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1 **Influence of fire and drainage on evapotranspiration in a degraded peat swamp**
2 **forest in Central Kalimantan, Indonesia**

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13 **Keywords:** Groundwater level; Eddy covariance technique; Net radiation; Precipitation;

14 Vapor pressure deficit

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17 **1. Introduction**

18 Tropical peat swamp forests (PSFs) are widely distributed in Southeast Asia, especially
19 Indonesia, Malaysia, Brunei, and Thailand (Page et al., 2011). However, in the recent
20 decades, land conversion of forests mainly for agricultural use has been expanding.
21 Deforestation and drainage accompanied by land use change result in peat aridification,
22 which increase the risk of fire. Within 15.7 Mha of peatland in Peninsular Malaysia,
23 Sumatra and Borneo, PSF decreased from 11.9 Mha in 1990 to 4.6 Mha in 2015,
24 whereas managed land cover area (industrial plantations and small holder areas)
25 increased from 1.7 Mha in 1990 to 7.8 Mha in 2015 (Miettinen et al., 2016).
26 Nonetheless, large fires occurred repeatedly in this region. In 2015, the worst fire of the
27 last two decades spread over Indonesia. As a result, smoke-induced haze engulfed
28 insular Southeast Asia for a few months (Huijnen *et al.*, 2016; Ismanto et al., 2019).

29 Evapotranspiration (ET) plays a significant role in energy exchange and the water
30 cycle between the terrestrial ecosystem and the atmosphere. Especially in tropical
31 forests, ET has a significant impact on regional and global climate since ET is high
32 enough to mitigate global warming by evaporative cooling effect (Bonan, 2008).

33 There are several studies examine how environmental disturbances such as fire,
34 drainage, and deforestation affect ET. For example, in the tropical Amazon forest,

35 deforestation decreased ET due to reduced transpiration and rainfall interception and
36 subsequent evaporation (Baker and Spracklen, 2018). In the other study from the
37 Amazon forest, ET in logged or burned forest was generally smaller than that in the
38 intact forest because of lower leaf index, whereas the difference became smaller under
39 extremely dry conditions (Longo et al., 2020). In boreal peatland where feather moss
40 dominated, ET increased or decreased depending on peat burn severity (Kettridge et al.,
41 2017; Kettridge et al., 2019; Wilkinson et al., 2020). They explained that evaporation
42 from peat soil surface increased as the capping layer of feather moss disappeared by a
43 severe fire, whereas ET decreased by light burning which made soil surface became
44 water-repellent and restrict the supply of water to the peat surface.

45 Other than peatland site, some studies observed reduction of ET after a fire, and cited
46 loss of transpiration due to leaf burning as the reason (i.e., Beringer et al., 2003; Clark et
47 al., 2012; Montes-Helu et al., 2009; Whelan et al., 2015). A decline in net radiation (R_n)
48 is also cited as the reason for decreased ET. For example, Liu et al. (2005) explained
49 that forest canopies cleared by fire increased ground temperature and upward longwave
50 radiation, resulting in a decrease in R_n . Montes-Helu et al. (2009) explained that the
51 exposure of the soil surface and the increase in bright-colored coarse woody debris
52 (CWD) increased the albedo after a fire.

53 On the other hand, drainage significantly and directly impacts the water budget by
54 increasing the underground outflow. Mezbahuddin et al. (2015) reported that drainage
55 reduced ET due to drawdown of groundwater level (GWL) and soil drying using a
56 process-based model that relied on field data from tropical PSFs. They explained that
57 the reduced water uptake of shallow roots due to aridification cannot be compensated by
58 the water uptake of deep roots. Alternately, Moore et al. (2013) found that ET was
59 lowest at the driest site among three adjacent peatland sites. Especially in peatlands,
60 desiccation of soils due to lowering of GWL create aerobic conditions and accelerate the
61 decomposition of peat then increase the release of CO₂ into the atmosphere.

62 Although previous studies revealed the influence of such disturbances on ET, Hirano
63 et al. (2015) is the only one of its kind with continuous field observation in tropical
64 PSFs. They had been conducted observations for 4-6 years until 2009 in three tropical
65 PSFs with different degrees of disturbances in Central Kalimantan, Indonesia. They
66 revealed that almost intact forest had high annual ET comparing with those in other
67 upland tropical forests. A significant difference in annual ET was not found between in
68 almost intact and drained forests, although minimum-monthly-mean GWL had a
69 positive linear relationship with the ET. The result suggested that tree species in drained
70 forest acclimatized to a low GWL environment after more than 5 years after drainage. In

71 burnt ex-forest, ET was decreased due to vegetation loss.

72 Nonetheless, the response of ET to change in environmental factors (e.g., R_n , VPD,
73 GWL) in the vegetation regenerating process immediately after the fire is still unknown
74 since the observation had started several years after the fire and drainage. And the
75 response to precipitation (P), which is the only water-supplying element to the system,
76 was not cleared under excessively GWL-lowered conditions.

77 We continued the observation in the ex-PSF site in Hirano et al. (2015) through 2016,
78 with a brief suspension by fire in 2009. During the continued observation period, the
79 study site experienced fires and drainage. In particular, the fire burned CWD mostly in
80 2009 then succeeding vegetation regenerated immediately in subsequent La Niña years
81 (Ohkubo et al., 2021b). Thus, the site turned to be carbon sink from CO₂ source. These
82 two disturbances are expected to have a lingering effect and to manifest at different time
83 scales. In other words, vegetation regeneration is long-term while GWL fluctuations
84 occur on a shorter time scale. Therefore, we need continuous and long-term observation
85 for examining the effect of the disturbances. Moreover, the continuous long-term
86 observation with a variety of environmental conditions enables us to reveal ET variation
87 through fire and drainage disturbances and to examine characteristics of ET response to
88 environmental changes with accumulated data.

89 Here, we have an unprecedented long-term dataset through fire and drainage events
90 from 2004 to 2016. In this study, we estimated ET considering the contribution to
91 energy and water balance and explored the significant controlling factors of ET through
92 the fire and drainage disturbances. Then, the data was also used to answer the following
93 specific questions: (i) how changes in ET were influenced by meteorological factors in
94 the process of vegetation recovery from fire, and (ii) how do the sensitivity of ET to *P*
95 and GWL change after canal excavation.

