

1 **POINT-BY-POINT REPLY TO THE REVIEWS:**

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4 **RESPONSE TO REFEREE 1:**

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6 Dear Referee,

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8 We appreciate your careful reading of our manuscript and the numerous insightful suggestions. Changes  
9 to the manuscript detailed below refer to the "markup copy" which is attached as a pdf to this comment.  
10 We also attached a clear copy of the manuscript as well as all figures.

11  
12 Sincerely,  
13 Alexander Röhl

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16 **General comments**

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18 **Referee:** The authors investigated the effect of age and micro-meteorological conditions on transpiration  
19 of oil palms in a humid tropical lowland in Indonesia. The authors investigated palms stands varying in  
20 age between 2 and 25 years. Medium ages stands had a 12-fold higher transpiration than 2 year old stands.  
21 This is a valuable dataset and interesting for the readership of Biogeosciences. The major weak point of  
22 this study, however, is that most of the 3-weeks sap flow measurements were not performed  
23 simultaneously but were conducted successively and thus under varying weather conditions. To get rid of  
24 this methodological problem the authors limited their data evaluation for each stand to the average of  
25 three comparably sunny and dry days. Therefore, I wonder how the authors come at the end to the  
26 conclusion that the temporal variability of oil palm transpiration is rather low. I do not agree with this  
27 conclusion. First of all, the statement itself is misleading. Over the day there is of course a huge temporal  
28 variation in transpiration. What the authors probably mean that the diurnal course of transpiration did not  
29 vary much among the three days and the stands.

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31 **Authors:** We agree with the reviewer that the non-simultaneous measurements in the 15 stands are a  
32 weakness of the study; however, it is very complicated under field conditions to conduct such extensive  
33 measurements in parallel. After careful exploratory analysis (see exemplary figures in the response to  
34 reviewer 2), we are confident that the approach of using three comparably sunny days for the analysis of  
35 spatial heterogeneity of transpiration is suitable to eliminate additional variability induced by varying  
36 weather conditions.

37 Regarding the low temporal variability of oil palm water use, we do not refer to the analysis of spatial  
38 variability among stands on three sunny days, but rather to the low day-to-day variability of oil palm  
39 transpiration in all examined stands, which is presented for four stands in this manuscript. We have tried  
40 to make this clearer throughout the manuscript.

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44 **Referee:** Secondly, to come up with such a conclusion it is not sufficient to evaluate three sunny, dry  
45 days. It would require a more sophisticated evaluation of the entire three weeks under contrasting weather  
46 conditions and the three plots (BO3, PA, PTPN6) that were monitored over longer periods in parallel.  
47 With regard to this aspect it would be very helpful if the authors could present some selected 3-week time  
48 series of transpiration.

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50 **Authors:** Figure 5 and the according sections in the results/discussion show, that our statement of low  
51 temporal variability of oil palm transpiration is not merely based on the analysis of three sunny days, but

52 rather time series of at least 3 weeks in each stand. In this manuscript, in Figure 5, four such series are  
53 presented and plotted against radiation and VPD, respectively. Both relationships show that water use  
54 seems to ‘level-off’ at relatively low VPD and radiation, respectively, i.e. after a steep initial increase,  
55 further increases in VPD and radiation do not induce substantial increases in water use rates; this lead us  
56 to conclude that the transpirational behavior of oil palms is rather ‘buffered’ to fluctuating environmental  
57 conditions, e.g. in contrast to some of the mentioned studies on other species. We tried to clarify our line  
58 of argument throughout the results and discussion.

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62 **Referee:** Another point that was somewhat disappointing for me as a reader is that the authors announced  
63 that their study will “shed first light on some of the hydrological consequences of the continuing  
64 expansion of oil palm plantations”. Unfortunately, this very interesting aspect is not lighted at all, and it  
65 would strengthen the manuscript if the authors would add one or two paragraphs in the Discussion about  
66 this issue.

67  
68 **Authors:** We agree with the reviewer that the manuscript previously under-delivered on this, and we tried  
69 to work out the main conclusions to be drawn from our study more clearly throughout the discussion and  
70 conclusions, i.e. relatively high (evapo)transpiration from oil palms and rather low day-to-day variability  
71 of transpiration rates.

