



1 **Observation-based implementation of ecophysiological processes for a rubber plant**  
2 **functional type in the community land model (CLM4.5-rubber\_v1)**

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31 **Running head:** Rubber plant functional type in the community land model\_v4.5

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33



34 **Abstract**

35 Land-use change has a strong impact on carbon, energy and water fluxes and its effect is  
36 particularly pronounced in tropical regions. Uncertainties exist in the prediction of future land-  
37 use change impacts on these fluxes by land surface models due to scarcity of suitable measured  
38 data for parametrization and poor representation of key biogeochemical processes associated  
39 with tropical vegetation types. Rubber plantations (*Hevea brasiliensis*) are a crucial land-use  
40 type across tropical landscapes that has greatly expanded in recent decades. Here, we first  
41 synthesize the relevant data for describing the biogeochemical processes of rubber from our past  
42 measurement campaigns in Jambi province, Indonesia. We then use these data-sets to develop a  
43 rubber plant functional type (PFT) for the Community Land Model (CLM4.5). Field measured  
44 data from small-holder plantations on leaf litterfall, soil respiration, latex harvest, leaf area index,  
45 transpiration, net primary productivity, and above-ground and fine root biomass were used to  
46 develop and calibrate a new PFT-based model (CLM4.5-rubber).

47 CLM-rubber predictions adequately captured the annual net primary productivity and  
48 above-ground biomass as well as the seasonal dynamics of leaf litterfall, soil respiration, soil  
49 moisture and leaf area index. All of the predicted water fluxes of CLM-rubber were very similar  
50 to a site-specific calibrated soil water model. Including temporal variations in leaf life span  
51 enabled CLM-rubber to better capture the seasonality of leaf litterfall.

52 Increased sensitivity of stomata to soil water stress and the enhancement of growth and  
53 maintenance respiration of fine roots in response to soil nutrient limitation enabled CLM-rubber  
54 to capture the magnitude of transpiration and leaf area index. Since CLM-rubber predicted  
55 reasonably well the carbon and water use, we think that the current model can be used for larger-  
56 scale simulations within Jambi province because more than 99% of the rubber plantations are  
57 smallholder owned in Jambi province and have low soil fertility.

58

59 **Keywords:** plant functional traits, leaf age, productivity, water use, stomatal conductance

60



## 61 Introduction

62 Historical records show that Indonesia has had accelerated rates of land-use change from  
63 forest to croplands due to economic development and policy reforms (Gellert, 2005). Within  
64 Indonesia, Jambi province on Sumatra has been a hotspot of land-use change with a relatively  
65 large area of forest converted to rubber plantations over the past two decades (Melati, 2017), in  
66 part due to projected increases in the demand of this commodity (Eleanor et al., 2015). Little is  
67 known about how these land-use changes alter the biogeochemical processes of the carbon and  
68 water cycles (Mann, 2009; Powers et al., 2011; Qui, 2009), which are fundamental for ecosystem  
69 services. Previous studies have shown that land-use changes to rubber plantation decrease above  
70 and below-ground carbon pools (de Blécourt et al., 2013; Ziegler et al., 2009) and affect the soil  
71 nitrogen cycle (Allen et al., 2015; Corre et al., 2006). Thus, quantifying land-atmosphere  
72 interactions of rubber plantations in the context of ongoing land-use and climate change is  
73 essential for understanding local, regional and even global carbon and water balances.

74 So far, insufficient field data are the main limiting factor of our current understanding of  
75 carbon and water cycling in rubber plantations (Blagodatsky et al., 2016; Carr, 2012). Although  
76 traditional field-based methods are critical for identifying how biogeochemical processes are  
77 affected by land-use changes to rubber plantations (e.g. Allen et al., 2015), they also have  
78 limitations, especially when analyzing interactions between different processes and extrapolating  
79 values to long-term temporal and large spatial scales. In contrast, remote sensing approaches  
80 provide essential information on past land-use changes and surface properties of rubber  
81 plantations (Ranganath et al., 2004; Senf et al., 2013), but they do not completely describe  
82 ecosystem-scale changes, nor the mechanisms behind the changes. Quantitative understanding of  
83 the physiological processes leading to biogeochemical disruption is critical for making future  
84 projections of the environmental implications associated with different land-use change  
85 scenarios, and that is only possible with modelling techniques such as process-based land surface  
86 models used in conjunction with the data sources described.

87 Numerous land surface models differ in their prediction of land-use change effects on  
88 carbon (Houghton et al., 2012) and water cycles (Boisier et al., 2012; Pitman et al., 2009). Such  
89 uncertainties in land surface models may stem from errors in measurements of meteorological  
90 variables (Rahul et al., 2014), incorrect initial conditions (Hanna et al., 2017), poor  
91 representation of processes (Ali et al., 2016) or errors in parameters (Bonan and Doney, 2018).



92 Errors in model parameters are considered to be the largest uncertainty in various land surface  
93 models (Bonan and Doney, 2018), including the Community Land Model (CLM). The CLM  
94 version 4.5, used here, represents naturally- and crop-vegetated land units (Oleson et al., 2013)  
95 as patches of plant functional types (PFTs) defined by key ecological functions (Bonan et al.,  
96 2002). The existing parameterization of CLM allows an adequate description of the specific  
97 land-use change effects on annual and perennial crops (Oleson et al., 2013). However, the  
98 biogeochemical cycles of most of the woody tree crops, including rubber are not yet  
99 implemented in CLM (but see Fan et al., 2015).

100 Rubber (*Hevea brasiliensis*) is a commercially important tree species native to the  
101 Amazon rainforest (Wycherley, 1992) but cultivated throughout the tropics. The species is  
102 evergreen in its native range, but drought deciduous in other tropical regions, including  
103 Indonesia (Kotowska et al., 2016), Thailand (Giambelluca et al., 2016) and China (Lin et al.,  
104 2018). The mechanistic basis for the leaf habit of rubber remains poorly understood. In regions  
105 having a marked dry season, the period of defoliation is short and re-foliation occurs before the  
106 commencement of the rainy season, triggered by an increase in day length (Maite et al., 2008). In  
107 contrast, if the dry season is less pronounced, leaf fall occurs more gradually, new leaves develop  
108 more slowly and, although the trees are never completely leafless, latex yields are reduced more  
109 than in situations where complete defoliation occurs.

110 In this study, we develop a sub-model called “CLM4.5-rubber\_v1”, within the framework  
111 of CLM4.5, which simulates the productivity, growth, yield, and water and energy cycles of  
112 rubber. To reflect the specific growth characteristic of rubber trees, we modify and develop the  
113 parameters and processes of the existing tropical deciduous forest PFT. The existing drought-  
114 deciduous phenology scheme of the tropical PFT is modified together with the carbon and  
115 nitrogen allocation module, where carbon exports through latex harvest influence both carbon  
116 and nitrogen allocation.

117 The main objectives of this paper are to (1) implement phenology, carbon and nitrogen  
118 allocation, and yield dynamics for to represent the physiology of rubber plants in CLM-rubber,  
119 (2) use the developed model to test the hypothesis that drought will reduce the latex yield of  
120 rubber plantation, and (3) use CLM-rubber to generate hypotheses that field experimentalists can  
121 investigate in the future. To achieve these objectives, we synthesized the data collected both by  
122 short-term field campaigns and intensive one-year measurements in small-holder rubber



123 plantations, which are commonly unfertilized, in Jambi, Indonesia and used part of the data for  
124 calibration and the rest for validation of CLM-rubber.

125

## 126 **Methodology**

### 127 *Overview*

128 We made several modifications to the parametrization of the drought deciduous tropical  
129 PFT and implemented phenology, carbon & nitrogen allocations and latex yield processes as we  
130 developed the rubber PFT in CLM using the measured data. We made these changes in a  
131 systematic way as described below and show the results that includes the effect of the overall  
132 change. To save space, we include figures for the model calibration in the main manuscript and  
133 put figures for the model validation in the supplementary section.

134

### 135 *Study Sites*

136 Our study site is located on mineral soils (Acrisols) located in the lowlands of Jambi  
137 province, Indonesia (2° 0' 57" S, 103° 15' 33" E, 40 - 100 m above sea level). The studied rubber  
138 plantations were owned by smallholders who did not fertilize 2-5 years prior to and during our  
139 field measurements that started in 2013. A large part of the Jambi province had been converted  
140 to rubber plantations in the past two decades (Margono et al., 2012), and thus this study area was  
141 selected as a hotspot of rubber expansion by our ongoing collaborative research center  
142 (Ecological and Socio-economic Functions of Tropical Lowland Rainforest Transformation  
143 Systems, <http://www.uni-goettingen.de/en/310995.html>). The mean annual temperature in Jambi  
144 is  $26.7 \pm 1.0$  °C and the mean annual precipitation is  $2235 \pm 385$  mm (Drescher et al., 2016). The  
145 dry season is usually from July to August and the rainy season occurs from October to April.

146 Measurements were performed in two landscapes within the Jambi province that differed  
147 mainly in soil texture: loam and clay Acrisol soils (Allen et al., 2015). The loam Acrisol soil was  
148 located about 80 km southwest of Jambi City, and hereafter referred to as the Harapan landscape.  
149 The clay Acrisol soil was located about 90 km west of Jambi City, and hereafter referred to as  
150 the Bukit Duabelas landscape. Within each of the two landscapes, four rubber plantations were  
151 chosen and within each plantation a 50 m x 50 m plot was established, totaling eight plots  
152 (Kotowska et al., 2015). On average, the rubber plantations in Bukit Duabelas landscape were  
153 five years younger than those in Harapan landscape.



