13}C$ values of the Ah horizons under forest, and l is the parameters estimated for the soils under forest. The difference between the estimated depth before conversion (d_b) and depth at which the sample was collected (d) corresponds to erosion. The erosion for one plantation site was calculated by averaging the erosion estimated for each sample collected in the site. We excluded Ah horizons and samples deeper than 77 cm, which corresponds to the deepest sample under forest.

6.7.3.4 Microclimatic effects of land use change

A 2.5 m aluminum mast was placed in the center of the plots. A thermo-hygrometer (Galltec Mella, Bondorf, Germany) was installed at 2m height in the mast and a soil temperature and moisture sensor (Trime-Pico 32, IMKO, Ettlingen, Germany) was placed 0.3m under the soil surface. Both sensors were connected to a data logger (LogTrans16-GPRS, UIT, Dresden, Germany). Data were recorded every hour, for 16 months from June 2013 on.

6.7.3.5 Micro-catchment related measurements

6.7.3.5.1 General catchment characteristics

Within two small catchments partly encompassing the oil palm and rubber plantations (plots HO1-4, HR1-4, **Figure 6.1**), we recorded streamflow and measured rainfall interception for four months. One catchment (extension of 14.2 ha) was dominated by 10-14 year-old oil palm plantations (90% of the area). The other catchment (4.9 ha) consisted of different rubber stands: eight year-old (19% of the area) and 30 year-old (56% of the area) mono-culture rubber plantations and jungle rubber (25 % of the area), a mix of rubber trees and naturally established dicot tree species. We selected a two week period (7 to 20 Nov 2013) of the recorded hydrographs encompassing both dry and rainy conditions. Rainfall interception of the oil palm and rubber monocultures in the respective catchments was assessed by measuring throughfall and stemflow, and subtracting them from incident rainfall.

6.7.3.5.2 Precipitation

We measured incident rainfall with three ombrometers (154 cm² collection area each) in open areas no more than 100 m from the respective catchments. Data were recorded manually at 6am every day. We observed 30 rainfall events during our measurement period from November 2012 to February 2013, ranging from light to heavy rain (see **Figure 6.4**).

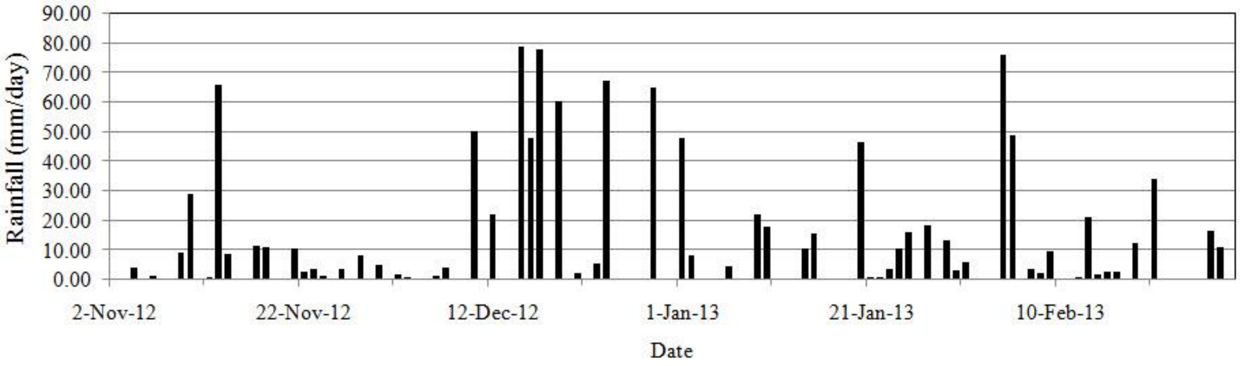

Figure 6.4. Quantities of daily rainfall in the study area from November 2012 to February 2013

6.7.3.5.3 Streamflow

The two catchments were instrumented with a rectangular weir. The water levels in the weirs were continuously recorded using a HOBO Water Level Data Logger (Type U20-001-01, Onset, Bourne, MA, USA). Recorded water levels were converted to discharge units using Equation 6.3.

$$Q_r = 0.57\ H^{1.44} \quad (6.3)$$

where Q_r is rectangular weir discharge (l s^{-1}) and H is the water level in the weir (cm).