96

97 **2. Materials and Methods**

98 **2.1 Site description**

99 The study site (2.34 ° S, 114.04 ° E) is located in tropical peatlands near Palangkaraya
100 City, Central Kalimantan, Indonesia (Fig. 1). The site was called DB - a drained burned
101 degraded PSF in our previous study (Hirano et al., 2015). The site was a tropical
102 degraded PSF until the fire in 1997. Since then, the site had been burned at least three
103 times in 2002, 2009, and 2014. The mean annual temperature and *P* measured at 1.5 m
104 height from 2005–2016 were 26.4 ± 0.3 °C and 2640 ± 473 mm (mean \pm 1 standard
105 deviation), respectively. The site experienced the dry season (monthly *P* < 100 mm),
106 usually from July to October. During the observation period from April 2004 to

107 December 2016, the study site experienced fires and canal excavation. In 2009, the
108 study site experienced moderate fire, and some aboveground herbaceous plants were
109 burned. In 2014, a less severe fire burned the study site again. In 2015, the surrounding
110 area experienced fire, although the study site was not affected. More detailed
111 information is described in Ohkubo et al. (2021b). In May–June 2014, a canal was
112 constructed in the vicinity of the site. To analyze the influence of the disturbances and
113 environmental changes, we divided the observation into three periods: Period I (May
114 2004–September 2009), Period II (December 2009–June 2014), and Period III (July
115 2014–October 2016) (Table 1). During Period I, CWD was present on the ground and
116 vegetation was slowly regenerating since the fire in 2002. Initially (April 2004), fern
117 (*Stenochlaena*, *Blechnum*, and *Lygodium* spp.) and sedge (*Cyperus*, *Scleria*, and
118 *Eleocharis* spp.) plants were sparsely distributed. In June 2005, peat soil was mostly
119 covered with 0.5 m high fern and sedge plants. A few young trees, comprised
120 predominantly of *Combretocarpus rotundatus*, reached a height of 0.8–0.9 m before the
121 fire in 2009. In September 2009, some of the trees died and a part of the above ground
122 herbaceous plants were burned by fire of moderate-severity. A large amount of CWD
123 was also burned out. During Period II, ferns and sedges covered the ground surface
124 immediately after the fire of 2009. Sparsely distributed young trees, predominantly

125 *Combretocarpus rotundatus*, grew up to 2-m high until 2013. Woody plants dominated
126 the latter phase of Period II. A water-logged condition lasted a long time following
127 abundant *P* during La Niña years (2010–2011). A small canal about 1.5-m deep and
128 1.5-m wide was excavated approximately 100 m away from the observation tower from
129 May–June 2014. In September 2014, the study site was burned again by fire of
130 low-severity. Herbaceous plants and some young trees were burned, whereas many trees
131 survived. In 2015, fire occurred in the surrounding area, but the study site was not
132 affected. Hence, during El Niño drought in 2014 and 2015, the site experienced severe
133 haze caused by the fires. Further information is described in earlier studies (Hirano et al.,
134 2014; Hirano et al., 2015; Itoh et al., 2017), and our accompanying papers on albedo
135 (Ohkubo et al., 2021a) and CO₂ flux (Ohkubo et al., 2021b).

136

137 **2.2 Measurements**

138 Observations were conducted from April 2004 to December 2016. Air temperature and
139 relative humidity at a height of 1.5 m were measured with a platinum resistance
140 thermometer and a capacitive hygrometer (HMP45; Vaisala, Helsinki, Finland) installed
141 in a non-ventilated radiation shield (DTR503A; Vaisala). *P* was measured with a
142 tipping-bucket rain gauge (TE525; Campbell Scientific Inc.) at a height of 1.5 m. R_n

143 was measured with a radiometer (CNR-1; Kipp & Zonen, Delft, the Netherlands). The
144 measurement height was raised following tree growth; height of 3.3 m (April 2004–May
145 2012), 6.8 m (May 2012–December 2013), and 13.6 m (December 2013–December
146 2016). Their 30-min averages were recorded using data loggers (CR1000 and CR10X;
147 Campbell Scientific Inc.). GWL was measured with a water level logger (DL/N; Sensor
148 Technik Sirmach AG, Sirmach, Switzerland or DCX-22 VG; Keller AG, Winterthur,
149 Switzerland) at an interval of every 30 min. GWL is the relative groundwater level from
150 the ground surface, and negative GWL means that water surface is below the ground
151 surface. Reference ground surface level was corrected since significant subsidence was
152 observed after fire in 2009. The soil heat flux (G) was not measured, and vapor pressure
153 deficit (VPD) was calculated from acquired air temperature and relative humidity data.
154 Eddy fluxes of sensible (H) and latent heat (λE) were measured with a sonic
155 anemometer-thermometer (CSAT3; Campbell Scientific Inc., Logan, UT, USA) and an
156 open-path CO₂/H₂O analyzer (LI7500; Li-Cor Inc., Lincoln Nebraska, USA) using the
157 eddy covariance technique. The measurement height was raised: height of 3.0 m (April
158 2004 to February 2011), 3.6 m (February 2011–March 2012), 7.2 m (March 2012–
159 December 2013), and 13.6 m (December 2013–December 2016). The two sensors were
160 separated by 0.2 m.

161 The monthly Δ GWL was calculated from the difference between the mean of GWLs
162 taken at half-hourly intervals of the last days of two adjacent months. The observation
163 system was suspended from September 20 to December 4, 2009, as the power cables
164 and sensors were severely damaged by fire. Eddy flux data of H and λE were available
165 up to November 5 and October 27, 2016, respectively, due to sensor malfunction.
166 Further information about instruments and data collection is described in Hirano et al.
167 (2015) and our accompanying paper on CO₂ flux (Ohkubo et al., 2021b).

168

169 **2.3 External data**

170 The enhanced vegetation index (EVI) in MODIS data (MOD13Q1 Version) was
171 downloaded from the “Land Processes Distributed Active Archive Center”
172 (<https://lpdaac.usgs.gov/products/mod13q1v006/>). The data were composited every 16
173 days at a spatial resolution of 250 m. Monthly Southern Oscillation Index (SOI) data
174 were collected from “National Oceanic and Atmospheric Administration”
175 (<https://www.ncdc.noaa.gov/teleconnections/enso/indicators/soi/>). SOI which is a
176 standardized index based on the observed sea level pressure differences between Tahiti
177 and Darwin, Australia, is an indicator of El Niño and La Niña episodes. In general,
178 prolonged periods of negative (or positive) SOI values coincide with El Niño (or La

179 Niña) episodes.

180

181 **2.4 Flux calculation**

182 H and λE were calculated using Flux Calculator software (Ueyama et al., 2012) with the
183 following procedures: (i) removal of spikes (Vickers and Mahrt, 1997), (ii) double
184 rotation for tilt correction, (iii) water vapor correction for virtual temperature, (iv)
185 correction for high frequency loss (Massman, 2000; Massman, 2001), and (v) correction
186 for air density fluctuations (Webb et al., 1980). Data with wind directions within $\pm 20^\circ$
187 from the north were excluded to avoid flow distortion by the tower. Data were also
188 removed when precipitation was detected. Data with $H \leq -200$, $H > 500$, $\lambda E \leq -100$, and
189 $\lambda E > 1000 \text{ W m}^{-2}$ were screened as outliers. A stationarity check was performed for each
190 30-min run (Foken and Wichura, 1996), and we calculated the difference between
191 covariance values for the entire 30 min and the average of six 5-min covariance values.
192 Data were excluded, in case the difference was more than 100%. To investigate the
193 development of the turbulence, integral turbulence characteristics (ITC) was calculated
194 every 30 min (Foken, 2017), then H and λE with $\text{ITC} > 250\%$ was excluded after
195 stationarity check. After these data quality controls, monthly data with high gap
196 fractions (e.g., more than 70% of half hourly data are missing) was removed from the

197 analysis. However, they are used to illustrate monthly variations and estimate annual
198 values.