154 We collated the following measured data-sets from each of the eight plots: above-ground  
155 biomass, net primary productivity, leaf litterfall, latex yield, fine root biomass; soil moisture, soil  
156 respiration, leaf area index, and transpiration. All of the data were obtained between 2012 and  
157 2014, except leaf area index, which was measured in 2018. Additional information on vegetation  
158 characteristics such as rubber tree density, tree height, and basal area can be found in Table 2 of  
159 Kotowska et al. (2015).

160

#### 161 *Rubber PFT development*

162 For the development of the rubber plant functional type in CLM, our main goal was to  
163 capture the growth characteristics of rubber trees and include a realistic representation of carbon  
164 exports via latex harvest. We adapted the rubber PFT to be partly based on the existing broadleaf  
165 tropical deciduous tree PFT. We modified the phenology scheme and implemented the harvest  
166 export using the field data described above.

167

#### 168 *Phenology, Carbon & Nitrogen Allocation and Yield*

169 First, we considered the default tropical drought deciduous phenology scheme in CLM4.5  
170 (Dahlin et al., 2015) that allows plants to shed their leaves through two alternative mechanisms:  
171 1) stress-deciduous leaf onset/offset switches triggered by a sustained period of dry soil; 2) a  
172 background leaf litterfall rate calculated based on leaf longevity that is not associated with a  
173 specific offset period but occurs over an extended period of time. Leaf onset and offset for the  
174 drought stress of deciduous phenology type (Dahlin et al., 2015) is based on the critical soil  
175 water potential and soil water index accumulator (see Table S1). Preliminary results of the CLM-  
176 rubber development showed that the default drought stress onset/offset mechanism did not  
177 capture well enough the declining trend of LAI of rubber plantation in the dry season. The  
178 determination of leaf shedding for tropical deciduous trees is generally a challenging problem  
179 (Dahlin et al., 2017) and very few studies have looked into this aspect to date (Medlyn et al.,  
180 2016; Xu et al., 2016). Based on the measurements of leaf litterfall (Kotowska et al., 2016), we  
181 incorporated seasonal changes in the leaf life span of rubber in order to improve the background  
182 leaf litterfall mechanism, wherein we set a higher leaf life span value in the wet season than in  
183 the dry season. A calendar month-dependent function of month was used to model leaf life span  
184 (“leaf\_long” (yrs)). This function computes leaf\_long in a step-wise fashion as follows,



$$185 \quad \text{leaf\_long} = \begin{cases} 2, \text{month} < 4 \\ 1.55, 4 \leq \text{month} \leq 5 \\ 0.55, 6 \leq \text{month} \leq 7 \\ 0.23, 8 \leq \text{month} \leq 9 \\ 4.1, \text{month} > 9 \end{cases} \quad (1)$$

186 The above implementation was necessary to ensure that the modeled background leaf litterfall  
187 considers the variability in leaf life span.

188 Four to five times in a week, stems of rubber trees are tapped and the latex is harvested  
189 (yield). Previous experimental work showed that tapped rubber trees grew less than untapped  
190 trees (Chantuma et al., 2009; Silpi et al., 2007). Since latex is rich in carbon, this was interpreted  
191 as active carbon allocation to storage in response to tapping (Chantuma et al., 2009; Silpi et al.,  
192 2007). In our model, latex yield is proportional to annual net primary productivity (Kotowska et  
193 al., 2015) and also considered from the partitioning of growth and storage carbon pools. We  
194 included the latter because in the field, latex yield could also result from the storage pools  
195 (Junjittakarn et al., 2012; Sara et al., 2014).

196 To our knowledge, calculation of latex yield from net primary productivity and  
197 calculation of latex yield from the partitioning of growth and storage carbon pool is a new  
198 concept and has not been considered in any of the rubber modeling studies (Kumagai et al.,  
199 2013). Subsequently, we introduced in the CLM-rubber two tapping-related parameters; tap\_npp,  
200 the proportion of latex yield taken from net primary productivity and tap\_partition, the  
201 proportion of latex yield taken from the partitioning of the growth and storage carbon pools (see  
202 Table S1).

203 CLM4.5 calculates carbon allocated to new growth based on five allometric parameters  
204 that relate allocation between tissue types (Oleson et al., 2013): 1) ratio of new fine root to new  
205 leaf carbon allocation ( $a_1$ ), 2) ratio of new coarse root to new stem carbon allocation ( $a_2$ ), 3) ratio  
206 of new stem to new leaf carbon allocation ( $a_3$ ), 4) ratio of new live wood to new total wood  
207 allocation ( $a_4$ ) and 5) ratio of growth respiration carbon to new growth carbon ( $g_1$ ). CLM4.5 has  
208 a dynamic allocation scheme (Oleson et al., 2013), which includes one dynamic allometric  
209 parameter ( $a_3$  as a function of annual NPP). For the drought deciduous tropical PFT,  $a_1$ ,  $a_2$ ,  $a_4$  and  
210  $g_1$  are constants ( $a_1 = 1$ ,  $a_2 = 0.3$ ,  $a_4 = 0.1$  and  $g_1 = 0.3$ ), whereas  $a_3$  is a dynamic parameter  
211 defined by the following equation,

$$212 \quad a_3 = \frac{2.7}{1 + e^{-0.004(\text{NPP}_{\text{ann}} - 300)}} - 0.4, \quad (2)$$





213 where  $NPP_{ann}$  is the annual sum of NPP of the previous year. The above equation for  $a_3$  increases  
 214 stem allocation relative to leaf when annual NPP increases. We assume that due to tapping, the  
 215 ratio of new stem to new leaf carbon allocation would change, thus, for CLM-rubber, we  
 216 modified  $a_3$  as follows,

$$217 \quad a_3 = \frac{2.7}{1 + e^{-0.004((1 - tap\_npp)NPP_{ann} - 300)}} - 0.4, \quad (3)$$

218 where  $tap\_npp$  is the proportion of latex yield taken from annual net primary productivity.

219 In addition to tapping from NPP, we also considered tapping from the partitioning of  
 220 growth and storage carbon pool. We recognized that for all deciduous PFTs, there is a fraction of  
 221 allocation that goes into the growth pool ( $f_{cur}$ ), which is currently set to 0 (unitless) and the  
 222 remainder ( $1 - f_{cur}$ ) goes to the storage pool. Subsequently, the deciduous phenology module  
 223 either uses the onset growth function or a background growth transfer rate ( $bgtr$ ; outside of onset  
 224 period) to move storage carbon to displayed growth pools. For CLM4.5-rubber, we partition  $f_{cur}$   
 225 into three portions; growth ( $f_{cur\_gr}$ ), storage ( $f_{cur\_st}$ ) and tapping ( $f_{cur\_tap}$ ). We assume that  
 226 the total fraction of allocation that goes into the growth, storage and tapping pool is 1 (unitless).  
 227 Next, we define  $f_{cur\_tap}$  as a parameter called “ $tap\_partition$ ” (see Table S1). We also define  
 228 the fraction of allocation that goes into the storage as “ $f_{cur\_st}$ ” and set  $f_{cur\_st} = 0.5$ . Because  
 229  $f_{cur\_tap}$  and  $f_{cur\_st}$  are known, we obtain the fraction of allocation that goes into the growth  
 230 pool ( $f_{cur\_gr}$ ) as follows,

$$231 \quad f_{cur\_gr} = 1 - (f_{cur\_tap} + f_{cur\_st}) \quad (4)$$

232 It is important to recognize that in Eq. 4 as  $f_{cur\_tap}$  increases,  $f_{cur\_gr}$  decreases. This  
 233 trade-off is in line with the notion that tapping limits growth (Chantuma et al., 2009; Silpi et al.,  
 234 2007). Given the above allocation parameters ( $a_1$ ,  $a_2$ ,  $a_3$ ,  $a_4$  and  $g_1$ ) and carbon to nitrogen ratios  
 235 of these tissues: leaf, fineroot, livewood (in stem and coarse root) and deadwood (in stem and  
 236 coarse root), which are constants, the total carbon and nitrogen allocation to new growth  
 237 ( $CF_{alloc}$ ,  $gC\ m^{-2}s^{-1}$ , and  $NF_{alloc}$ ,  $gN\ m^{-2}s^{-1}$ , respectively) can be expressed as functions of  
 238 new leaf carbon allocation ( $CF_{GPP,leaf}$ ,  $gC\ m^{-2}s^{-1}$ ):

$$239 \quad CF_{alloc} = CF_{GPP,leaf}C_{allom}, \quad (5)$$

$$240 \quad NF_{alloc} = CF_{GPP,leaf}N_{allom},$$

241 where  $C_{allom}$ ,  $N_{allom}$  are the carbon and nitrogen allometry (Oleson et al., 2013). From the  
 242 stoichiometric relationship in Eq. 5, the associated carbon allocation flux is:



$$243 \quad CF_{\text{alloc}} = NF_{\text{alloc}} \frac{C_{\text{allom}}}{N_{\text{allom}}} \quad (6)$$

244 Total allocation to new leaf carbon ( $CF_{\text{alloc,leaf\_tot}}$ ,  $gCm^{-2}s^{-1}$ ) is calculated as:

$$245 \quad CF_{\text{alloc,leaf\_tot}} = CF_{\text{alloc}} / C_{\text{allom}} \quad (7)$$

246 In CLM4.5, there are two carbon pools associated with each plant tissue: 1) growth and  
 247 2) storage. The carbon pools that represent growth include carbon in leaf (leafc), carbon in fine  
 248 roots (frootc), carbon in live stem (livestemc), carbon in dead stem (deadstemc), carbon in live  
 249 coarse roots (livecrootc) and carbon in dead coarse roots (deadcrootc). The carbon pools that  
 250 represent storage have a suffix “\_storage” and include leafc\_storage, frootc\_storage,  
 251 livestemc\_storage, deadstemc\_storage, livecrootc\_storage and deadcrootc\_storage. In CLM4.5,  
 252 the carbon allocation fluxes have a prefix “cpool\_to\_”.