## 72 73 74 75 **Specific comments**

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77 **Referee:** p. 9209: The title does not clearly reflect the content of the paper. The title does not reflect the  
78 aspect of micro-meteorological drivers, which is a substantial part of the manuscript.

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80 **Authors:** While we agree that the title does not reflect the influences of micrometeorological drivers, we  
81 believe that the strong focus on plantation age throughout the manuscript justifies our current, relatively  
82 precise and ‘catchy’ title. After careful consideration, we thus decided to keep the original title.

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86 **Referee:** p. 9216, line 10: Please add some additional information how the eddy covariance data were  
87 processed. Did you gap fill the data? If yes, how did you do that? Did you use quality flags to filter the  
88 data or did you use all data? What’s about the energy balance closure of the EC flux data. It would help to  
89 assess the quality of the EC flux data if the authors could add some data about the energy balance closure.  
90 Did you apply any method to post-close the energy balance (e.g. Bowen ratio method) or did you use the  
91 raw latent heat flux data?

92  
93 **Authors:** We added further information to the method section on eddy covariance measurements.  
94 Generally, no method was applied to post-close the energy balance. Possible methods would be the WPL  
95 correction, as suggested by Liu et al. (2006), or the suggested Bowen ratio method. The first one is a  
96 correct assumption in the case that the energy balance closure is based on an incorrect determination of  
97 the fluxes by the EC method, but this is not always the reason for the missing energy, so we pRefereed  
98 not to use it. The second method might be too simple in some cases, since it is unknown whether scalar  
99 similarity can be assumed for the processes that cause an underestimation of the EC flux under the  
100 assumption that the scalar similarity is fulfilled. Our analysis of sensible and latent heat flux in both sites  
101 showed no similarity between both of them. Therefore we decided not to apply any method to post-close

102 the energy balance (see Ch4. Corrections and Data Quality Control, in Aubinet et al., 2012, Eddy  
103 Covariance, a practical guide to Measurement and Data Analysis SPRINGER ATMOSPHERIC  
104 SCIENCES 2012, DOI: 10.1007/978-94-007-2351-1).

105 **Markup document (page 7):**

106 The eddy covariance technique (Baldocchi, 2003) was used to measure evapotranspiration (ET, mm  
107 day<sup>-1</sup>) in two of the 15 oil palm stands, the 2-year-old (PA) and the 12-year-old (PTPN6) stand (Table  
108 1). Towers of 7 m and 22 m in height, respectively, were equipped with a sonic anemometer (Metek  
109 uSonic-3 Scientific, Elmshorn, Germany) to measure the three components of the wind vector, and an  
110 open path carbon dioxide and water analyzer (Li-7500A, Licor Inc., Lincoln, USA) to derive  
111 evapotranspiration rates (Meijide et al., in preparation). Fluxes were calculated with the software EddyPro  
112 (Licor Inc), planar-fit coordinate rotated, corrected for air density fluctuation and quality controlled.  
113 Thirty-minute flux data were flagged for quality applying the steady state and integral turbulence  
114 characteristic tests (Mauder and Foken, 2006). Data were also filtered according to friction velocity to  
115 avoid the possible underestimation of fluxes in stable atmospheric conditions. Due to the amount of data  
116 gaps created by lack of power and instrument failure, in the two year-old plantation we calculated the  
117 energy balance closure for the selected three sunny days included in the analysis (see Table 1), for which  
118 it was 82%. In the 12 year-old stand, the energy balance closure for the respective full measurement  
119 period (May 2014-February 2015) was 84%. Data used for this analysis were not gap-filled. We selected  
120 three sunny days when most of the thirty-minute measurements during the day were available. When a  
121 single thirty-minute value was missing, the value was filled by linear interpolation between the previous  
122 and the next 30 min value. Measurements were conducted between July 2013 and February 2014 in the 2-  
123 year old and from May 2014 to February 2015 in the 12-year old stand. For the analysis, we used the  
124 average of the same three sunny days that were selected for the sap flux analysis in the respective plots  
125 (see Table 1). Daytime (6am–7pm) evapotranspiration rates were used for the analyses and comparison to  
126 transpiration rates in order to avoid possible measurement errors as a consequence of low turbulent  
127 conditions during nighttime hours.