6.7.3.5.4 Throughfall

Throughfall samplers were made of 10-liter-canisters with funnels attached to the top for water collection. In oil palm plantations, the samplers were installed in diagonal patterns between adjacent palms. In total, the measurements were carried out in eight diagonal lines, where four lines represent 2m and 4m distance from respective trunks and the remaining four lines represent 1 m and 3 m distance from the trunk. Combined, the throughfall data thus had a resolution of 1 m. In rubber plantations, throughfall samplers were placed between adjacent rubber trees at distances of 1 m and 2 m from the trunk. Recordings were taken daily between November 2012 and February 2013.

6.7.3.5.5 Stemflow

Stemflow was measured by circling and sticking semicircle-shaped metal sheets from the top to the bottom of the trunk. The circling ended 50 cm above ground to allow for the placement of water collectors beneath it. Stemflow collectors were installed on four oil palm and six rubber trunks, respectively. The measurements were conducted between November 2012 and February 2013.

6.7.3.5.6 Interception

Interception was calculated by subtracting stemflow and throughfall from incident rainfall at the plot scale. Given that interception is based on the area of palm or tree canopy cover, stemflow data were normalized with canopy area before subtraction. Throughfall values on the canopy level were obtained by averaging measurements at various distances from the trunks of several individuals.

6.7.4 References Appendix Chapter 6

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Chapter 7: Synthesizing a 'broader eco-hydrological picture'

7.1 Consequences of rainforest transformation on the water cycle in 'maritime' Indonesia

In the light of the rapidly continuing transformation of remaining tropical rainforests to agricultural monocultures, particularly on the 'Maritime Continent' of Indonesia, this work intends to contribute to acquiring thus far scarce knowledge on the eco-hydrological consequences of such transformation processes (**Chapter 1**). Four tropical land use types in lowland Jambi, Indonesia – forests, jungle rubber agroforests and oil palm and rubber monoculture plantations – were compared regarding their spatial and temporal water use characteristics. The results were broadly confronted with other hydrological studies related to tropical land use change (**Chapters 2-6**).

As a first step (**Chapters 2 and 3**), a commonly applied sap flux technique, the thermal dissipation probe (TDP, Granier 1985) method, was tested and adjusted for measurements on tropical monocot and dicot species. The experiments confirmed recommendations made by other authors (see review in Vandegehuchte and Steppe 2013) that the TDP method should be species-specifically calibrated when working on previously unstudied species, and particularly on monocot species. For four tropical bamboos (**Chapter 2**) as well as oil palm (**Chapter 3**), substantial estimation errors occurred when using the original Granier (1985) sap flux equation; after species-specific calibration, estimates were in good agreement with reference measurements (see similar results e.g. in Dierick et al. 2010, Kume et al. 2010). When working on (diffuse porous) dicot species, it has been suggested (e.g. review in Lu et al. 2004) that the TDP method, if carried out according to the original instructions (Granier 1985), can yield precise estimates independent of species. In our work, this was confirmed in exploratory laboratory experiments on four locally occurring tree species including rubber (see **Chapter 5.6**). As no previous sap flux based studies on oil palms were available, **Chapter 3** also focused on establishing an appropriate sampling scheme for estimating stand-level water use of oil palms including error margins; statistically-derived 'optimal' sample sizes suggested measurements on a per-site minimum of 13 leaves on four different palms in an un-stratified scheme, which resulted in sample-size related estimation errors of stand transpiration of 13%. For trees (in forest, jungle rubber and rubber stands), we followed recommendations made in previous studies (e.g. Granier et al. 1996) and adjusted the number of replicates to the heterogeneity of the stands (i.e. two sensors each on six trunks in rubber and on eight trunks in jungle rubber and forest, see **Chapter 5.6** for details). This approach is associated with uncertainties in transpiration estimates of less than 10% in rubber monoculture (Kobayashi et al. 2014), but potentially up to 35% in heterogeneous (natural) forest stands (Granier et al. 1996, also see **Chapter 5.6**).