253 For CLM-rubber, we made changes to all of the above carbon pools, we show below the  
 254 key carbon allocation fluxes for CLM-rubber in the leaf, fineroot and tapping pools. Given  
 255  $CF_{\text{alloc,leaf\_tot}}$ ,  $f_{\text{cur\_gr}}$ ,  $f_{\text{cur\_st}}$  and  $f_{\text{cur\_tap}}$ , the allocation fluxes of carbon to growth and  
 256 storage pools for the various tissue types can be calculated as follows,

$$257 \quad \text{cpool\_to\_leafc} = CF_{\text{alloc,leaf\_tot}} * f_{\text{cur\_gr}}, \quad (8)$$

$$258 \quad \text{cpool\_to\_leafc\_storage} = CF_{\text{alloc,leaf\_tot}} * f_{\text{cur\_st}},$$

$$259 \quad \text{cpool\_to\_frootc} = CF_{\text{alloc,leaf\_tot}} * a_1 * f_{\text{cur\_gr}},$$

$$260 \quad \text{cpool\_to\_frootc\_storage} = CF_{\text{alloc,leaf\_tot}} * a_1 * f_{\text{cur\_st}}$$

261 The carbon flux of the latex yield is the sum of yield from net primary productivity and  
 262 partitioning pool, which is calculated as follows,

$$263 \quad \text{cpool\_to\_tappingc} = \text{tap\_npp} * \text{NPP\_ann} * \frac{1}{3600*24*365} + CF_{\text{alloc,leaf\_tot}} * f_{\text{cur\_tap}} \quad (9)$$

264 Besides the new tapping mechanism, one of the major differences between CLM4.5 for  
 265 tropical deciduous PFT and CLM-rubber with respect to the above carbon allocation fluxes is  
 266 that CLM4.5 does not have a carbon export flux for latex yield. Further, CLM4.5 used a fixed  
 267 “fcur” term in all of the equation 8 to partition carbon fluxes to growth pools and to storage pools  
 268 associated with each tissue type. In contrast, CLM-rubber partitions allocation fluxes to the new  
 269 tapping pools as well as growth and storage, which are defined above in Eq. 4.

270 The nitrogen pools follow the stoichiometric relationship with carbon pools. The nitrogen  
 271 pools for the growth include nitrogen in leaf (leafn), nitrogen in fine roots (frootn), nitrogen in



272 live stem (livestemn), nitrogen in dead stem (deadstemn), nitrogen in live coarse roots  
273 (livecrootn) and nitrogen in dead coarse roots (deadcrootn). Similar to the carbon pools, the  
274 nitrogen pools also have corresponding storage pools and displayed growth pools The  
275 corresponding nitrogen allocation fluxes are calculated as ratios of carbon allocation fluxes using  
276 the inverse of respective carbon to nitrogen ratios of different tissue types.

277 In the CLM-rubber, tapping of rubber trees started at the age of six years. The model  
278 updates the ratio of carbon to nitrogen of latex yield every half hour.

279

#### 280 *Initial model simulations*

281 To mimic the vegetation and soil state prior to rubber plantation, a Tropical Evergreen  
282 forest PFT was first spun-up and run until 1997 using the standard procedures of CLM4.5 spin-  
283 ups (Fan et al., 2015; Koven et al., 2013). We used the Tropical Evergreen PFT for the spin-up  
284 because we assumed that the natural vegetation prior to land-use change was evergreen. A  
285 comparison of the modeled above ground biomass and net primary productivity of the spin-up  
286 phase with the observed above ground biomass and net primary productivity of tropical  
287 evergreen forests at our site (Kotowska et al., 2015) showed that these matched reasonably well  
288 (see Figure S1). Following the spin-up phase, a clear-cut in 1998 was simulated by setting the  
289 above ground carbon and nitrogen pools to zero.

290 Second, using the site-level measurements on soil texture (Allen et al., 2015) and climate  
291 data for 2013 (Meijide et al., 2018) at the Harapan landscape, a rubber plantation simulation was  
292 performed from 1998 to 2014. First, we used the default parametrization of stress deciduous  
293 tropical PFT of CLM4.5, but the generic model performance was poor relative to some of the  
294 measurements (see below for details). Hence, we performed a model calibration exercise using  
295 data collected specifically for rubber plantations.

296

#### 297 *Observational data for model calibration*

298 We briefly outline all of the measured data that we used for parametrization and  
299 calibrating the CLM-rubber in the Harapan landscape. Except for fine root biomass, all other  
300 data, which consist of carbon pools and net primary productivity in above- and below ground  
301 tree biomass at our plots are adapted from Kotowska et al. (2015). We used measurements of  
302 fine root biomass from Kurniawan et al. (2018) because it was measured down to a depth of 100



303 cm. This data-set is not from a different site and was measured across all eight rubber plots. The  
304 overall measurement campaign for the rubber inventory data spanned from August 2012 to  
305 March 2014. Leaf litterfall of data were collected using 16 litter traps (placed in a random grid)  
306 at each of the eight plots (see Kotowska et al., 2016 for details). Litter was collected at monthly  
307 intervals from March 2013 to April 2014.

308 Soil respiration was measured using vented static chamber, to which four permanent  
309 chamber bases were placed randomly at each of the eight plots. Concurrent to soil respiration  
310 measurement, soil moisture was measured by the gravimetric method using four samples taken  
311 near to the chambers within a depth of 5 cm. Both soil respiration and moisture content were  
312 measured monthly at all plots from December 2012 to December 2013 (Hassler et al., 2015).

313 Rubber tree water use ('transpiration') was measured using two commonly applied sap  
314 flux techniques, the thermal dissipation probe (TDP) method (Granier, 1985) and the heat field  
315 deformation (HFD) method (Nadezhdina et al., 2012). Two TDPs per tree yielded averages of  
316 sap flux density in the outer xylem (0-2.5 cm) for each sample tree. The HFD method, with  
317 multiple measurement points from 0-8 cm into the xylem, yielded typical radial sap flux profiles  
318 for rubber trees and thus allowed the calculation of cross-sectional water conductive areas.  
319 Combining the output of the two methods allowed us to calculate water use rates of the six  
320 sample trees per plot, which was further extrapolated to stand transpiration (using the tree  
321 density and diameter distribution from Kotowska et al., (2015)) (Niu et al., 2017).

322

### 323 *Model calibration steps & resource limitations*

324 During the initial model – measurement comparison, we noted several discrepancies  
325 between the model and measurements. Compared to the modeled values, the measured  
326 transpiration and leaf area index were substantially lower while soil respiration was higher. To  
327 minimize the mismatch between the model and measurements, we decided to calibrate the  
328 model. Due to the long computing time required to run the CLM model (from 1998 to 2014), in  
329 this study, we used a simple calibration method (Fan et al., 2015; Rahul et al., 2014) as opposed  
330 to more complex methods such as Monte Carlo Markov Chain approaches (Ali et al., 2016).

331 Our initial model calibration step involved obtaining a “realistic” seasonal dynamics of  
332 leaf area index. Although we did not have the seasonal data on leaf area index, our educated  
333 guess (as well as through “pers. comm.”) indicates that the seasonal dynamics of leaf area index



334 would be relatively “smooth” with a depth of the dip not so large in the dry season, that is, it will  
335 have something like a “brevi-deciduous” phenology. We do not expect the leaf area index in the  
336 dry season to decrease suddenly with a strong intense as observed in rubber plantations from  
337 other sub-tropical regions (see Fig.2; Giambelluca et al., 2016). We increased the critical value  
338 of the soil water potential (from -2 MPa to -0.5 MPa) to trigger leaf shedding in the model. In  
339 this case, the seasonal dynamics of the modeled leaf area index resulted in a sudden decrease in  
340 leaf area index with a narrow depth of the dip – a seasonal trend of leaf area index that we do not  
341 expect at our study sites.

342 In CLM4.5, soil water influences stomatal conductance directly by multiplying the  
343 minimum conductance by a soil water stress function  $\beta_t$  and also indirectly through net  
344 photosynthesis (Oleson et al., 2013). The latter effect is achieved by multiplying the maximum  
345 carboxylation rate ( $V_{cmax}$ ) and dark respiration ( $R_d$ ) by  $\beta_t$ . The function  $\beta_t$  ranges from one  
346 when the soil is wet to near zero when the soil is dry and depends on the soil water potential of  
347 each soil layer, the root distribution of the plant functional type, and a plant-dependent response  
348 to soil water stress

$$349 \quad \beta_t = \sum_i w_i r_i \quad (10)$$

350 where  $w_i$  is a plant wilting factor for layer  $i$  and  $r_i$  is the fraction of roots in layer  $i$ . The plant  
351 wilting factor  $w_i$  is

$$352 \quad w_i = \begin{cases} \frac{\varphi_c - \varphi_i}{\varphi_c - \varphi_o} \left( \frac{\theta_{sat,i} - \theta_{ice,i}}{\theta_{sat,i}} \right) \leq 1, T_i > T_f - 2 \text{ and } \theta_{liq,i} > 0 \\ 0, T_i \leq T_f - 2 \text{ or } \theta_{liq,i} \leq 0 \end{cases} \quad (11)$$

353 where  $\varphi_i$  is the soil water matric potential (mm) and  $\varphi_c$  and  $\varphi_o$  are the soil water potential (mm)  
354 when stomata are fully closed or fully open (respectively). The term in brackets scales  $w_i$  by the  
355 ratio of the effective porosity (accounting for the ice fraction;  $\theta_{sat} - \theta_{ice}$ ) relative to the total  
356 porosity.