199 Gaps in H and λE data were filled using the lookup table method. Look-up tables for
200 each H and λE were created for every three months considering climate conditions as
201 the previous study applied (Hirano et al., 2015), i.e., February–April, May–July,
202 August–October, November–January, using half-hourly R_n and VPD. First, the data
203 were binned equally into ten classes according to R_n . Second, the classified data in each
204 class were binned equally into three classes according to VPD. Finally, values in 30
205 classes were determined by averaging each binned data. Look-up tables of H and λE
206 from August to October 2016 were substituted for those of November–December 2016,
207 respectively, due to the lack of eddy flux data. The mean half hourly $(H+\lambda E)/R_n$ was
208 0.74 ± 0.06 (mean ± 1 standard deviation) on an annual basis (Table S1). To settle the
209 energy imbalance, after filling the gaps, $H+\lambda E$ was forced to balance with R_n on a daily
210 basis, maintaining a constant ratio of cumulative daily H and λE at this study site
211 (Twine et al., 2000). We used this adjusted λE for calculating ET in this study. Detailed
212 procedures are described by Hirano et al. (2015).

213

214 **2.5 Bulk parameters**

215 Physiological regulation of vegetation canopy (i.e., integrating stomatal regulation of
 216 individual leaf) or surface wetness for ET could be expressed by surface conductance
 217 (G_s). Decoupling between vegetation and the atmosphere for ET was evaluated by index
 218 Ω , where ET is controlled by stomatal regulation when $\Omega \approx 0$ and by available energy
 219 when $\Omega \approx 1$. We used $H + \lambda E$ instead of $R_n - G$ because G was not measured. Then, the
 220 bulk parameters of G_s and Ω were calculated following the method of Hirano et al.
 221 (2015) as:

$$222 \quad \frac{1}{G_s} = \frac{1}{G_a} \left[\frac{\varepsilon(H + \lambda E) + \rho C_p G_a \frac{VPD}{\gamma}}{\lambda E} - \varepsilon - 1 \right], \quad (1)$$

$$223 \quad G_a = \left[\frac{2}{k u_*} \left(\frac{dh}{dv} \right)^{\frac{2}{3}} + \frac{u}{u_*^2} \right]^{-1} \quad (2)$$

$$224 \quad \Omega = \frac{\varepsilon + 1}{\varepsilon + 1 + \frac{G_a}{G_s}} \quad (3)$$

225 where G_a is the bulk aerodynamic conductance (m s^{-1}), ε is the slope of the relationship
 226 between saturated vapor pressure and temperature, ρ is air density (kg m^{-3}), C_p is the
 227 specific heat of air at constant pressure ($=1007 \text{ J kg}^{-1} \text{ K}^{-1}$), γ is the psychrometric
 228 constant ($=0.067 \text{ kPa K}^{-1}$), k is the von Karman constant ($=0.4$), u_* is the friction
 229 velocity (m s^{-1}), dh/dv is the ratio of thermal diffusivity to molecular diffusivity of water
 230 vapor, and u is the wind speed (m s^{-1}). To avoid instability and divergence, we used
 231 midday ecosystem conductance (1000–1400 h) without rain data to calculate mean
 232 monthly values.

233

234 **2.6 Path analysis**

235 We conducted path analysis to explore the main controlling factors of monthly ET using
236 the R package *sem* version 3.1-11. P , R_n , VPD, GWL, and EVI were selected as
237 explanatory variables. Each path coefficient, i.e., the direct effect of each explanatory
238 variable was standardized. The total effect was determined by the sum of the direct and
239 indirect effects. The model structure was adjusted as goodness-of-fit index (GFI)
240 improved. Sun et al. (2018) described the criteria that the GFI of an adequate model is
241 greater than 0.9.

242

243 **3. Result**

244 **3.1 Overview of time-series variations**

245 We compared ET with environmental factors and energy fluxes in a time series (Fig. 2).
246 ET seemed to be stable regardless of P fluctuation, although it decreased with deep
247 GWL conditions ($GWL < -0.5$ m) (Fig. 2a, b). The mean annual ET was 1457 ± 152 mm
248 (mean ± 1 standard deviation) (Table 2). Until the canal excavation from May–June
249 2014, GWL generally deepened in the dry season and increased and reached the ground
250 surface level in the wet season. However, GWL never recovered to the ground surface

251 level after canal excavation despite much P in 2016. VPD showed seasonal variation
252 with high values in the dry season. The monthly average VPD exceeded 10 hPa during
253 the fires in 2004, 2009, 2014, and 2015 (Fig. 2c). λE and R_n fluctuated in synchrony and
254 had prominent troughs in 2004, 2006, 2014, and 2015 (Fig. 2d). In contrast, H
255 fluctuated slightly. The annual Bowen ratio ($\beta = H/\lambda E$) calculated from cumulative H
256 and λE for whole year, was 0.31 ± 0.07 (mean ± 1 standard deviation) but β
257 occasionally increased with fire. (Fig. 2e, Table 2). Maximum β (0.74) was recorded in
258 October 2014. G_s decreased with increased VPD in the dry season (Fig. 2f). Ω had
259 constant high values of approximately 0.8 under water-logged conditions (2010–2013)
260 and decreased with increasing VPD (Fig. 2f). EVI decreased with fire in 2009, 2014,
261 and 2015, and subsequently increased gradually after every fire (Fig. 2g). Negative
262 values of SOI were seen in El Niño years (2004–2005, 2006–2007, 2009–2010 and
263 2014–2016) whereas the positive values were seen in La Niña years (2005–2006,
264 2007–2008, 2008–2009, 2010–2012 and 2016) (Fig. 2h). Especially, SOI had been
265 positive for a long period during 2010–2012 and there was much of P . During or after
266 fires, a decrease in ET was observed in 2004, 2006, 2014, and 2015 with temporarily
267 lowered R_n very likely due to fire-induced haze. Immediately after drainage, ET did not
268 decrease but decreased thereafter when GWL was extremely deep.