To provide some first insights into the basic, thus far little explored eco-hydrological characteristics of oil palms, the newly-established measurement scheme (**Chapter 3**) was applied in the field, first in an extensive long-term monitoring sap flux plot (**Chapter 3**) and then to study effects of stand characteristics on water use rates along an age gradient (i.e. in 15 different oil palm plantations between two and 25 years old) in the Jambi Province (**Chapter 4**). Oil palm stand transpiration rates increased almost eight-fold from an age of two years to a stand age of five years and then remained constant with further increasing age, but were highly variable among medium-aged plantations. Other water fluxes besides transpiration, e.g. from the soil, grasses and epiphytes, contributed substantially and variably to evapotranspiration (eddy covariance derived, **Chapter 4**), reducing the large difference between the stands transpiring at the lowest and highest rates to a less than two-fold difference in evapotranspiration. The substantial observed spatial variability of stand transpiration among the 15 plantations was largely explained by differences in stand characteristics, i.e. stand age and density. In the diurnal course, most oil palms showed a strong hysteresis between water use and VPD; on the day-to-day basis this resulted in a relatively low temporal variability of oil palm water use regardless of fluctuations in VPD and radiation. Generally, our observed stand transpiration rates of productive oil palm stands compare to - and in some cases even exceed - values reported for a variety of tropical forests (Calder et al. 1986, Becker 1996, McJannet et al. 2007) and 'forest-like' land use types (e.g. Dierick and Hölscher 2009, Köhler et al. 2009, Kunert et al. 2010, Dierick et al. 2010), indicating yet unexplained substantial water use of oil palms under certain site or management conditions (**Chapter 4**). Our eddy-covariance derived evapotranspiration estimate for a highly productive oil palm plantation is similar to values reported in other oil palm studies (e.g. Henson 1999, Kallarackal et al. 2004, Henson and Harun 2005, Yusop et al. 2008) and for tropical forests in South East Asia (e.g. Tani et al. 2003, Kumagai et al. 2005). Thus, there are indications that both transpirational and total evapotranspirational water fluxes from oil palm plantations are relatively high (i.e. as high as from rainforests), despite e.g. a much lower biomass per hectare than in natural forests (Kotowska et al. 2015). However, the values available for comparison for both transpiration and evapotranspiration are reported in studies encompassing a variety of methodological approaches and climatic regimes, and deriving over-arching scientific findings is further hindered by a lack of sufficient spatial replication and reference systems. While some conclusive findings have been presented e.g. for hydrological consequences of rainforest transformation to pasture in Amazonia (e.g. Zhang et al. 2001, Brown et al. 2005, Sampaio et al. 2007, Aragoa 2012, also see **Chapter 1**), knowledge on transformation processes to 'forest-like' ecosystems such as oil palm plantations on the 'Maritime Continent' remains limited. However, the region is the current global hotspot of rainforest transformation (Koh and Wilcove 2008, Carlson et al. 2012, Hansen et al. 2013, FAO 2015).

To provide a more comprehensive picture of the consequences of tropical rainforest transformation in a ‘maritime’ lowland landscape on the central ecosystem water flux of stand transpiration, we assessed sap-flux derived transpiration rates of 32 sites in four land use types (forest, jungle rubber, rubber and oil palm) in Jambi Province, Indonesia (**Chapter 5**). As in other lowland areas of Indonesia, oil palm and rubber monocultures are the dominant elements in the Jambi landscape, with natural forests and extensive agroforestry systems gradually disappearing (e.g. Koh and Wilcove 2008, Laumonier et al. 2010, FAO 2015). We found substantial differences in stand transpiration between forests and transformation systems as well as among transformation systems at varying spatial and temporal scales. The magnitude of fluxes (i.e. yearly transpiration) was highest in forests, closely followed by jungle rubber and oil palm; it was substantially lower in rubber plantations (partly due to partial leaf shedding during pronounced dry periods). For the continental conditions of the Amazon basin, reduced land-atmosphere water fluxes from pasture have been connected with shifts in regional precipitation patterns (e.g. Aragoa 2012). For our ‘maritime’ study region and for ‘forest-like’ transformation systems such as oil palm plantations, however, large-scale positive and negative feedback mechanisms of land cover change on land-atmosphere water fluxes have not yet been convincingly addressed (van der Molen et al. 2006).

