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2 Influence of disturbances and environmental changes on albedo in tropical peat

3 ecosystems

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- 21

22 Abstract

Tropical peat swamp forests have been experiencing drastic disturbances, such as deforestation, drainage, and fire. We examined how such disturbances influence albedo, which regulates radiative energy exchange between the terrestrial surface and the atmosphere. We conducted continuous field observations at three sites: undrained forest (UF), drained forest (DF), and drained burned ex-forest (DB), in Central Kalimantan, Indonesia, for over 13 years.

Observed albedo was strongly influenced by haze caused by fire because the haze layer covering the canopy has a relatively high reflectance. Under severe haze conditions in October 2015, apparent albedo increased to 0.156, 0.162, and 0.183 at the UF, DF, and DB sites respectively. Mean monthly albedos excluding fire periods were 0.094 ± 0.005 , 0.092 ± 0.006 , and 0.099 ± 0.017 (mean ± 1 standard deviation) at the UF, DF, and DB sites respectively. Seasonal fluctuation in albedo at the DB site, where ferns were dominant, was greater than at the UF and DF sites.

36 Albedo at the DF site was significantly lower than that at the UF site from February to August (p < 0.05). At the forest sites the albedo increased as groundwater level 37 38 decreased. Albedo was higher under high vapor pressure deficit at all sites. At the DB 39 site albedo decreased when the soil surface was water-saturated and patched with 40 puddles, potentially due to the low albedo of open water. The albedo at the DB site was 41 lower than that at the forest sites at the beginning of the observation period. 42 Subsequently, the albedo increased and exceeded those at the UF and DF sites immediately after fire damage in 2009. This could be explained by the expansion of 43 44 bright-colored ferns and sedges over dark-colored peat soil. According to our results, haze, groundwater level, and vegetation cover significantly influence albedo in tropical 45

46 peat swamp forests.

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- 48

49 **1. Introduction**

50 Tropical peatlands sequester 105 Gt of soil organic carbon, accounting for 21% of the 51 global peat carbon reserves, and are a major carbon reservoir (Page et al., 2011; Dargie 52 et al., 2017). A significant portion of tropical peat, accounting for approximately 43% of 53 all the tropical peat areas, occurs in Southeast Asia. The environments in numerous 54 tropical peatlands in the region have changed due to the conversion of land, mainly into 55 oil palm and acacia plantations (Miettinen et al., 2016). Drainages is often undertaken to 56 lower the groundwater level (GWL) to facilitate agricultural activities. Consequently, 57 soil aridification occurs, and fire risks increase in the dry season, since dry peat is 58 highly combustible.

59 The Mega Rice Project (MRP) represents a case where a tropical peatland ecosystem 60 has been degraded (Hoscilo et al., 2011). This project was launched in Central 61 Kalimantan, Indonesia in 1996 to transform a vast peat swamp forest area into farmland, 62 mainly rice fields. However, the MRP was officially canceled in 1999 mainly because of 63 a prevailing economic crisis, leaving behind an abandoned peatland (Rieley and 64 Muhmad, 2002). Consequently, more than 60% of the peat swamp forest in the MRP 65 area disappeared from 1997 to 2000 (Page et al., 2009). In addition, in recent decades, oil palm has attracted the attention of farmers as a profitable cash crop. Consequently, 66 67 oil palm plantations have expanded rapidly in recent times, especially in Southeast Asia. 68 For example, in Kalimantan, 206,400 ha of peat swamp forest, equivalent to 3.8% of all 69 Kalimantan swamp were converted into oil palm plantations by 2010 (Gunarso et al.,

70 2013).

71 Numerous studies on tropical peatlands have evaluated the effects of peatland 72 disturbance on carbon dioxide (CO₂) dynamics from a global warming perspective (e.g., Page et al., 2002; Hirano et al., 2012; Itoh et al., 2017; Warren et al., 2017). Drainage of 73 74 peatlands, which creates aerobic conditions in the environments, stimulates the 75 degradation of peat via microbial activity, which in turn increases CO₂ efflux from the 76 soil to the atmosphere (e.g., Sundari et al., 2012; Hirano et al., 2014; Itoh et al., 2017). 77 Drainage of peatlands also increases fire risk and accelerates fire propagation. Fire is a 78 disturbance that contributes considerably to global warming. In recent decades tropical 79 peatlands in Indonesia, particularly in Sumatra and Kalimantan, repeatedly experienced 80 large-scale fires in El Niño years (1997, 2002, 2009, 2014, and 2015). Huijnen et al. 81 (2016) noted that widespread forest and peatland fires burned over a large area of 82 maritime Southeast Asia in September and October 2015. The CO_2 emission rate (11.3) 83 Tg CO₂ per day) in the region in September–October 2015 exceeded the fossil fuel CO_2 84 emissions from the European Union (EU28) (8.9 Tg CO₂ per day) for that period. The 85 large-scale fires in the region emitted large amounts of smoke and caused a dense haze which spread out up to the Malay Peninsula and Borneo. 86