269 Comparing the mean monthly ET in the three periods (Table 3), ET was the largest
270 with 136 mm month⁻¹ in Period II followed by 119 mm month⁻¹ in Period I and 109 mm
271 month⁻¹ in Period III. As for the comparison of meteorological conditions, the largest P
272 (253 mm month⁻¹) and R_n (407 MJ m⁻² month⁻¹), and lowest VPD (6.27 hPa) were
273 observed in Period II. In Period III, GWL was deepest (- 0.50 m), although P was
274 similar to that in Period I. Smallest β (0.23), and largest G_s (10.76 mm s⁻¹) and Ω (0.69)
275 were recorded in Period II.

276

277 **3.2 Water and energy balance**

278 In terms of water balance, P is a unique factor that supplies water to the ombrotrophic
279 peatland. We examined the relationship between ET and P on a monthly basis (Fig. 3),
280 and a positive correlation ($R = 0.38$, $p < 0.01$) was found for the whole observation
281 period. However, when P was greater than ET, ET fluctuated around 127 ± 17 mm
282 (mean ± 1 standard deviation) independently of P . Therefore, annual ET/ P became
283 smaller as P became larger. The mean annual ET/ P was 0.56 ± 0.07 (Table 2). In
284 contrast, when P was less than ET, ET decreased in some months when $\text{GWL} < -0.5$ m
285 in Periods I and III, although, decreased ET (~ 50 mm month⁻¹) was observed for one
286 month (October 2015) even when $\text{ET} < P$. On the contrary, there was no condition with

287 GWL < -0.5 m in Period II.

288 We examined the relationship between monthly changes in GWL (Δ GWL) and
289 precipitation surplus ($P-ET$) (Fig. 4). We exclude the data with $GWL \geq -0.1$ m to
290 exclude the case of surface outflow, which could not be evaluated quantitatively in this
291 study. Significant positive correlations between $P-ET$ and Δ GWL were observed for all
292 periods. Significant difference ($p < 0.01$) was not found between the fitted lines in
293 Periods I and II. X-axis intercepts of the fitted lines were -6.3, 1.0, and 117.4 mm in
294 Periods I, II, and III, respectively. The underground outflow specifically increased in
295 Period III. Additionally, the slopes of the fitted lines were 3.60×10^{-3} , 2.74×10^{-3} and
296 1.30×10^{-3} m mm⁻¹ in Period I, II and III, respectively.

297 We examined the relationship between β and R_n , and β and VPD in case of $R_n \geq 600$,
298 respectively (Fig. 5). As R_n increased, β became larger and the increasing rate became
299 gentle in all periods. In period II, R_n -filtered ($R_n \geq 600$) β had a decreasing trend with
300 VPD contrary to the increasing trend which were seen in Period I and III.

301

302 **3.3 Relationship between ET and environmental factors**

303 Half-hourly ET had a strong positive correlation with R_n throughout the observation
304 period ($R=0.89$, $p < 0.01$, Fig. 6a). VPD also had a positive correlation with ET when

305 VPD<20 hPa, and ET was stable irrespective of VPD when VPD≥20 hPa (Fig. 6b).
306 Quadratic curve of GWL was applied for each Period but positive correlation was seen
307 when GWL<-0.5 m (Fig. 6c). No significant correlation was found between ET and EVI
308 for each of the three periods as well as for the whole measurement period (-0.08–0.22
309 and 0.00, Fig. 6d). ET had positive relationship with G_s . The increasing trend of ET to
310 G_s became more gradual as G_s increased (Fig. 6e). In Period II, G_s fluctuated in the
311 higher G_s range, as compared with G_s in Periods I and III. ET seems to be stable
312 irrespective of Ω when $\Omega \geq 0.5$. When $\Omega < 0.5$, increasing trend of ET with Ω was seen in
313 Period III whereas ET hardly fluctuated in Period I.

314

315 **3.4 Path analysis**

316 To analyze the contribution of each environmental factor, we drew a path diagram (Fig.
317 7a). P had a positive (Fig. 7b) and R_n had the largest effect (0.73–0.92) in all periods.
318 VPD had negative effects in Period I (-0.64), III (-0.26), and whole period (-0.27),
319 whereas the effect was negligible in Period II (0.05). GWL had a positive effect in
320 Period I (0.35) and II (0.34), whereas the effect was negative in Period III (-0.09). EVI
321 had a significant effect (0.18) only in Period III. The goodness-of-fit index (GFI) is
322 0.86–0.96. All path coefficients are listed in Table 4.

323

324 4. Discussions

325 4.1 Comparison of ET with other studies

326 The mean monthly ET (109–136 mm, Table 3) at the study site was larger than those
327 observed in three boreal peatland sites (12–103 mm (Petroni et al., 2014; Sottocornola
328 and Kiely, 2010; Wu et al., 2010). In other words, even though the mean ET decreased
329 after drainage in Period III, it was still larger than the maximum ET recorded in the
330 growing season at the boreal peatland site. In contrast, ET/P (0.56) in the study site
331 (Table 2) was smaller than those in boreal peatland sites ($ET/P=0.90$ (Brust et al., 2018),
332 $ET/P=0.79$, (Fraster et al., 2001), and $ET/P=1.07$ (Morison et al., 2020)). On the other
333 hand, annual ET and ET/P (1222–1662 mm and 0.44–0.66, Table 2) in this study site
334 were generally similar to those in Borneo’s forest (1210–1545 mm and 0.46–0.72,
335 Kumagai et al., 2005; Kume et al., 2011). A small ET/P would be characterized by a
336 large amount of P in this tropical regions, although ET was somewhat larger than those
337 in boreal peatland sites. Compared with λE in other tropical sites reported by Fisher et
338 al. (2009), λE in our study was generally smaller than λE in rainforests in America
339 ranged 1.72°S–10.42°N, and was similar to λE in plantations in Congo and Vanuatu and
340 pastures in America which ranged 3.01°S–15.44°S. Similar λE would be because have

341 nearly identical above-ground biomass. Being different from the result of comparison in
342 ET, λE in this study was smaller than λE in other tropical forest. Nevertheless, the
343 difference of λE will be closer if λE in our study is corrected so that the energy balance
344 ($R_n - G = H + \lambda E$) is closed. Wet condition with sufficient P would increase evaporation
345 thus ET, even when peatlands experienced terrestrial disturbances. Compared with ET/ P
346 in Period I, the smaller ET/ P in Period II could be explained by significantly increased
347 P due to a La Niña event, although ET increased somewhat (Table 3). Alternately,
348 smaller ET/ P in Period III could be explained by smaller ET because P in Period III was
349 similar to that in Period I. As shown in Fig. 4, drainage increased underground outflow,
350 i.e., available rainwater for ET would be reduced in Period III.