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131 *Referee:* p. 9220, line 5: Please introduce the Hill function or give at least a reference to this  
132 function.

133  
134 *Authors:* We provide a reference to the Hill function in the according section.

135  
136 **Markup document (page 9):**

137 Converted to leaf water use, a clear non-linear trend over stand age became apparent ( $R^2_{adj} = 0.61$ ,  $P <$   
138  $0.01$  for the Hill function, see Morgan et al., 1975, fit shown in Appendix Fig. 1b, not shown in Fig. 3b):

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142 *Referee:* p. 9220, line 16-17: “There was no significant relationship between water use and radiation”  
143 Firstly, this finding is very surprising, because evapotranspiration must be a function of radiation, and

144 secondly this statement contradicts the results that the authors show in Fig. 5b. There, the authors found,  
145 at least for the sites BO3, PTPN6 and HAR\_old, a pronounced linear relationship between leaf water use  
146 and radiation. Please explain!

147  
148 *Authors:* The wording was imprecise here, we did not refer to a general relationship between radiation  
149 and water use, but to the particular relationship between transpiration (on the respective three sunny days)  
150 and the radiation values (on these respective three sunny days), i.e. transpiration differences among sites  
151 could not be explained by differences in radiation during the respective time of measurement. We  
152 adjusted the wording in the according section.

153  
154 **Markup document (page 10):**

155 Potentially, this could be related to differences in radiation on the respective three sunny days that were  
156 chosen for the analysis. However, there was no significant relationship between average water use rates  
157 on the respective three sunny days in the 15 stands and the respective average radiation (or VPD) on those  
158 days (linear regression,  $P > 0.05$ ), i.e. observed spatial variability in transpiration among the 15 stands  
159 could not be explained by differences in weather conditions. A further analysis of the water use rates of  
160 eight medium-aged stands with highly variable transpiration rates also gave no indications of variability  
161 being induced by differences in radiation.

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165 *Referee:* p. 9220, line 23-26: I do not agree with the argumentation that the dynamics of leaf water use is  
166 buffered. I think it would help a lot if the authors would discuss their result more in the light of plant  
167 physiological aspect (e.g. light and temperature response curve, stomatal conductance, photosynthesis  
168 etc.). If the light response curve, for example, reaches already at low radiation its maximum than any  
169 further increase in radiation would not increase transpiration but this does not mean that the response of  
170 the water use is buffered.

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172 *Authors:* We agree that the use of the word ‘buffered’ might have originally been misleading and have  
173 adjusted the respective section by elaborating further and partly rephrasing.  
174 While we agree that a discussion involving further plant physiological aspects would be highly  
175 interesting, unfortunately the available data basis on oil palm physiology is at this point insufficient to do  
176 so comprehensively. Such issues will certainly have to be addressed in further studies on the water use  
177 characteristics of oil palm.

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179 **Markup document (page 18):**

180 At the day-to-day scale, in all 15 oil palm stands, the response of water use rates particularly to changes in  
181 VPD seemed ‘buffered’, i.e. near-maximum daily water use rates were reached at relatively low VPD, but  
182 better environmental conditions for transpiration (i.e. higher VPD) did not induce strong increases in  
183 water use rates (i.e. 1.2-fold increase in water use for a two-fold increase in VPD). Likewise, for both  
184 photosynthesis rates (Dufrene and Saugier, 1993) and water use rates (Niu et al., 2015) of oil palm leaves,  
185 linear increases with increasing VPD were reported at relatively low VPD, until a certain threshold  
186 (1.5–1.8 kPa) was reached, after which no further increases in photosynthesis and water use rates,  
187 respectively, occurred

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**Referee:** Chapter 3.3: Why did you limit your analysis of the environmental drivers to VPD and radiation? Evapotranspiration also depends heavily on wind speed, temperature and atmospheric stability. Did you have also a look on these drivers? Please explain and discuss it in the text!

**Authors:** We had recorded a variety of further environmental and micrometeorological parameters (e.g. soil moisture and temperature, air temperature and humidity, air pressure, wind speed, net radiation) and did not limit our analysis to (global) radiation and VPD, but none of the other variables had any significant relationship with water use ( $P > 0.05$  for linear, non-linear and multiple linear regressions), or they had a similar, but weaker relationship as the presented drivers (as e.g. the case for net radiation and global radiation), and we thus did not present them in the manuscript. We included this information in the environmental measurements section of the Methods to make clearer why we focus on VPD and radiation exclusively in this manuscript.