Energy balance between terrestrial surfaces and the atmosphere should be considered, in addition to greenhouse gas fluxes in the evolution of the impact of various disturbances on global warming. Sensible heat, which directly warms the atmosphere, is referred to as net radiation energy. Albedo and incoming solar radiation influence net radiation a great deal. For example, forestation in boreal peatlands caused positive net radiative forcing at one of four sites by decreasing albedo (Lohila et al., 2010), indicating that forestation does not necessarily mitigate global warming. Burakowski et

94 al. (2018) quantified the impact of deforestation on surface temperature in the Eastern 95 United States using on-site data and a model. They reported that surface cooling due to 96 increased albedo that was caused by deforestation was lower than 0.2°C in summer. 97 Zhang et al. (2020) also assessed the contribution of reforestation to global warming by 98 comparing data from six paired forest-grassland sites in temperate zones. They 99 estimated that the albedo warming effect due to reforestation was, on average, 2.3°C. 100 Both studies demonstrated that decreased albedo over forestlands causes surface 101 warming.

102 Conversely, several studies have also reported that deforestation increases albedo. For 103 example, Loarie et al. (2011) showed that deforestation increased albedo by 2.8% and 104 flooding increased albedo due to the submergence of vegetation in South America. 105 Oliveira et al. (2019) also demonstrated increases in albedo in pasture, agricultural land, 106 and secondary forest following the land conversion from primary tropical forests in 107 southwestern Amazonia. Sabajo et al. (2017) also concluded that albedo in intact forests 108 was lower than in other types of land cover: clear-cut land, palm oil plantation, and 109 rubber plantation in Sumatra. As for peatland, the above-canopy albedo in a burned 110 swamp forest was significantly higher than that of an unburned swamp forest in Finland 111 (Thompson et al., 2015). Kuusinen et al. (2013) reported that the albedo of a clear-cut 112 area was higher than those of forests, excluding that of a birch forest in Finland.

Many studies have evaluated albedo over large areas using satellite products such as MODIS. For example, Li et al. (2015) showed a difference in albedo between forest and open land at the global scale. They revealed that forests have lower albedo than open land, especially in northern mid-latitudes in winter. In the tropical zone (20°S–20°N), however, the mean albedo difference between forest and open land was low when 118 compared with differences in the other latitudinal ranges. They also concluded that the 119 cooling or warming effects of forests are mainly driven by evapotranspiration and 120 albedo.

Satellite products are useful in acquiring large-scale data for target areas but there is 121 122 still room for improvement with regard to precision and resolution. Oliveira et al. 123 (2019) reported that satellite data overestimate albedo as compared to field data. In 124 addition, He et al. (2014) reported that the estimated albedo depends on the type of 125 satellite data employed. Cescatti et al. (2012) analyzed field data obtained from 53 126 FLUXNET sites and found some mismatch between in situ measurements and those 127 from satellite products, especially in grasslands and crop lands, largely due to spatial 128 heterogeneity. Field observations could reveal the characteristics of albedo under 129 different environmental conditions. However, only a few studies based on long-term 130 field observations in tropical peatlands has been conducted (e.g., Hirano et al., 2015; 131 Tang et al., 2019; Kiew et al., 2020). Considering rapidly expanding land conversion, it 132 is very important to evaluate the albedo which would change significantly in tropical 133 peatlands. Albedo affects not only radiation balance directly but also evapotranspiration 134 through energy balance. Evapotranspiration is a key component in water balance and 135 affects GWL, which governs oxidative peat decomposition. Thus, it is important to 136 know how albedo changes following disturbance. In this study we measured 137 meteorological variables, GWL and albedo at three tropical peat ecosystems under 138 different degrees of disturbance, namely undrained forest (UF), drained forest (DF), and 139 drained burned ex-forest (DB) in Central Kalimantan, Indonesia, for more than 13 years. 140 By comparing the albedo responses to environmental variations we examined how the drainage and fire environmental disturbances influenced albedo. 141

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145 **2. Materials and Methods**

146 **2.1. Site description**

147 The study area was in the upper catchment of the Sebangau river, approximately 20 148 km south of Palangkaraya City in Central Kalimantan, Indonesia (Fig. 1). The area was 149 partly within the western section (Block C) of the former Mega Rice Project (MRP). 150 Fire frequently occurred during the dry season and the burnt area increased in size in El 151 Niño periods including 2002-2003, 2004-2005, 2006-2007, 2009-2010, 2012, and 152 2014-2016, defined NOAA as by 153 (https://www.ncdc.noaa.gov/teleconnections/enso/indicators/sst/). In Central Kalimantan the dry season in normal years lasts for approximately three months, 154 155 between July and October.