351 Compared with mean ET in undrained (136 mm month⁻¹, 2004–2008) and drained
352 (129 mm month⁻¹, 2002–2008) PSFs in the vicinity of the study site (Hirano et al.,
353 2015), ET in Period II was similar to the above values, whereas ET in other periods was
354 smaller. Specifically, with waterlogged conditions during La Niña years, ET was
355 comparable to those in forest sites under normal meteorological conditions, even though
356 some above-ground vegetation was burned. These results indicated that continuous
357 rainfall which brings waterlogged condition has potential to increase ET in tropical
358 peatlands.

359

360 **4.2 Low β with recovered vegetation and wet condition after fire**

361 Mean annual β (0.22–0.39) was smaller than tropical savanna (1.4–7.0, Beringer et al.,
362 2003), boreal peatland (1.10–1.19, Morison et al., 2020), upland forest of North
363 America (0.5–1.0, Moore et al., 2013) and arctic wetlands at several sites (0.56 on
364 average, Lafleur, 2008), and similar to the average in tropical ecosystems which mostly
365 comprise of forests (0.3, Fisher et al., 2009)). This indicates that a large part of R_n was
366 distributed to λE irrespective of fire and drainage disturbances at this tropical site,
367 although there was some residual energy ($R_n - H - \lambda E$). Contrary to the results of earlier
368 studies (e.g., Beringer et al., 2003; Morison et al., 2020; Whelan et al., 2015), fire
369 decreased β in Period II. Earlier studies described that β increased with decrease in ET
370 due to loss of vegetation. D’Acuncha et al. (2018) reported that fire decreased ET from
371 4.5 to 2.5 mm day⁻¹ by burning species of trees. In the study site, vegetation recovered
372 immediately in post-fire years due to large P with La Niña events. This could be one
373 reason for the small β with recovered ET after fire at this site. Under conditions where
374 the effect of R_n on β was small, decreasing β with VPD was found in Period II whereas
375 the increasing trend was found in Period I and III (Fig. 5b). As mentioned in the
376 previous subsection, waterlogged condition lasted for a long period with prolong rain

377 after fire in Period II (Fig. 2b). Always wet condition which increases evaporation could
378 be another reason for the small β , although decrease in β does not necessarily mean
379 increase in ET. Thus, our result showed the case that subsequent meteorological
380 condition somewhat counteracts the effect of fire on β , although fire potentially increase
381 β due to loss of transpiration.

382

383 **4.3 Strong dependence of ET on R_n through the fire and drainage**

384 R_n had a significantly high positive correlation with ET ($R = 0.89$, $p < 0.01$, Fig. 6a) and
385 the largest effect on ET throughout the observation period (0.73–0.92, Fig. 7b). A strong
386 correlation was found in other studies (Morison et al., 2020; Wang et al., 2020). This
387 indicates that fire and drainage disturbances did not change the characteristics of strong
388 dependence on R_n . And fire could indirectly decrease ET by generating haze which
389 attenuate incoming radiation. On the other hand, Ω became larger ($\Omega = 0.69$) with
390 shorter vegetation of ferns and sedges in Period II and became smaller ($\Omega = 0.56$) with
391 emerging woody plants in Period III (Table 3). These results explained that stomatal
392 regulation became significant for ET via change of transpiration rate as canopy layer
393 became thicker. On the other hand, atmospheric conditions (e.g., R_n , VPD) control ET
394 rather than stomatal behavior in short vegetation since incoming solar radiation is likely

395 to reach the ground surface and evaporation contributes to ET more. The variation of Ω
396 coincide with those of previous studies. Jarvis and McNaughton (1986) reported that Ω
397 is larger with shorter vegetation and vice versa: grassland 0.8, wheat 0.6, and forest 0.2.
398 Ω of regenerating forest decreased from that of the bog in Central Siberia (Valentini et
399 al., 2000). Fire would increase the dependence on R_n by clearing vegetation.

400

401 **4.4 Vegetation succession post fire controls ET sensitivity to EVI**

402 A significant correlation between EVI and ET was not seen in this study (Fig. 6d),
403 whereas previous studies found a positive correlation between vegetation indices and
404 ET. For example, Wang et al. (2020) reported that ET increased with land conversion
405 from bog to pasture. They estimated an increase of λE with 54 Wm^{-2} for a unit
406 difference of EVI (pasture minus bog). Prater et al. (2006) reported a positive
407 correlation between the Normalized Difference Vegetation Index (NDVI) and ET on
408 post-fire bunchgrass or sagebrush. A positive correlation was also found in upland
409 forests that experience fire (Clark et al., 2012). One possible reason for the
410 non-correlation observed in this study is the lack of transpiration due to burning of
411 vegetation was sufficiently compensated by evaporation with long-lasting precipitation
412 in Period II. Moreover, another reason could be that the influence of other

413 meteorological factors (e.g., R_n and VPD) on ET were not excluded in the correlation
414 between EVI and ET. Subsequently, the results of path analysis showed that EVI had a
415 significant influence on ET only in Period III (coefficient of path b9 in Fig. 7, Table 4).
416 This may be due to the larger fluctuation of LAI in Period III, although there was no
417 clear difference in the observed EVI range among the three periods (Fig. 6d). It was
418 reported that the relationship between EVI and LAI differs depending on vegetation
419 type (e.g., Kang et al., 2016; Qiao et al., 2019). For example, using regression equations
420 between EVI and LAI by Qiao et al. (2019), they reported that the variations in LAI
421 correspond to the variation of EVI (0.25–0.50) and were estimated to be 0.87–2.84,
422 0.38–2.63, and 0.62–1.94 in deciduous forest, cropland, and grassland, respectively.
423 These estimations would indicate that fluctuation of LAI was larger in woody plants
424 than in herbaceous plants for the same variation of EVI. In period III, woody plants had
425 been dominant, whereas it was sparsely distributed in Periods I and II. Therefore, a
426 significant influence of EVI on ET may be found in Period III because of the large
427 variation in LAI for a certain change in ET.