357 To induce stomatal closure via soil water in CLM-rubber, we increased the sensitivity of  
358 stomata to soil water stress (Verhoef and Egea, 2014) by modifying the default soil water  
359 potential for drought deciduous tropical PFT in the model for stomatal opening "smpso = -17500  
360 mm" to "smpso = -8750 mm" and stomatal closing "smpsc = -112000 mm" to "smpsc = -56000  
361 mm". These changes are equivalent to modifying stomatal opening from -0.34 MPa to -0.17 MPa  
362 and full closure from -2.19 MPa to -1.09 MPa. The above two changes are within the range of  
363 plausibility, if we consider rubber trees to be sensitive to drought. The values of soil water



364 potential for stomatal opening and full closure in CLM depend on plant functional type. The  
365 default values for stomatal opening of PFTs range from -0.35 to -0.83 MPa while for full closure  
366 Oleson et al. (2013) quote values ranging between -2.24 and -4.28 MPa. These stomatal opening  
367 and full closure values in CLM are known to vary a lot by species and are based on White et al.  
368 (2000).

369 Rubber plantations at our sites are known to have low soil nitrogen availability and are  
370 not fertilized. In particular, the rubber plantations have low gross nitrogen mineralization rate,  
371 microbial nitrogen and mineral nitrogen (Allen et al., 2015; Hassler et al., 2015) and therefore,  
372 growth and productivity of our rubber plantations could be limited by nitrogen and possibly by  
373 other nutrients e.g. low phosphorus and base saturation (Allen et al., 2016). These were  
374 attributed to the fact that our studied plantations were on highly weathered acrisol soils (which  
375 have inherently low levels of extractable phosphorus and exchangeable base cations) and were  
376 not fertilized for two to five years prior to the start of our field measurements in 2012 (Allen et  
377 al., 2015; Hassler et al., 2015; Kurniawan et al., 2018). In an attempt to capture the magnitude of  
378 the relatively low leaf area index and low transpiration, we made the following change based on  
379 the idea that if nutrients are limiting in the soil, then in real ecosystems roots will have to pay a  
380 cost. In this version of the model, we assume that maintenance respiration of fine roots is high to  
381 pay for nitrogen uptake, so the base rate of maintenance respiration was increased by 50% for the  
382 fine roots in line with Doughty et al. (2018). In CLM4.5, the base rate of maintenance respiration  
383 per unit nitrogen content is fixed for all tissues (leaf, livestem, livecroot and fineroot) and is  
384 defined as  $MR_{\text{base}} = 2.525 \text{ e}^{-6} \text{ gC gN}^{-1} \text{ s}^{-1}$ . For CLM-rubber, we set  $MR_{\text{base}}$  to  
385  $3.7875 \text{ e}^{-6} \text{ gC gN}^{-1} \text{ s}^{-1}$  when we calculate the maintenance respiration for fineroots. This  
386 change to represent local nutrient limitation made the model predict a relatively high soil  
387 respiration rate (sum of autotrophic and heterotrophic respiration), thus reducing net primary  
388 productivity and lowering leaf area index.

389 Preliminary calibration results showed that the modeled soil respiration still  
390 underestimated the measured soil respiration by approximately 25%. To improve this, we  
391 increased the growth respiration of fine roots, which is currently fixed and set as 0.3 for tropical  
392 deciduous PFTs in CLM4.5 by a factor of 3 for CLM-rubber. This is a relatively large change.  
393 There is one reason to support this increase on growth respiration of fine roots. On average, these  
394 rubber plantations lose 20% of the original organic carbon in the soil after 4 years from forest



395 conversion (van Straaten et al., 2015), yet soil respiration was comparable to that of the reference  
396 forest (Hassler et al., 2015). These findings suggest that the proportion of heterotrophic  
397 respiration would be lower than the contribution of autotrophic respiration to the soil respiration.  
398 The decreases in available nitrogen, extractable phosphorus and base saturation (Allen et al.,  
399 2016; Allen et al., 2015) suggest that there may be strong competition for phosphorus such that  
400 trees have to allocate more carbon for their root growth and root–mycorrhizal system to obtain  
401 these nutrients (Fisher et al., 2016; Shi et al., 2016).

402 In the model – measurement comparison for soil organic carbon, CLM-rubber initially  
403 predicted only 9% decline in soil carbon for rubber plantation since clear-cut; however, a study  
404 by van Straaten et al. (2015), who conducted soil carbon measurements on heavily weathered  
405 soils for rubber plantations in Jambi and showed that on average, rubber plantations have 20%  
406 lower soil carbon stocks than forests. To increase the modeled decline in soil carbon, we  
407 increased the value of Q10 (“the increase of soil respiration per 10°C increase in temperature”)  
408 of soil temperature, from 1.5 to 3, on the grounds that rubber plantations at our study sites are  
409 0.5°C hotter than forests (Meijide et al., 2018).

410

#### 411 *Model validation in the Bukit Duabelas landscape*

412 Using the soil texture measurements from the Bukit Duabelas landscape (Allen et al.,  
413 2015), a model spin-up was performed till year 2002. The spin-up for the model validation was  
414 carried out in the same way as the spin-up for the model calibration. Then a clear-cut was  
415 introduced in 2003. Using climate data from 2013 (Meijide et al., 2018), we performed a  
416 simulation from year 2003 till 2014 by recycling the climate data every year. We used the same  
417 rubber PFT parameterization as obtained for the Harapan landscape except the tap\_npp  
418 parameter. The latter was adjusted because (1) the proportion of measured latex yield relative to  
419 measured NPP in the Bukit Duabelas landscape is 10% higher than that in the Harapan landscape  
420 (Kotowska et al., 2015), and (2) the amount of measured latex yield was also higher in the Bukit  
421 Duabelas landscape than the Harapan landscape (Kotowska et al., 2015), although it was not  
422 statistically different. To save space, we include figures for the model calibration in the main  
423 manuscript and put figures for the model validation in the supplementary section.

424

#### 425 *Hypothesis testing*



426           Understanding tropical droughts is important because it affects the growth and mortality  
427 of trees (e.g. Bretfeld et al., 2018; Moser et al., 2014; Phillips et al., 2010). Sometimes drought  
428 can be really hard on forests, where too much heat, low humidity and not enough water can  
429 drastically alter which trees survive (Lewis et al., 2011; Rowland et al., 2015). In the future,  
430 drought is projected to increase (Jiménez-Muñoz et al., 2016; Neelin et al., 2006); however, our  
431 ability to predict how future dry conditions would impact rubber tree productivity and yield is  
432 limited. Therefore, we used CLM-rubber to investigate the impacts of future drought on rubber  
433 yield. We expected drought to reduce the productivity of rubber trees in addition to the latex  
434 yield. We focused on five low rainfall scenarios; two simulations assumed low rainfall to occur  
435 throughout the year and so these simulations had 20%, 50% lower precipitation than the default  
436 precipitation; the other two simulations assumed low rainfall to occur with the extended dry  
437 season and so precipitation from April to October was reduced by 30%, 50%, in these  
438 simulations; and the final simulation considered shorter dry season but with intense drought so in  
439 this simulation precipitation from 8<sup>th</sup> May to 12<sup>th</sup> September was reduced by 50%. We then  
440 performed six simulations of 10-year period from 2015 to 2024; first using the present-day  
441 climate data, and then for the other five simulations, we used the climate data that imposed  
442 drying.

443

444 *Leaf life span and specific leaf area*

445           In the current version of the CLM-rubber, specific leaf area (SLA) is fixed; which is the  
446 case for many land surface models. It has been suggested that SLA could decline with leaf age  
447 e.g. due to leaf economics. We do not have temporal data on SLA for rubber. Because we  
448 developed a rubber model where we included the temporal changes in leaf life span for better  
449 model fit to the leaf litterfall data, we decided to investigate the effect of a dynamic SLA on the  
450 modeled photosynthesis of the rubber at the leaf-level. In CLM4.5 as well as in CLM-rubber,  
451 SLA is referred to as “slatop” – the SLA at the top of the canopy. To have a dynamic SLA, we  
452 let SLA to be low when the leaf life span is relatively high and SLA to be high when leaf life  
453 span is relatively low. The leaf life span is high in the wet than the dry season. We used a  
454 calendar month-dependent function to model the dynamics of slatop:

$$455 \quad \text{slatop} = \begin{cases} 0.0197, & \text{month} \leq 5 \\ 0.024, & 6 \leq \text{month} \leq 9 \\ 0.0197, & \text{month} > 9 \end{cases} \quad (12)$$





456 In Eq. 12, slatop is low in the wet than the dry season, where we reduced slatop by 18% in the  
457 wet season.

458

#### 459 *Comparison with other models and locations*

460 We do not have a flux-net tower in the rubber plantations in Jambi, Indonesia. However,  
461 the CLM-rubber model has been calibrated to carbon and water flux related variables for rubber  
462 plantations at Jambi, Indonesia. Therefore, we think that the modeled estimates of carbon and  
463 water fluxes of CLM-rubber at Jambi, Indonesia can be considered as a “proxy” of measured  
464 fluxes of rubber plantation in Jambi, Indonesia. Thus, we have an opportunity now to compare  
465 modeled estimates of carbon and water fluxes of CLM-rubber in Jambi, Indonesia with  
466 measurements of fluxes from two rubber plantations at other locations in the Southeast Asia  
467 (Giambelluca et al., 2016). To check the robustness of the CLM-rubber in prediction of the water  
468 fluxes, we compared its modeled water fluxes with the predicted values from a soil water model  
469 (Kurniawan et al., 2018), that is parameterized with the site-specific soil physical and  
470 hydrological parameters from our studied plots. Finally, to identify the relative ranking of the  
471 above-ground carbon stock of rubber plantations, we compared the measured and modeled  
472 estimates of carbon from our site in Jambi province, Indonesia with measurements from China,  
473 Africa and Brazil (Kotowska et al., 2015; Wauters et al., 2008; Yang et al., 2016).