The observed pronounced differences in the magnitude of transpirational fluxes among transformation systems (**Chapter 5**), i.e. oil palm and rubber plantations, are of more acute interest in another context: Severe soil erosion of similar magnitude after rainforest transformation was reported for rubber and oil palm plantations in Jambi Province (Guillaume et al. 2015, also see **Chapter 6**) as well as for a variety of transformation systems in general (de Blécourt et al. 2013, Gharibreza et al. 2013, Chiti et al. 2014). Soil erosion is associated with reduced soil water infiltration rates (e.g. Malmer and Grip 1990, Ilstedt et al. 2007, Yimer et al. 2008) and consequently with much higher landscape-scale water losses by run-off after pronounced precipitation than in forests. Thus, groundwater recharge after rainfall can be reduced in transformed landscapes, which can subsequently lead to reduced water availability e.g. in dry periods (e.g. Lal 1996, Bruijnzeel 2004, Krishnaswamy 2013, also see **Chapter 6**). However, this may not create substantial problems after transformation to rubber plantations, as erosion-induced losses in soil infiltration capacity could be outbalanced by the much lower transpiration of rubber plantations compared to forests (‘infiltration-(evapo)transpiration trade-off hypothesis’, Bruijnzeel 1989, 2004, Krishnaswamy 2013). Oil palms, on the other hand, were found to (almost) transpire as much water as rainforests (**Chapters 4 and 5**). Further, oil palms showed a ‘buffered’ transpirational day-to-day behavior compared to forests, agroforests and rubber monocultures (**Chapter 5**), i.e. relatively constant transpiration rates regardless of fluctuations in environmental conditions. Combined, the severe losses in soil water storage capacity associated with erosion, the relatively high water use of oil palms (e.g. in contrast to rubber) as well as the 'buffered' temporal behavior of oil palms could potentially result in severe water shortages in oil palm landscapes e.g. during ENSO-related droughts. In accordance, depleted ground water reserves and water shortages during pronounced dry periods were reported for some oil palm dominated regions in South East Asia (Obidzinski et al. 2012, Larsen et al. 2014). However, the eco-hydrological mechanisms behind the occurring (periodic) water scarcity had previously not been convincingly addressed.

We conducted an interdisciplinary social and environmental study (**Chapter 6**) in Bungku District (Jambi, Indonesia), which was reportedly particularly affected by periodically occurring water shortages; the study region is characterized by a transformation mainly to oil palm plantations in recent decades. Interviews highlighted the concerns of people regarding decreasing water levels in wells during dry periods and increasing fluctuations in streamflow between rainy and dry periods; increasing water scarcity was commonly associated with the expansion of oil palms in the region. Several villagers strongly emphasized the viewpoint that oil palm is a major consumer of water per se and thus largely responsible for decreasing local water supplies. Analyses of eco-hydrological, micrometeorological and pedological processes in nearby forests and oil palm and rubber plantations generally supported these perceptions and also confirmed reported substantial differences between rubber and oil palm plantations. However, there was some added eco-hydrological complexity to the local interpretations: Results from **Chapters 3, 4 and 5** suggest that oil palms use about as much water as rainforests for transpiration, and that evapotranspirational fluxes might also be similar to those of forests. Thus, rather than to a high water use of oil palms per se, local water scarcity seems connected to the redistribution of water after precipitation at the landscape scale. In (natural) rainforest, the largest part of rainfall water is taken up by the soil and thus contributes to the transpiration of plants and groundwater recharge (e.g. Lal 1996, Yimer et al. 2008). Under oil palm plantations, however, precipitated water cannot well penetrate the severely eroded soil (Guillaume et al. 2015, also see **Chapter 6**). Consequently, a significant amount of water leaves the landscape as run-off and less water is available for groundwater recharge (Bruijnzeel 2004, also see **Chapter 6**). Large-scale transformation of natural forests to oil palm plantations can thus induce or enhance periodic water scarcity under certain conditions, suggesting potentially severe and thus far neglected landscape-scale eco-hydrological consequences of oil palm expansion, e.g. in contrast to rubber expansion.

The observed hydrological consequences of the transformation of lowland rainforest in a 'maritime' region (Jambi, Indonesia) to the agricultural monocultures oil palm and rubber can be summarized in a 'sponge and pump' approach (**Figure 7.1**). The ability of rainforests to soak up and store precipitated water ('sponge effect') in a heterogeneous complex of organic litter and soil layers and highly root-penetrated mineral topsoils with a high organic carbon content (e.g. Lal 1996, Franzluebbers 2002, Bronick and Lal 2005, Yimer et al. 2008) is lost after transformation to both oil palm and rubber plantations due to erosion (Guillaume et al. 2015). This was reflected in high post-precipitation streamflow peaks from both oil palm and rubber landscapes (**Chapter 6**, **Figure 7.1**). However, stream base flow was much lower from oil palm than from rubber, which can be explained by differences in the 'pump effect' among the transformation systems. In oil palm plantations transpiration was as high as in forests ('pump') while it was much lower in rubber plantations, i.e. despite comparably severe erosion much less water remains in oil palm dominated than in rubber dominated landscapes. During pronounced dry periods this can lead to periodic water scarcity in oil palm dominated regions, i.e. very low streamflow and groundwater levels, as was reported by villagers in a qualitative social study in Jambi (**Chapter 6**, **Figure 7.1**).