428

429 **4.5 Low ET sensitivity to VPD after fire**

430 The results of path analysis (Fig. 7) showed that almost no effect of VPD on ET was

431 observed in Period II, whereas VPD affected ET negatively in Periods I and III. This
432 could be explained by the difference in land cover. Previous studies observed the
433 stomatal regulation of fern by showing that their stomatal conductance decreased
434 corresponding to increased VPD (Brodribb and McAdam, 2011; Cardoso et al., 2019;
435 Hōrak et al., 2017; Martins et al., 2016). In our study site, there were fewer herbaceous
436 plants, and some ponds were formed due to large P in Period II. Evaporation from the
437 exposed free water surface increases with an increase in VPD. In contrast, transpiration
438 decreases with increasing VPD due to stomatal closure (e.g., McAdam et al., 2016).
439 These two effects cancel each other out of the VPD change. Furthermore, observed
440 range of G_s was high in Period II comparing with those in Period I and III (Fig. 6e,
441 Table 4). ET does not change much at higher range of G_s ($G_s \geq 10 \text{ mm s}^{-1}$). This might
442 indicate that the rate of increase of ET for G_s was gradual for a higher range of G_s (Fig.
443 6). This result implies that stomatal regulation for atmospheric dryness became less
444 significant for ET in Period II. This could be an additional reason for the negligible
445 VPD effect in Period II with low VPD and high G_s .

446

447 **4.6 ET becomes easier to be decreased due to drainage**

448 Decreased ET under the conditions $P \leq ET$ and $GWL < -0.5$ (Fig. 3) might be related to

449 the disconnection of capillary force that transfers the water upward. Ishikura et al.
450 (2016) described that the discontinuity of capillary pores is likely to occur in cases with
451 deep GWL. Another possible reason is disabled root water uptake. For example, in
452 boreal poor (weakly minerotrophic) forested fen, most roots lived above -0.4 m soil
453 depth (Dimitrov et al., 2014). The rooting depth of purple moor grass in Dutch
454 peatlands was -0.5 m (Spieksma et al., 1997). From these results, it is inferred that the
455 limitation of root water uptake could be another reason for the decline of ET with
456 $GWL < -0.5$ m. On the other hand, ET was relatively stable with $GWL > -0.5$ m even if
457 ET exceeded P . Taufik et al. (2017) described that GWL fluctuation influences
458 hydrological drying (or wetting) upper peat layer and the soil moisture is depleted to
459 fulfill the evapotranspiration flux. It could be assumed that shortage of rainwater for ET
460 is compensated with soil water as long as GWL kept above -0.5 m.

461 In Fig. 4, we can theoretically evaluate underground outflow, which is equivalent to
462 the required water to stabilize the GWL, from x-axis intercept of fitted lines, although
463 head water pressure (i.e., GWL) should be considered for accurate evaluation. We can
464 also evaluate the increasing rate of GWL with unit water supply, which is proportional
465 to soil porosity, from the slope of the fitted lines. Similar fitted lines in Periods I and II
466 as shown in Fig. 4 indicate that the physical properties of soil were not changed by fire

467 in 2009. This may explain the deep soil that was not damaged by fire, although some
468 parts of the peat surface and above ground biomass were burned. The more gradual
469 slope of the fitted line for Period III indicates that a larger amount of water is required
470 to raise a unit GWL. This may be due to the difference in porosity in the range of GWL
471 fluctuation. Specifically, GWL fluctuated in the shallower peat soil layer with lower
472 porosity in Periods I and II, and in the deeper peat soil layer with higher porosity in
473 Period III. In support of this hypothesis, Itoh et al. (2017) reported higher bulk density
474 (corresponding to lower porosity) of peat soil in the shallower layer compared with that
475 in the deeper layer at the study site. The increase in underground outflow in Period III
476 from Period II was estimated at 116 mm month⁻¹ from the regression lines as in Fig. 4.
477 Although the estimation was not based on direct measurement, it is confirmed that the
478 underground outflow was increased after canal excavation and the outflow water was as
479 large as the ET at the study site. Therefore, *P* would become a significant factor to
480 control ET through the change of GWL after canal excavation, as GWL never reached
481 the ground surface level. In contrast, *P* had generally exceeded the required water
482 volume to maintain the shallowest GWL (i.e., waterlogged condition), at least in the wet
483 season before canal excavation.

484 Although our study site experienced fire and the vegetation was damaged, water was

485 generally and stably supplied from the peatland to the atmosphere via ET, irrespective
486 of *P*. However, drainage might disable this function because of the available
487 groundwater loss due to deepened GWL resulting from increased underground outflow.

488

489 **4.7 Drainage alters ET sensitivity to GWL**

490 As for the effect of GWL on ET, a small negative effect was found in Period III,
491 whereas the effect was positive in Periods I and II (Fig. 7b). This seems contradictory to
492 the GWL-ET relationship (Fig. 6c) which illustrates the positive relation within the
493 observed range in Periods III. This could be explained that sole GWL-ET relationship
494 would include confounding factors, whereas path analysis excludes the influence of
495 other factors on ET. The small negative effect in Period III could be explained by the
496 following reasons. First, if the GWL is below a certain level where the capillary force is
497 disconnected and root water uptake does not work, transpiration would not be further
498 reduced by GWL deepening. In other words, when the GWL is fluctuating at a deep
499 level, changes in GWL have little effect on ET. In Period III, the GWL was deepened
500 extremely. Second, less rainwater may infiltrate the extremely dried peat soil and
501 evaporation from the peat soil surface may increase. Perdana et al. (2018) reported that
502 peat soil becomes more hydrophobic as it becomes drier. As a result, the duration of the

503 dry period was longer, the GWL deepened, and the peat surface became drier.
504 Specifically, unchanged transpiration and increased evaporation may negatively effect
505 GWL under drier conditions in Period III. Both positive and negative relationships
506 between GWL and ET would also depend on the range of GWL's in boreal peatland bog
507 and pasture (Wang et al., 2020). They explained this complicated relationship by several
508 factors: the impossibility of linear estimation of soil surface moisture by GWL, spatial
509 heterogeneity, and complexity of peat hydrology. Additionally, in Fig. 6c, the fitting
510 curves estimated that ET decreased by 33-69% with GWL drawdown from 0 to 1 m
511 depth. Simultaneously, the same 1 m drawdown decreased ET by 15% in phreatophyte
512 shrubs in arid areas (Nichols, 1994). The rate of decrease in ET for 1 m drawdown was
513 larger at the study site compared with that in the shrub land. Cooper et al. (2006)
514 reported that shrubs have deeper roots than herbaceous plants. These results indicate
515 that ET in herbaceous plant-dominated sites is susceptible to GWL drawdown because
516 of their shallower root depth.