474

## 475 **Results**

### 476 *Dynamics of carbon use*

477 CLM-rubber was able to simulate the dynamics of net primary productivity (Figure 2; a),  
478 above-ground biomass (Figure 2; b) and total soil organic carbon (Figure 2; c) of the rubber  
479 plantation in the Harapan landscape. The modeled biomass of fine roots and the annual latex  
480 yield were also within the measured range (Figure 3; a, b). When validated in the Bukit Duabelas  
481 landscape, the modeled net primary productivity (Figure S2; a) and above ground biomass  
482 (Figure S2; b) were quite close to the measurements. The modeled biomass of the fine roots and  
483 the annual latex yield were much closer to the measurements in the model validation case  
484 (Figure S3; a, b) than the model calibration case (Figure 3; a, b).



485 Despite the large variability across plots for the measured values, CLM-rubber captured  
486 the seasonal dynamics of the leaf litterfall (Figure 4a) far better than the seasonal trends of soil  
487 respiration (Figure 4b) and soil moisture (Figure 4c) in the Harapan landscape. For leaf area  
488 index, the measured values in 2018 were below our simulated values for 2014 (Figure 4d); there  
489 may be also an inter-annual variability of leaf area index, aside from seasonal variability, since  
490 for the leaf litterfall to be captured well by the CLM-rubber the LAI must be predicted  
491 reasonably well for 2014. The modeled seasonal patterns of carbon and water dynamics at the  
492 Bukit Duabelas landscape (Figure S4) were similar with those at the Harapan landscape.

493

#### 494 *Dynamics of water use*

495 The calibrated model in the Harapan landscape was close to the pattern and magnitude of  
496 the measured diel transpiration in a dry (Figure 5; a) and wet month (Figure 5; b). The modeled  
497 and measured diel courses of transpiration were characterized by relatively low hourly maxima  
498 ( $< 0.25 \text{ mm h}^{-1}$ ; Figure 5). The model had an early onset as well as an early offset of  
499 transpiration than the measurements (Figure 5; a, b). This is consistent with the diurnal effects  
500 that nitrogen limitation is known to have in CLM4.5 (see Fig.1; Ghimire et al., 2016). The model  
501 successfully predicted the average transpiration of a 2-year and 5-year old rubber plantations  
502 (Figure 6; a, b).

503 The validated results in the Bukit Duabelas landscape showed that the diel trends of  
504 predicted and measured transpiration were quite similar (Figure S5; a-c) to those in the Harapan  
505 landscape. The model captured the long-term seasonal trends of transpiration well (Figure S6),  
506 except for a minor discrepancy for a few weeks in June, where there was some period of partial  
507 leaf shedding. The magnitude of the modeled transpiration was also quite close to the  
508 measurements (Figure S6).

509

#### 510 *Leaf life span and specific leaf area*

511 Since in the CLM-rubber the trees have a drought-deciduous leaf phenology, we  
512 investigated the effect of fixed versus dynamic specific leaf area (Figure 7; a, b) and found that  
513 the mass-based photosynthesis of rubber leaves had a stronger dependence on leaf life span when  
514 the specific leaf area is dynamic (a higher  $r^2$  value; Figure 7; b) rather than fixed. Interestingly,



515 the model predicted that a higher mass-based photosynthesis of the rubber leaf can be associated  
516 with a lower leaf life span - this is a proposition that cannot be drawn if the specific leaf area is  
517 fixed (i.e. Figure 7; a). This finding suggests that long-lived rubber leaves could have a low  
518 mass-based photosynthesis, and that rubber plants could spend carbon in the construction of  
519 other tissues such as those associated with protection against insects or prevention of leaf  
520 diseases.

521

### 522 *Model Projection*

523 CLM-rubber predicted reduced yield in response to different drought scenarios as the  
524 intensity of drought increased (Figure 8). Modeled yield tended to have a non-linear relationship  
525 with soil moisture. CLM-rubber predicted up to a 18% reduction in yield when the intensity and  
526 duration of drought was largest (Figure 8). Currently, we do not have field data to confirm the  
527 magnitude of the effect of drought on yield, predicted by the model.

528

### 529 *Comparison with other sites and models*

530 CLM-rubber predicted a lower carbon uptake in the wettest month for Jambi, Indonesia  
531 compared to measurements of a similar plantation from Thailand (Table 1). The model also  
532 predicted a lower carbon release in the driest month for Jambi than a similar plantation from  
533 Thailand (Table 1). It should be pointed out that the rubber plantations in Jambi were unfertilized  
534 in the recent years and are on highly weathered Acrisol soils with low fertility while the rubber  
535 plantation in Thailand are highly fertilized. The CLM-rubber carbon fluxes suggest that rubber  
536 plantations from our sites are unlikely to have high carbon uptake or releases at the ecosystem  
537 scale compared to rubber plantations from other parts of Asia because the rubber plantations  
538 from our sites are not fertilized and have low leaf area index. At the ecosystem scale, CLM-  
539 rubber predicted a lower annual evapotranspiration and higher sensible heat fluxes from our sites  
540 than a similar plantation from Thailand (Table 1). These results indicate that rubber plantations  
541 from our sites are likely to have a high canopy openness than rubber plantations from other parts  
542 of Asia.

543 The comparison of water fluxes of CLM-rubber with a site-parameterized soil water  
544 model showed that CLM-rubber can predict the water fluxes reasonably well (Table 2). When  
545 comparing the carbon stocks of Jambi, Indonesia with other tropical countries, we found that the



546 above-ground biomass of rubber plantations was mostly similar except for a plantation from  
547 Africa (Table 3).

548

## 549 **Discussion**

### 550 *Phenology and Carbon & Nitrogen Allocation*

551 The seasonality observed in the empirical leaf litterfall data represented a challenge for  
552 the development of the CLM-rubber. During CLM-rubber development, we realized that the  
553 version of CLM-rubber that did not consider the temporal changes in leaf life span (that had  
554 fixed leaf life span as 1 year) failed to capture the seasonality of leaf litterfall. We have  
555 demonstrated in this study the importance of temporal changes in leaf life span. Seasonal data on  
556 leaf life span and leaf area index for rubber trees will be invaluable to capture well the carbon  
557 cycle of CLM-rubber. Similar data sets for tropical deciduous trees should be collected, which  
558 currently are rare (Dahlin et al., 2017). Our study suggests that land surface models should not  
559 use fixed leaf life span for simulating carbon dynamics of tropical deciduous PFTs if the focus of  
560 the study is examining seasonal pattern.

561 Radiation intensity has been suggested to play an important role in the onset of rubber  
562 leaves for the sub-tropics (Hoong-Yeet, 2007). At this stage, we did not integrate radiation  
563 intensity to trigger the onset of rubber leaves in the CLM-rubber because we do not have  
564 sufficient phenology data. Currently, the trigger for leaf onset in CLM-rubber is based on soil  
565 water potential. The carbon cycle of CLM-rubber can therefore be further improved by  
566 examining possible controls on leaf shedding and flushing in rubber and their interactions, e.g.  
567 soil water potential and radiation intensity.

568 The seemingly higher latex yield of rubber plantation in the Bukit Duabelas landscape  
569 compared to the Harapan landscape (despite being five years younger than Harapan) could be  
570 due to differences in management practices between the two landscapes (e.g. tapping frequency,  
571 planting density; Kotowska et al., 2015) and/or differences in soil texture, which influences  
572 differences in fertility (Allen et al., 2016; Allen et al., 2015; Kurniawan et al., 2018). The change  
573 in Q10 value of soil temperature enabled CLM-rubber to predict a 16% decline in soil carbon  
574 since clear-cut – a finding that is similar to a study by van Straaten et al. (2015). Indeed, in a



575 recent study, Meyer et al. (2018) have shown that Q10 has a lot of variability across PFTs,  
576 ranging from 1.25 to 2.75.

577

#### 578 *Low transpiration rates*

579 The inclusion of increased sensitivity of stomata to soil water stress and the enhancement  
580 of growth and maintenance respiration of fine roots in response to soil nutrient limitation enabled  
581 CLM-rubber to capture the magnitude of transpiration and leaf area index; however, the model  
582 had an earlier onset of diel transpiration (Figure 5; a, b) as well as an earlier offset of  
583 transpiration (Figure 5; a, b) than the measurements. The early onset of modeled transpiration  
584 around 8 am can be explained by the relatively high radiation (Figure S7; a) while the early  
585 offset of modeled transpiration around 6 pm (Figure 5; a) can be related to the absence of the  
586 stem water storage term in the model. The sap flow measurements could also have uncertainties  
587 due to their set-up. The sensors were inserted in the tree trunk at about 2 m height. Above this  
588 height, there could be considerable water storage in the plant. Early in the morning, transpiration  
589 may make use of this water storage – as indicated by the modeled transpiration. In the evening,  
590 the plant water storage above the sap flow sensors may be refilled, and thus water flow at the  
591 trunk is measured. Another source of error in the measurements of transpiration can be related to  
592 the fact that there were only 5 sap flow sensors, which were then used to upscale transpiration to  
593 the canopy-level.

594 CLM-rubber showed that rubber plantations can exhibit two peaks of leaf photosynthesis  
595 during a day (Figure S8; a), which could be due to the existence of optimal climatic conditions  
596 operating at multiple times within a day (Figure S7; a-c). Although absorbed PAR remained  
597 relatively high around noon time (Figure S8; b), the modeled leaf photosynthesis declined due to  
598 limitations in soil water and stomatal conductance (Figure S8; a). The model simulated the long-  
599 term dynamics of transpiration close to measurements (Niu et al., 2017). Our results are not  
600 consistent with reports speculating that rubber trees could be large carbon sinks (Kumagai et al.,  
601 2013) and behave as ‘water pumps’ (Tan et al., 2011; Ziegler et al., 2012).