156 The UF, DF, and DB sites were located within 15 km of each other. UF site was a relatively intact forest, though it had been selectively logged until the late 1990s. DF 157 158 site had also been selectively logged during the same period, and a large canal was 159 excavated in 1996 and 1997. Although UF and DF sites were evergreen broad-leaved 160 forests, some defoliation was seen, namely not all the leaves were fallen at the end of 161 the dry season (Fig. 2). Hirano et al. (2007) reported that leaf area index (LAI) slightly 162 decreased from October to December. The DB site was burned at least four times; in 163 1997, 2002, 2009, and 2014. In 2009 sensors and cables on and under the ground were 164 severely damaged by fire. After vegetation was burned in 2009, ferns rapidly grew and 165 covered most of the soil surface. In September 2014 the density of young trees, mainly

166 *Combretocarpus rotundatus* (DBH > 3 cm) was 846 trees ha⁻¹. The forest floor was 167 uneven with hummocks and hollows at UF and DF site. Hummocks forming on dense 168 tree roots are generally 20–30 cm higher than surrounding vegetation-free hollows. In 169 contrast, no such microtopography was found in DB site, because hummocks were 170 burned. Further information on the three sites is presented in Table 1 and described by 171 Hirano et al. (2012).

172

173 **2.2. Measurement**

The variables used in the present study are listed in Table 2. Observations were conducted on towers from July 2004 to June 2017 at the UF site, from November 2001 to June 2017 at the DF site, and from April 2004 to February 2017 at the DB site. Some of the data are listed in Table 1.

178 At the UF and DF sites, downward and upward shortwave radiations were measured 179 using a radiometer (CNR-1; Kipp & Zonen, Delft, the Netherlands) at heights of 36.3 180 and 40.6 m respectively. At the DB site the height of measurement was elevated twice 181 owing to growth of vegetation (Table 1). Air temperature and relative humidity were 182 measured using a platinum resistance thermometer and a capacitive hygrometer 183 (HMP45; Vaisala, Helsinki, Finland) at heights of 36.3, 41.7, and 1.5 m at the UF, DF, 184 and DB sites respectively, while precipitation was measured using a tipping-bucket rain 185 gauge (TE525; Campbell Scientific Inc., Lorgan, UT, USA) at heights of 36.0, 41.0, and 186 1.5 m at the UF, DF, and DB sites respectively.

187 Sensor signals were measured every 10 s and each 30-min average was logged with a
188 datalogger (CR10X or CR1000; Campbell Scientific Inc.). Groundwater level (GWL),
189 defined as the distance between the groundwater surface and the ground surface, was

measured half-hourly with a water level logger (DL/N; Sensor Technik Sirnach AG, Sirnach, Switzerland or DCX-22 VG; Keller AG, Winterthur, Switzerland) within 5 m from experimental towers at the three sites. Positive GWLs denote the water levels are aboveground, whereas negative GWLs denote the water levels are belowground. Hirano et al. (2012) provided additional information on measurements.

195

196 **2.3. Data processing**

197 We defined albedo using the following equation:

$$198 \quad albedo = S_u / S_d \tag{1}$$

where S_u is the upward shortwave radiation (W m⁻²) and S_d is the downward shortwave radiation (W m⁻²). We used half-hourly data from 10:00 to 14:00 to minimize the effects of solar altitude. Furthermore, data during rain and within an hour after rain events were excluded to eliminate the influence of raindrops on the dome of the radiometer.

203 As an index for fire scale around the experimental sites, monthly burned fraction 204 (BF) data in each 0.25° grid cell were extracted from the Global Fire Emission Database 205 (https://globalfiredata.org/pages/data/). The cell for the UF site (cell 1) was within 2.25-206 2.5°S and 113.75–114°E and the cells for the DF and DB sites (cell 2) were within 2.25– 207 2.5°S and 114-114.25°E. The data were available up until the end of 2016. Albedo 208 chiefly reflects the color and structure of the plant canopy covering the ground surface. 209 The light reflectance of leaves is influenced by leaf moisture and generally increases 210 with a decrease in moisture. We used GWL and vapor pressure deficit (hPa, VPD) as 211 indices of pedospheric and atmospheric dryness. VPD was calculated based on the air 212 temperature and relative humidity data at each site.