517

518 **5. Conclusions**

519 Fire would have reduced transpiration by burning some of the above-ground vegetation,
520 whereas evaporation from open water contributed to ET in water-logged conditions with

521 subsequent La Niña events. As a result, ET did not decrease immediately after fire. At
522 that time, the effect of reduced transpiration by stomatal closure and increased
523 evaporation from free water surface cancelled each other for atmospheric drying.
524 Additionally, fire-induced haze attenuated incoming solar radiation, then the decrease in
525 R_n reduced ET. On the other hand, drainage could decrease ET. When GWL is deeper
526 than -0.5m , rainwater shortage was not compensated by soil water for stable ET. This
527 would be due to disconnected capillary force and disabled root water uptake. At that
528 time, ET was hardly influenced by GWL fluctuation. Thus, we have shown that fire and
529 drainage potentially reduce ET. However, how much transpiration contributes to ET is
530 not yet well understood. This is very important because transpiration is definitely
531 related to vegetation recovering and which plays a significant role in water cycle or
532 hydrological processes. Therefore, in future research, partitioning ET into evaporation
533 and transpiration would deepen our understanding in such dynamically changing
534 peatland ecosystems.

535

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546

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725

726 **Figure legends**

727 Fig. 1 Locations of the study site in Central Kalimantan, Indonesia.

728 Fig. 2 Monthly variations in (a) P and ET, (b) GWL, (c) VPD, (d) energy fluxes, (e) β ,
729 and (f) G_s and Ω , along with (f) EVI at 16-days intervals. Monthly SOI is
730 shown at the bottom (h). P (blue bars) and ET (red bars) are displayed over
731 each other (i.e., overlapped volume are displayed by purple). EVI data were
732 classified into two ranks according to reliability: useful or better (solid circles)
733 and others (open circles). The red line denotes a moving average of seven
734 consecutive points excluding low-ranked data. Vertical dashed lines indicate the
735 borders of Period I, II and III. Two triangles in the uppermost graph indicate the
736 moment when the measurement height was changed.

737 Fig. 3 Relationship between ET and P observed on monthly basis. Data were
738 classified into three observation periods: Period I (black), Period II (red), and
739 Period III (green). The data with $-0.5 \leq \text{GWL} < -0.3$ m and $\text{GWL} < -0.5$ m are
740 indicated by triangle and cross, respectively.

741 Fig. 4 Relationship between monthly change in GWL (ΔGWL) and P -ET. The data
742 with $\text{GWL} < -0.1$ m were selected to exclude the contribution of surface
743 outflow. Data classification was same as in Fig. 3.

744 Fig. 5 Relationship between daytime β and R_n (a) or VPD in case of $R_n \geq 600$ (b).
745 Half-hourly data with $R_n > 0$ are binned into 10 classes of R_n (a) or VPD in case
746 of $R_n \geq 600$ (b) in each Period I, II and III. The average of β with standard
747 deviation in each class are illustrated by circles with error bars.

748 Fig. 6 Relationship between ET and environmental factors: (a) R_n , (b) VPD, (c) GWL,
749 (d) EVI, (e) G_s , and (f) Ω . Half-hourly ET are binned into 20 classes of each
750 environmental factor except the case that monthly ET was used with EVI. The
751 average of ET with standard deviation in each class are illustrated by circles
752 with error bars.

753 Fig. 7 (a) Path diagram of ET. (b) Total effect of P , R_n , VPD, GWL, and EVI on ET,
754 determined with standardized path coefficients. Analyses were conducted using
755 monthly data for three periods (Period I, II and III) and whole observation
756 period.

757

1 **Abstract:**

2 Tropical peat swamp forests (PSFs) play a significant role in the exchange of water
3 between land and the atmosphere. However, fire and drainage have been expanding in
4 PSFs in recent decades. Although there is concern on the influence of fire and drainage
5 on water circulation, their influence on evapotranspiration (ET) is insufficiently
6 understood. Furthermore, repeated fire occurrences and their corresponding influence on
7 the ET by recurrent burning and smoldering is unexplored. To elucidate these influences,
8 we examined long-term variation of ET in a degraded peat swamp forest in Central
9 Kalimantan, Indonesia that was affected by drainage and repeated fire. The continuous
10 observation of energy fluxes was conducted for approximately 13 years between 2004
11 and 2016 by using the eddy covariance technique. The site burned in 2009 and 2014, and
12 was drained in 2014. Monthly ET and net radiation (R_n) fluctuated in synchrony and thus
13 they decreased considerably under fire-induced dense haze during the El Niño drought.
14 Troughs of ET, groundwater level (GWL) and R_n and crests of vapor pressure deficit
15 (VPD) coincided in their time-series variations. In the case of $ET > precipitation (P)$, ET
16 decreased when the GWL was deeper than -0.5 m. Half-hourly ET had a strong positive
17 correlation with R_n ($R=0.89$, $p < 0.01$), and partial positive relationship with VPD when
18 $VPD < 20$ hPa and with GWL when $GWL < -0.5$ m. ET had no correlation with the

19 Enhanced Vegetation Index (EVI), which represents above ground biomass for the entire
20 observation period. Alternately, the results of path analysis showed that some
21 environmental factors controlled ET differently depending on environmental conditions.
22 Generally, VPD negatively affected ET due to stomatal regulation functions under dry
23 atmospheric conditions. However, the effect was negligible during the water-logged
24 periods. This is because atmospheric dryness facilitated evaporation from exposed water
25 on the ground surface, which canceled out the negative effect of transpiration due to
26 stomatal closure. After drainage by canal excavation, fluctuation of GWL did not
27 significantly influence ET, although ET decreased. This may be due to the hydrophobic
28 dried peat soil, which prevents rainwater infiltration, disconnection of capillary force, or
29 disabled root water uptake as GWL excessively deepened. Fire potentially decreased ET
30 due to decreased transpiration by burning of vegetation. However, the decreasing effect
31 was cancelled by increased evaporation from the waterlogged ground surface during the
32 subsequent La Niña event. Drainage undoubtedly deepened the GWL, and ET severely
33 decreased in cases with extremely deep GWL.

1 Table 1

2 Characteristics of each period.

Period	Term	Characteristics
I	May 2004–September 2009	Herbaceous plants dominated.
II	December 2009–June 2014	Vegetation rapidly recovered after fire. Water-logged condition lasted for a long term.
III	July 2014–October 2016	Woody plants have become dominant. Severe haze occurred in 2014 and 2015.