602 Other factors such as carbon economy, plant health and soil degradation (Sitorus and  
603 Pravitasari, 2017) could also constrain the productivity and water use of rubber at our studied  
604 sites. CLM-rubber clearly provides additional opportunities to test hypotheses of the effects of



605 climate scenarios, management practices to alleviate nutrient limitations or their combinations on  
606 carbon economy of rubber plantations.

607

#### 608 *Dynamic traits & uncertainties in leaf area index*

609 From this CLM-rubber development, we can derive suggestions for improving current  
610 land surface models. While the carbon, water and nutrient cycles in land surface models have  
611 improved considerably, the development of trees from seedlings to mature growth phases is less  
612 well represented (Fisher et al., 2018). Our model clearly demonstrates that some of the basic  
613 plant functional traits, e.g. leaf life span, even specific leaf area that are currently considered  
614 fixed parameters in land surface models, need a dynamic seasonal component (Girardin et al.,  
615 2016; Lopes et al., 2016; Wu et al., 2016). This may further apply for longer-term dynamics, e.g.  
616 with regards to different growth phases. Follow-up research is needed to align seasonal and  
617 growth phase-related plant traits, e.g. leaf life span, fruiting of rubber trees, and leaf area index.

618 From a theoretical point of view, very young and old leaves are unlikely to have a mass-  
619 based photosynthetic rate as high as that of fully expanded mature leaves. Broadly, this finding  
620 has some support from tropical studies (Albert et al., 2018) but needs to be evaluated for rubber.

621 The fact that CLM-rubber did not capture the magnitude of the measured leaf area index  
622 in 2018 (measured with a LAI 2000 measurements, LiCor Biosciences Inc.) can be due to large  
623 variability in climatic factors, such as flux density of photosynthetically active radiation as well  
624 as the time of measurement (Cotter et al., 2017). We also obtained leaf area index for year 2014  
625 from MODIS satellite on clear sky days for the studied rubber plantations. The MODIS leaf area  
626 index was as high as  $4 \text{ m}^2 \text{ m}^{-2}$ , which is similar to the predictions of CLM-rubber.

627

#### 628 *Opportunities for CLM-rubber*

629 As CLM-rubber predicted reasonably well the carbon and water use, we think that the  
630 current model can be used for larger-scale simulations within Indonesia, in particular, the  
631 lowland areas with mineral soils of Jambi province by incorporating in the prediction soil texture  
632 as the surrogate variable for the control of soil fertility and soil moisture. CLM-rubber can aid in  
633 science-based management and policy recommendations, as the model can be applied to  
634 scenarios of soil management intensities, climate variations, and policy-driven land-use change



635 projections. CLM-rubber model can also be applied to rubber plantations in other regions in  
636 Southeast Asia but it will require validation against measured carbon, water and energy flux data  
637 from the Asia flux community (Giambelluca et al., 2016; Kumagai et al., 2013; Tan et al., 2011).

638 Plot-level simulations can potentially be performed for so called jungle rubber plantations  
639 (Feintrenie and Levang, 2009; Gouyon et al., 1993), where the rubber and the trees from the  
640 natural tropical forest coexist. Here, we can use the newly developed CLM-FATES model,  
641 which has a demographic component that considers processes such as height-structured  
642 vegetation and competition between individuals for light (Fisher et al., 2015). In Jambi province,  
643 jungle rubber represents a smallholder rubber agroforestry system, which is established by  
644 planting rubber trees into (often previously logged) rainforests. Similar measured data used in the  
645 current study exists for eight jungle rubber plots differing in soil texture, nutrient levels and  
646 water characteristics. The abundance of natural and rubber trees need to be incorporated in the  
647 model and then carbon and water cycles can be investigated.

648 Additional experimental data in the dry season on leaf aging and fruiting of rubber should  
649 be collected to investigate if rubber plants take advantage of the high light availability, while  
650 coping with high atmospheric water demand and low water supply. These empirical data can be  
651 an indicator of adaptive strategies of how rubber plants optimize reproduction and resource  
652 acquisition.

653

#### 654 **Final Remarks**

655 Incorporating a dynamic leaf life span enabled CLM-rubber to better capture the  
656 seasonality of leaf litterfall. Increased sensitivity of stomata to soil water stress and the  
657 enhancement of growth and maintenance respiration of fine roots in response to soil nutrient  
658 limitation enabled CLM-rubber to capture the magnitude of transpiration and leaf area index.  
659 Our results show that rubber plantations in Jambi are less likely to have similarly high carbon  
660 fluxes and water use compared to highly fertilized rubber plantations from other parts of South-  
661 east Asia such as those from Thailand and Cambodia.

662

663

664



665 **Code & Data Availability**

666 Code is available on GitHub ([https://github.com/ashehad/CLM4.5\\_rubber\\_v1/tree/master/codes](https://github.com/ashehad/CLM4.5_rubber_v1/tree/master/codes))  
667 and data used in this paper can be found in this repository  
668 ([https://github.com/ashehad/CLM4.5\\_rubber\\_v1/tree/master/data/measured\\_data\\_for\\_model\\_calibration](https://github.com/ashehad/CLM4.5_rubber_v1/tree/master/data/measured_data_for_model_calibration)).  
669  
670

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681  
682  
683

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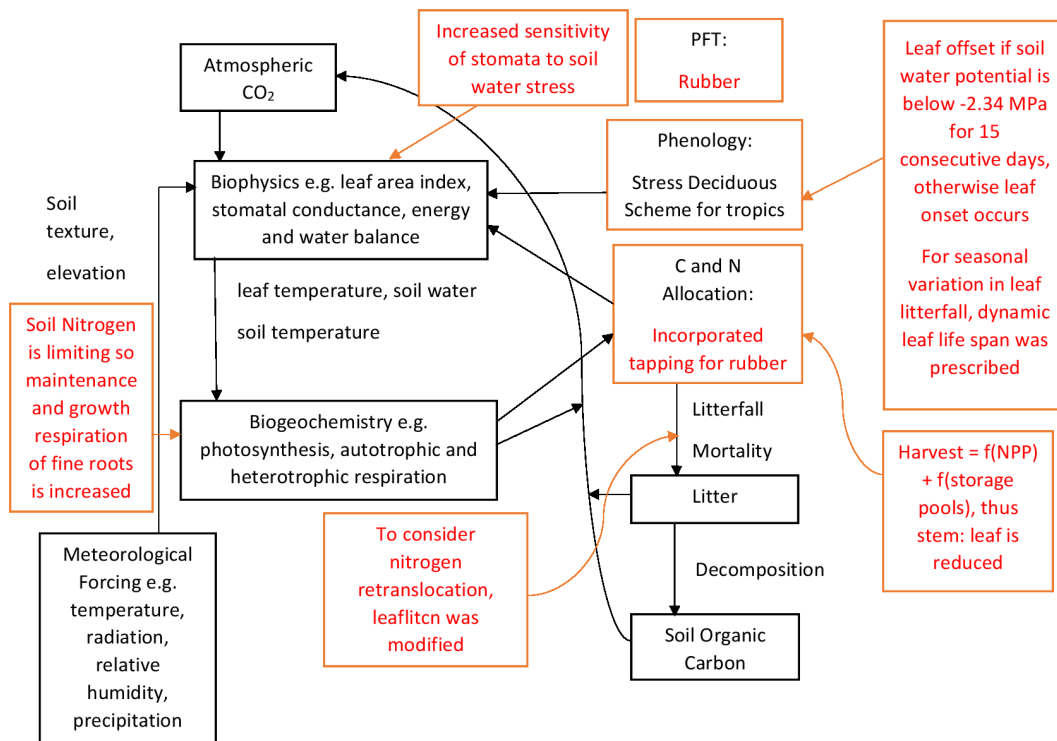




941 **Figures**

942 **Figure 1** Illustration of the original and modified structure and functions of CLM4.5 for  
 943 incorporating the rubber plant functional type (PFT). The original functions in CLM4.5 are  
 944 represented in black while the new rubber PFT in CLM4.5 are represented in red, which includes  
 945 changes to phenology, allocation of carbon and nitrogen, and harvest algorithm.

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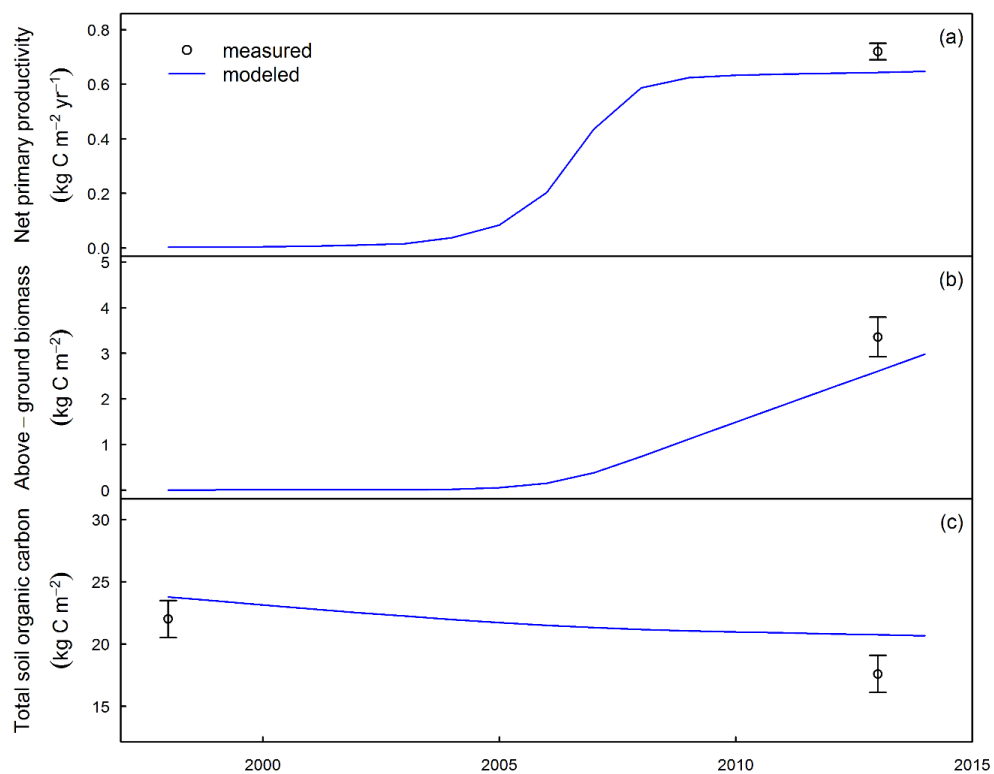
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950 **Figure 2** Temporal trends of annual net primary productivity (NPP;  $\text{kg C m}^{-2} \text{ yr}^{-1}$ ) annual above  
 951 ground biomass (AGB;  $\text{kg m}^{-2}$ ), and total soil organic carbon content up to 3 m (TSOC;  $\text{kg m}^{-2}$ )  
 952 of rubber, simulated by CLM-rubber following clear-cut in 2001 in the Harapan landscape.  
 953 Measured NPP, AGB and TSOC (lines are standard errors,  $n = 4$  plots) are indicated for 2014.