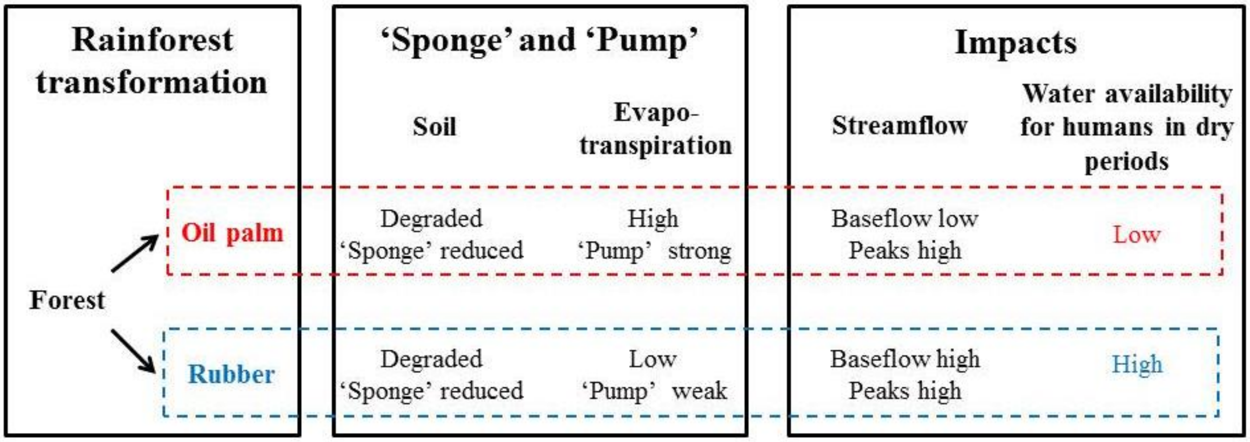

Figure 7.1. Major eco-hydrological consequences of rainforest transformation to oil palm and rubber plantations in Jambi Province illustrated by a 'sponge and pump' approach. The consequences of transformation on the soil ('sponge'), on (evapo)transpiration ('pump') as well as the impact of changes on river streamflow and water availability for humans in dry periods are assessed for oil palm and rubber plantations, respectively.

7.2 Future outlook

By laying out a methodological foundation (**Chapters 2 and 3**) for first deriving basic water use characteristics of oil palm plantations in an isolated manner (**Chapter 4**) and then in comparison to other tropical land use types (**Chapter 5**), we were able to assess and discuss some of the eco-hydrological consequences of rainforest transformation to oil palm and rubber plantations on the

‘Maritime Continent’ (**Chapters 6 and 7**). We gave a first explanation of how reported water scarcity and oil palm expansion may be connected (**Chapter 6**). However, we are only at the very beginning of understanding the broad hydrological consequences associated with tropical rainforest transformation. Future studies (as e.g. proposed for the second phase of the CRC990) will have to address eco-hydrological consequences of (‘maritime’) rainforest transformation across a broader variety of site and management conditions. Likewise, insight into the eco-hydrological functioning of oil palms, e.g. regarding potential internal water storage mechanisms, remains limited and will have to be followed up upon in methodologically broader experiments to comprehensively assess the dynamics of different water fluxes from oil palm plantations. A further major step will comprise the developing of tools for a more rapid assessment of stand eco-hydrological characteristics across sites and landscapes (e.g. based on aerial imaging), so that hydrological consequences of the continuing rainforest transformation to agricultural monocultures can be scaled up accordingly in order to comprehend their regional and supra-regional impacts.

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Index of Figures

Index of Tables

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Declaration of honor

I hereby declare that I am the sole author of this dissertation entitled “CHANGES IN ECO-HYDROLOGICAL FUNCTIONING AFTER TROPICAL RAINFOREST TRANSFORMATION TO RUBBER AND OIL PALM PLANTATIONS” and that all references and data sources have been acknowledged as such. I further declare that this work has never been submitted in any form as part of any other dissertation procedure.

Göttingen, October 2015, ________________________________
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