3

4 Table 2

5 Annual values of ET and environmental factors.

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Mean \pm sd.
(Period)	(I)	(I)	(I)	(I)	(I / II)	(II)	(II)	(II)	(II)	(II / III)	(III)	(III)	
ET (mm yr ⁻¹)	1494 (1234)	1271 (1098)	1434 (1169)	1353 (966)	1357 ^a (1020)	1662 (1271)	1613 (1328)	1630 (1318)	1648 (1329)	1374 (1175)	1222 (1076)	1426 ^a (1222)	1457 \pm 152 (1184 \pm 122)
<i>P</i> (mm yr ⁻¹)	2620	1977	2555	2603	2239 ^d	3750	3021	2460	2776	2220	2388	3077 ^d	2641 \pm 474
ET/ <i>P</i>	0.57	0.64	0.56	0.52	0.61 ^a	0.44	0.53	0.66	0.59	0.61	0.51	0.46 ^a	0.56 \pm 0.07
GWL (m)	-0.08	-0.25	0.00	-0.03	-0.19 ^b	0.01	-0.04	-0.08	-0.06	-0.22	-0.59	-0.42 ^c	-0.16 \pm 0.18
<i>R_n</i> (GJ m ⁻² yr ⁻¹)	4.54	4.13	4.67	4.58	4.53 ^b	4.91	4.90	4.89	4.98	4.45	4.06	4.46 ^a	4.59 \pm 0.30
<i>H</i> (GJ m ⁻² yr ⁻¹)	0.76	0.90	0.97	0.92	0.96 ^a	0.66	0.80	0.75	0.79	0.98	0.96	0.81 ^a	0.86 \pm 0.10

λE (GJ m ⁻² yr ⁻¹)	3.00	2.67	2.84	2.35	2.47 ^a	3.09	3.23	3.20	3.23	2.85	2.61	2.97 ^a	2.88 ± 0.30
β	0.25	0.34	0.34	0.39	0.39 ^a	0.22	0.25	0.23	0.25	0.37	0.36	0.28 ^a	0.31 ± 0.07
VPD (hPa)	6.95	7.42	7.20	6.79	7.75 ^b	6.00	6.43	6.36	6.22	7.60	7.74	6.21	6.89 ± 0.64
G_s (mm s ⁻¹)	9.33	7.55	8.78	7.89	7.37 ^a	11.33	10.02	10.39	10.57	8.50	6.36	9.10 ^a	8.93 ± 1.48
Ω	0.65	0.45	0.52	0.59	0.56 ^a	0.72	0.68	0.68	0.67	0.55	0.52	0.65 ^a	0.60 ± 0.08
EVI	0.42	0.43	0.41	0.43	0.39	0.29	0.36	0.41	0.44	0.36	0.35	0.41	0.40 ± 0.04

6 Uncorrected ETs without energy balance closure are shown in parentheses.

7 ^a Including consecutive gap-filled data for more than one month.

8 ^b Including data gaps for approximately 2.5 months.

9 ^c Including data gaps for approximately 1 month.

10 ^d Data gaps for approximately 2.5 months were filled with the data measured at a nearby forest site.

11

12 Table 3

13 Mean monthly values of ET and environmental factors. Uncorrected ETs without energy balance closure are shown in parentheses. The

14 p values of one-way ANOVA are listed in the extreme-right column. Different letters in the same row denote significant difference

15 ($p < 0.05$) among the three periods according to Tukey's HSD.

	Period I	Period II	Period III	ANOVA (p)
ET (mm month ⁻¹)	119 ± 15 a	136 ± 9 b	109 ± 22 c	<0.001
	(97 ± 13)	(109 ± 9)	(95 ± 17)	
P (mm month ⁻¹)	191 ± 135 a	253 ± 121 b	206 ± 151 ab	0.041
ET/ P	0.62	0.54	0.53	
GWL (m)	-0.13 ± 0.27 a	-0.04 ± 0.10 a	-0.50 ± 0.30 b	<0.001
R_n (MJ m ⁻² month ⁻¹)	376 ± 37 a	407 ± 26 b	354 ± 67 a	<0.001

H (MJ m ⁻² month ⁻¹)	74 ± 24 a	62 ± 11 b	79 ± 23 a	<0.001
λE (MJ m ⁻² month ⁻¹)	235 ± 31 a	265 ± 22 b	231 ± 42 a	<0.001
β	0.32	0.23	0.34	
VPD (hPa)	7.26 ± 1.30 a	6.27 ± 1.02 b	7.51 ± 1.73 a	<0.001
G_s (mm s ⁻¹)	8.14 ± 2.38 a	10.76 ± 1.65 b	7.31 ± 2.32 a	<0.001
Ω	0.62 ± 0.11 a	0.69 ± 0.04 b	0.56 ± 0.10 c	<0.001
EVI	0.41 ± 0.05 a	0.38 ± 0.06 b	0.39 ± 0.07 ab	0.020

16

Mean ± 1 standard deviation

17

18 Table 4

19 Standardized path coefficients of path diagram (Fig. 6a) for each period. The significant
20 level is denoted by * for $p < 0.05$ and ** for $p < 0.01$.

Path	Period I	Period II	Period III	Whole period
b1	-0.22	0.10	0.10	0.10
b2	0.31**	0.02	0.52**	0.47**
b3	0.08	0.37*	0.38**	0.15*
b4	-0.82**	-0.57**	-0.28*	-0.52**
b5	-0.70**	-0.34**	-0.59**	-0.54**
b6	0.62**	0.87**	0.97**	0.80**
b7	0.35	0.34**	-0.09	0.15**
b8	-0.34	0.24**	-0.29**	-0.18**
b9	-0.17	0.11	0.18**	0.08*
GFI	0.88	0.86	0.89	0.96

21

22

23

24 Table S1

25 Summary of energy balance closure. Values were determined with the observed half
 26 hourly data in each year. The slopes, intercepts, and coefficient of determination (R^2)
 27 were determined by linear regression between R_n (x-axis) and $H+\lambda E$ (y-axis).
 28 $(H+\lambda E)/R_n$ were annual averages of each year.

Year	Slope	Intercept (W m^{-2})	R^2	$(H+\lambda E)/R_n$
2004	0.54	40.8	0.80	0.66
2005	0.55	45.2	0.76	0.70
2006	0.62	23.8	0.84	0.72
2007	0.59	27.8	0.88	0.72
2008	0.48	35.2	0.81	0.65
2009	0.65	29.4	0.86	0.74
2010	0.57	33.6	0.81	0.68
2011	0.62	41.2	0.76	0.75
2012	0.67	27.9	0.84	0.75
2013	0.71	20.7	0.85	0.77
2014	0.73	23.3	0.85	0.80
2015	0.73	29.2	0.81	0.83

2016	0.75	13.2	0.85	0.81
Mean \pm 1SD	0.63 \pm 0.08	30.5 \pm 8.3	0.82 \pm 0.04	0.74 \pm 0.06

29