**Markup document (page 8):**

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Soil moisture fluctuated only little at the respective locations and during the respective measurement periods and even on a yearly scale, e.g. between  $32 \pm 2\%$  and  $38 \pm 2\%$  between June 2013 and June 2014 (minimum and maximum daily values, mean  $\pm$  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. Likewise, further recorded micrometeorological variables (e.g. air pressure, wind speed) had no significant relationship with water use rates in our study (linear regression,  $P > 0.1$ ) and were thus also omitted. We instead focused on the micrometeorological drivers VPD and global radiation; among an array of micrometeorological variables (e.g. also including temperature, humidity, net radiation) exploratory analysis had shown that they were best suited to explain fluctuations in water use rates. This has also been demonstrated in other studies on plant water use (e.g. Dierick and Hölscher, 2009; Köhler et al., 2009, 2013)

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**Referee:** p. 9222, line 14-26: This is a Result part, and please describe in the Material and Methods which statistical method you applied to get these numbers.

**Authors:** As suggested by the reviewer, we moved the according section to the results and now merely provide a quick summary of these results in the discussion. We included information on the statistical procedure (providing function type, i.e. Hill function, as well as  $R^2$  values, i.e. the percentage of variability that can be explained by the fit) directly into the section.

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**Markup document (page 10/13):**

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**Results:** On comparably sunny days, the stand-level transpiration among the 15 oil palm stands varied 12-fold, from 0.2 mm day<sup>-1</sup> in a 2-year old to 2.5 mm day<sup>-1</sup> in a 12-year old stand. A large part of this spatial variability was explained by different stand variables when applying the Hill function. Stand age explained 45% of the observed spatial variability of stand transpiration (i.e.  $R^2_{adj} = 0.45$  at  $P < 0.01$ , Appendix Fig. 1), and variables correlated to stand age, i.e. by average stand trunk height and by stand

235 water conductive area, explained 44% and 43%, respectively (Table 2). Much of the remaining variability  
236 in stand transpiration rates could be explained by varying stand densities (variations of up to 30%  
237 between stands of similar age, see Table 1). Thus, when shifting from the stand level to the palm level, up  
238 to 60% of the spatial variability in palm water use rates could be explained by age and correlated  
239 variables (see Fig. 3c and Table 2). Much of the variability that remains on the palm level is induced by  
240 three stands where palm water use was much higher ( $> 150 \text{ kg day}^{-1}$ ) than in the other 12 stands ( $< 125$   
241  $\text{kg day}^{-1}$ ); excluding these three stands from the analysis, 87% of the spatial variability in palm water use  
242 rates could be explained by age (Table 3).

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244 **Discussion:** The observed substantial stand-to-stand variability of transpiration among the 15 stands,  
245 particularly among medium aged plantations, could to 60% be explained by the variables stand age and  
246 density, and up to 87% when excluding three stands with much higher water use. The remaining  
247 unexplained variability as well as the high water use rates in the three mentioned stands could be related  
248 to differences in site and soil characteristics.

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252 **Referee:** p. 9223, line 9-15: Please avoid to repeat too many results in the Discussion. Pick up shortly the  
253 main finding and then discuss it.

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255 **Authors:** We followed the advice of the reviewer and shortened parts of the discussion that repeated  
256 results in too much detail.

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258 **Markup document (page 14):**