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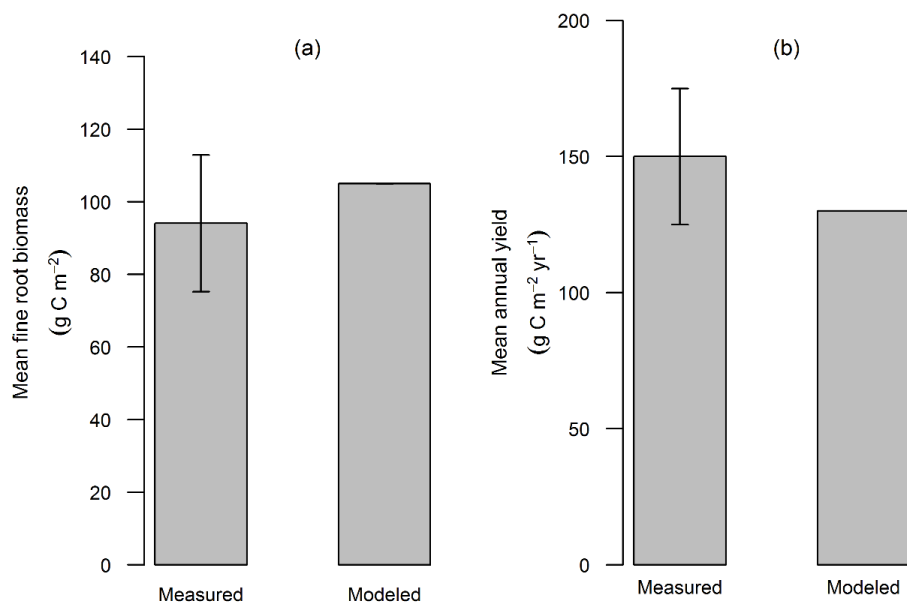
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958 **Figure 3** Measured (lines are standard error,  $n = 4$  plots) and CLM-simulated fine root biomass  
959 (a) and annual latex yield (b) of rubber plantation in 2013 in the Harapan landscape.

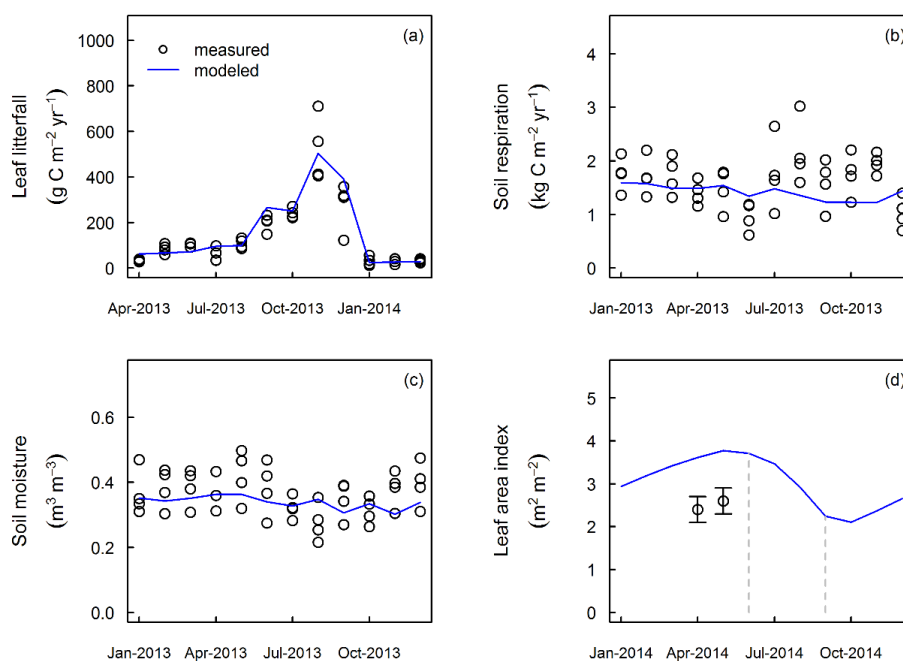


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962 **Figure 4** Monthly trends of leaf litter fall ((a);  $\text{g C m}^{-2} \text{ yr}^{-1}$ ),  
 963 soil respiration ((b);  $\text{kg C m}^{-2} \text{ yr}^{-1}$ ),  
 964 soil moisture up to 5 cm ((c);  $\text{m}^3 \text{ m}^{-3}$ ) and leaf area index ((d);  $\text{m}^2 \text{ m}^{-2}$ ) of rubber plants simulated  
 965 by CLM-rubber (blue line) and observed values (open circles) during the mature phase of growth  
 966 of rubber. The leaf area index (LAI) was measured in 2018. In April, LAI was measured in only  
 967 one plot whereas in May, LAI was measured across all four plots. The vertical line in April is the  
 968 standard error across the first plot while the vertical line in May is the standard error across all  
 four plots.



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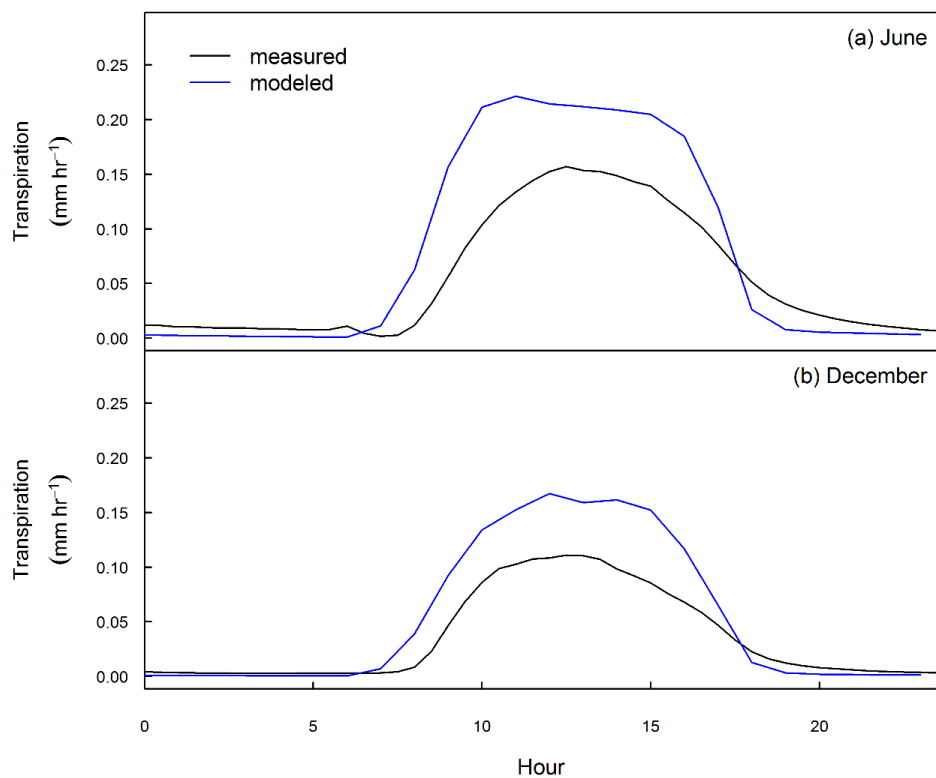
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974 **Figure 5** Measured and modeled diel transpiration ( $\text{mm hr}^{-1}$ ) of rubber averaged over June (dry  
975 month) and December (wet month) in the Harapan landscape in 2013.



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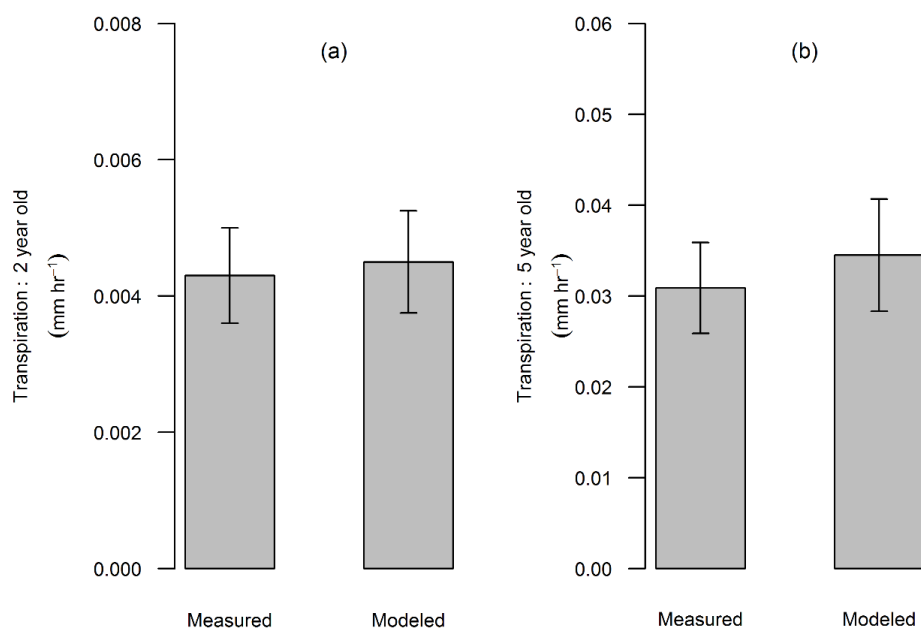
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981 **Figure 6** Measured and CLM-simulated transpiration of (a) a 2-year old rubber over December,  
982 2013 and (b) a 5-year old rubber over January, 2014 in the Harapan landscape. The bars and the  
983 lines are means and standard errors, respectively, over half-hourly data of each month.