259 Our eddy-covariance derived evapotranspiration estimates of 2.8 and 4.7 mm day<sup>-1</sup> (on sunny days, in 2-  
260 and 12-year old stands, respectively) compare very well to the range reported for oil palms in other  
261 studies: For 3–4 year old stands in Malaysia, eddy-covariance derived values of 1.3 mm day<sup>-1</sup> and  
262 3.3–3.6 mm day<sup>-1</sup> were reported for the dry and rainy season, respectively (Henson and Harun, 2005).  
263 For mature stands, a value of 3.8 mm day<sup>-1</sup> was given, derived by the same technique (Henson, 1999).  
264 Micrometeorologically-derived values for 4–5 year old stands in Peninsular India were 2.0–5.5 mm day<sup>-1</sup>  
265 during the dry season (Kallarackal et al., 2004). A catchment-based approach suggested values of 3.3–3.6  
266 mm day<sup>-1</sup> for stands in Malaysia between 2 and 9 years old (Yusop et al., 2008); evapotranspiration rates  
267 derived from the Penman-Monteith equation and published data for various stands were 1.3–2.5 mm  
268 day<sup>-1</sup> in the dry season and 3.3–6.5 mm day<sup>-1</sup> in the rainy season (Radersma and Ridder, 1996). The  
269 values reported in most available studies as well as our values overlap in a corridor from about 3 mm  
270 day<sup>-1</sup> to about 5 mm day<sup>-1</sup>; this range compares to evapotranspiration rates reported for rainforests in  
271 South East Asia (e.g. Tani et al., 2003a; Kumagai et al., 2005). Considering that oil palm stands e.g. have  
272 much lower stand densities and biomass per hectare than natural tropical forests (Kotowska et al., 2015),  
273 this indicates a quite high evapotranspiration from oil palms at both the individual and the stand level.

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277 **Referee:** p. 9228: The Conclusions section is in large parts a summary and not a conclusion. Please revise  
278 it and put the focus on your conclusions.

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280 **Authors:** We tried to sharpen the conclusions with respect to a stronger focus on the eco-hydrological  
281 implications of the results of our study.

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283 **Markup document (page 19):**



284 The study provides first insights into eco-hydrological characteristics of oil palms at varying spatial and  
285 temporal scales and first estimates of oil palm stand transpiration rates across an age gradient. Stand  
286 transpiration rates increased almost 8-fold from an age of two years to a stand age of five years and then  
287 remained constant with further increasing age, but were highly variable among medium-aged plantations.  
288 In some of the studied stands, transpiration was quite high, i.e. higher than values reported for tropical  
289 rainforests. There may be a potential trade-off between water use and management intensity of oil palm  
290 plantations. Total evapotranspirational water fluxes from a two and a 12 year-old oil palm plantation were  
291 also relatively high, i.e. other water fluxes besides transpiration (e.g. from the soil) contributed  
292 substantially and variably to evapotranspiration. This reduced a 12-fold difference in transpiration  
293 between the two stands to a less than two-fold difference in evapotranspiration. In the diurnal course,  
294 most oil palms showed a strong hysteresis between water use and VPD. On the day-to-day basis this  
295 results in a relatively low variability of oil palm water use regardless of fluctuations in VPD and radiation.  
296 In conclusion, oil palm dominated landscapes show some spatial variations in (evapo)transpiration rates,  
297 e.g. due to varying age-structures and stand densities, but the day-to-day variability of oil palm  
298 transpiration is rather low. Under certain site or management conditions, (evapo)transpirational water  
299 fluxes from oil palms can be substantial.

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303 **Referee:** Figure 3: Please plot the Hill function. That helps to assess the quality of the fit.

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305 **Authors:** We did not include the Hill function into Figure 3, but now provide an additional figure in the  
306 Appendix that shows that Hill fit for the respective sub-figures.

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308 **Markup document:** Attached as pdf.

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312 **Referee:** Figure 5: It would facilitate the interpretation of the figure if the authors would add the slope of  
313 the regression to the plots.

314

315 **Authors:** We now provide the regression functions in the figure.

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317 **Markup document:** Attached as pdf.

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320 Technical corrections

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322 **Referee:** p. 9214, line 17: Please state the manufacturer and give some more information about the probe  
323 type.

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325 **Authors:** We included manufacturer and a reference for the technical specifications of the sensors.

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327 **Markup document (page 5):**

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329 Following a methodological approach for sap flux measurements on oil palms (Niu et al., 2015), we  
330 installed thermal dissipation probe (TDP, Granier, 1985; Uniwerkstätten Universität Kassel, Germany;  
see Niu et al. 2015 for technical specifications) sensors in the leaf petioles of 16 leaves, four each on four

331 different palms, for each of the 15 examined stands. Insulative materials and aluminum foil shielded the  
332 sensors to minimize temperature gradients and reflect radiation.  
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