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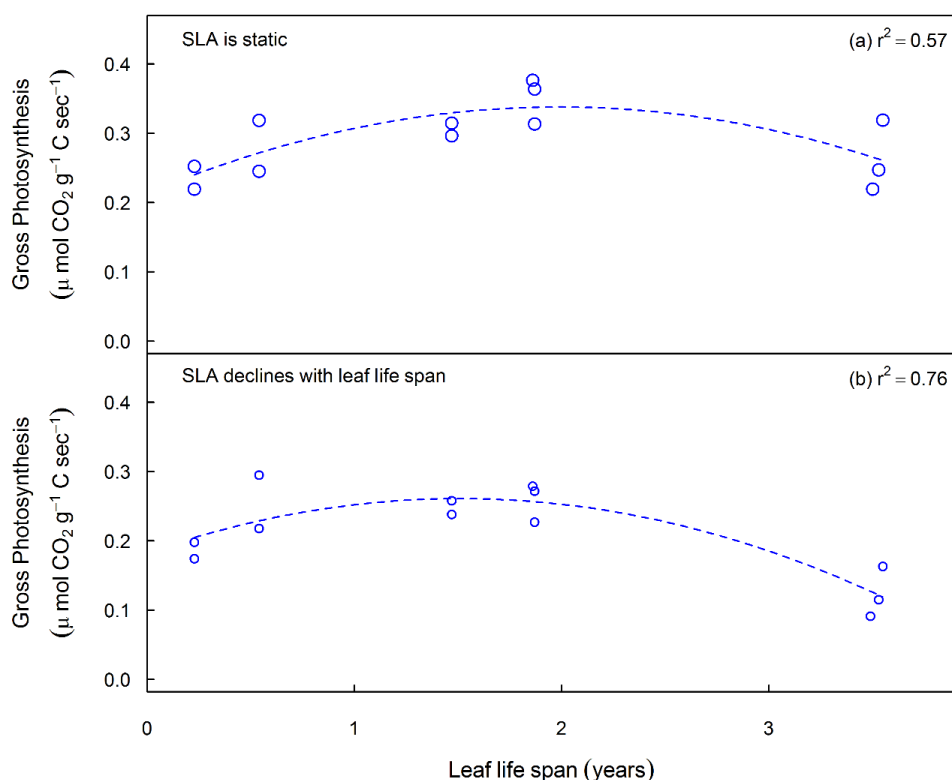
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988 **Figure 7** Effect of fixed specific leaf area (SLA) (a) versus dynamic SLA (b) on the CLM-  
989 simulated photosynthesis of rubber leaves, expressed on leaf mass basis, as a function of leaf life  
990 span. Each data point corresponds to the monthly value, which is an average of the peak  
991 photosynthesis between 10 am and 2 pm. The data points corresponding to the lowest leaf life  
992 span belong to the dry season while those at mean leaf life span correspond to the period before  
993 the leaf fall. The data points corresponding to the highest leaf life span correspond to the period  
994 after the leaf fall. The blue dashed line is the best fit with the goodness of fit indicated by the  $r^2$   
995 value.



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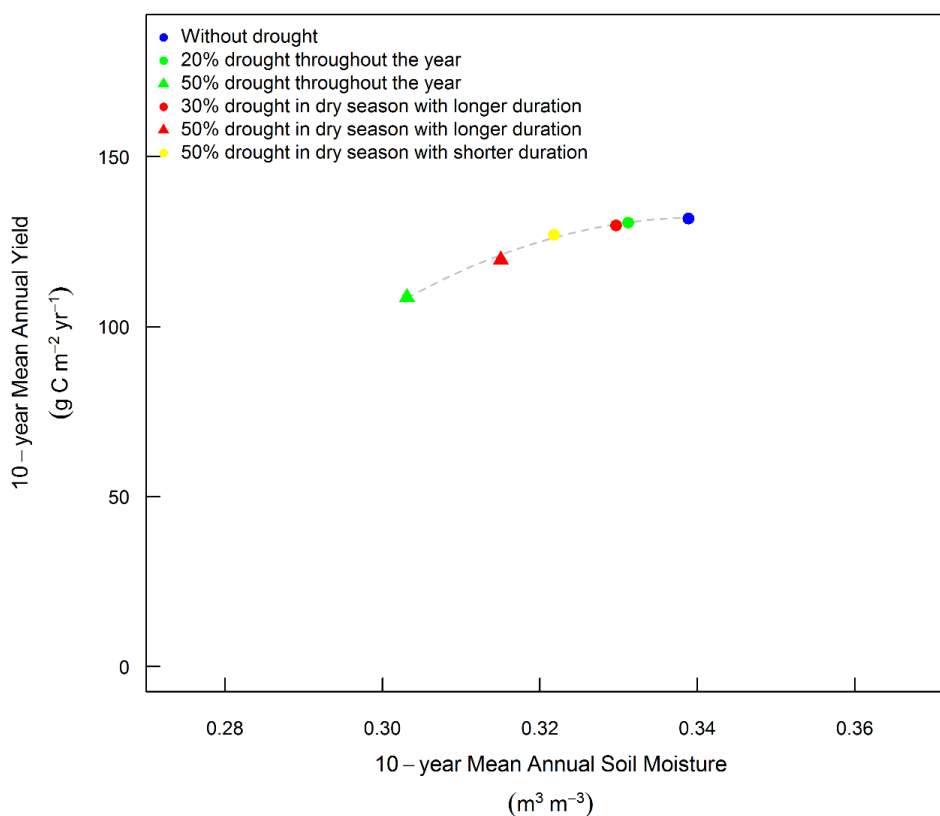
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1000 **Figure 8** Relationship of modeled mean annual latex yield and mean annual soil moisture for a  
 1001 rubber plantation over a 10-year period of simulated scenarios. The without drought simulation  
 1002 used the default climate conditions while there were five simulations that considered different  
 1003 types of drought; two simulations assumed drought to occur throughout the year and so these  
 1004 simulations had 20%, 50% lower precipitation than the default precipitation; the other two  
 1005 simulations assumed drought to occur with the extended dry season and so precipitation from  
 1006 April to October was reduced by 30%, 50%, in these simulations; and the final simulation  
 1007 considered shorter dry season but with intense drought so in this simulation precipitation from 8<sup>th</sup>  
 1008 May to 12<sup>th</sup> September was reduced by 50%.

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1012 **Tables**

1013 **Table 1** Summary of net ecosystem exchange (NEE = net CO<sub>2</sub> uptake), latent (LE) and sensible  
1014 (H) heat flux densities, and evapotranspiration (ET) estimates for rubber plantations across  
1015 Southeast Asia. The italicized values are estimates derived from the CLM-rubber model.  
1016 Negative values indicate a flux toward the land surface (= sink) while positive values indicate a  
1017 flux toward the atmosphere (= source). R<sub>net</sub> is net radiation.

1018

Location	Mean NEE of the wettest month (kg C m <sup>-2</sup> yr <sup>-1</sup> )	Mean NEE of the driest month (kg C m <sup>-2</sup> yr <sup>-1</sup> )	Mean Annual Rainfall (mm yr <sup>-1</sup> )	Mean Annual R <sub>net</sub> (W m <sup>-2</sup> )	Mean Annual ET (mm yr <sup>-1</sup> )	Mean Annual Latent Heat (W m <sup>-2</sup> )	Mean Annual Sensible Heat (W m <sup>-2</sup> )
Xiushuangbanna, China	NA	NA	1504	123.3	1125	87.4	NA
CRRI, Cambodia	NA	NA	1439	151	1459	112.5	NA
Som Sanuk, Thailand	-2.35	0.68	2145	129.5	1211	93.5	26.9
This study - Jambi, Indonesia	-0.25	0.09	2849	139.4	964	76.4	62.9

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1021 **Table 2** Comparison of water fluxes from CLM-rubber with a soil water model (Kurniawan et  
1022 al., 2018) that is parameterized with the site-specific characteristics of the rubber plantations in  
1023 the Harapan landscape.

1024

	CLM-rubber	Soil Water Model
Transpiration (mm yr <sup>-1</sup> )	625	594
Evapotranspiration (mm yr <sup>-1</sup> )	964	1077
(Runoff + drainage)/Precipitation (unitless)	0.66	0.68

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1026

1027 **Table 3** Comparison among above ground biomass (AGB) of rubber plantations in the tropics  
1028 with similar age.

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	AGB (kg C m <sup>-2</sup> )	Source
South-West China	3.92 ± 0.82	Yang et al. (2016)
Western Ghana, Africa	5.72 ± 0.96	Wauters et al. (2008)
Mato Grosso, Brazil	3.12 ± 0.72	Wauters et al. (2008)
Harapan Indonesia	3.36 ± 0.43	Kotowska et al. (2015)
CLM-rubber model for Harapan, Indonesia	2.98	This study

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