213 We used the aerosol optical depth (AOD) as a reference value for the degree of

attenuation of shortwave radiation by haze. AOD was measured with a photometer at a height of 27 m at the Palangkaraya AERONET site (2.23°S, 113.95°E), which is approximately 11 km north of the UF site and approximately 16 km northeast of the DF and DB sites. The observations began on 19 July, 2012. The data were acquired from the AERONET database (https://aeronet.gsfc.nasa.gov/new_web/aerosols.html). We used the highest quality data categorized at level 2.0 (cloud cleared and quality assured).

221 **2.4 Quantitative evaluation of the haze effect on albedo**

222 Frequent fires in the dry season cause haze and affect the atmospheric optical 223 environment, namely through transmission, scattering, and absorption of shortwave 224 radiation. We examined the haze effect quantitatively by calculating the increases or 225 decreases from the values under no-haze conditions. The haze layer between the 226 observation height (H_{obs}) and canopy height (H_{cano}) was used for calculations. We also 227 examined the validity of our directly measured albedo with radiometers by comparing 228 observed albedo and theoretically calculated albedo at the observation heights. To do 229 this (refer to Fig. 3), we defined the reflectance, absorbance, and transmittance of the 230 haze layer as β , γ , and λ ($\beta + \gamma + \lambda = 1$). Incoming S_d at H_{obs} is distributed into reflected 231 upward radiation at H_{obs} (βS_d), absorbed radiation in the layer (γS_d), and transmitted 232 radiation to H_{cano} (λS_d). Defining albedo at the canopy as α_{cano} , λS_d was reflected upward 233 as $\alpha_{cano}\lambda S_d$, and then attenuated through the haze layer and reached H_{obs} as $\alpha_{cano}\lambda^2 S_d$. 234 Therefore, S_u and albedo at H_{obs} (α_{obs}) are expressed as follows:

235
$$S_u = \alpha_{cano} \lambda^2 S_d + \beta S_d \tag{2}$$

236
$$\alpha_{obs} = \frac{s_u}{s_d} = \frac{\alpha_{cano}\lambda^2 s_d + \beta s_d}{s_d} = \alpha_{cano}\lambda^2 + \beta$$
(3)

237 Note that $\lambda \approx 1$ and $\beta \approx 0$ under no haze conditions because the distance between H_{obs} 238 and H_{cano} was relatively short (less than 15 m).

239 The transmittance λ was calculated using the Beer-Lambert Law, as follows:

240
$$\lambda = \exp\left(-b_{ext}x_L\right) \tag{4}$$

where x_L is the distance between H_{obs} and H_{cano} , and b_{ext} is the extinction coefficient. According to the results of laboratory experiments under daylight viewing conditions, λ =0.02 is usually employed as the perceptible threshold for visual range calculations (Seinfeld and Pandis, 2006). When λ =0.02, the visibility distance x_v can be evaluated using the following equation (the Koschmeider equation):

246
$$x_v = \frac{3.912}{b_{ext}}$$
 (5)

247 To facilitate the comparison of the results of the present study with those of previous 248 studies we performed calculations under the most severe haze conditions with AOD = 3for the DF site. According to Kusumaningtyas et al. (2016) x_v is shorter than 500 m at an 249 AOD of 3. Therefore, b_{ext} is calculated to be more than 7.82×10^{-3} m⁻¹. In addition, 250 applying the distance x_L =14.6 m between H_{obs} =40.6 m and H_{cano} =26 m at the DF site in 251 Eq. 4, λ is calculated to be lower than 0.89, which indicates that $\beta + \gamma$ is greater than 0.11 252 253 (1 - 0.89 = 0.11). According to Seinfeld and Pandis (2006), light scattering by particles 254 with sizes comparable to the wavelength of visible light is largely responsible for 255visibility reduction in the atmosphere and scattering by particles accounts for 50-95% 256 of light extinction. In non-urban sites scattering and absorption account for 80-95% and 257 10–25% light extinction respectively. Assuming that backscattering radiation to the atmosphere (βS_d) is 80% of the extinction of S_d ($\beta / (\beta + \gamma) = 0.80$), β is calculated as 258 259 0.086. The above equations and calculations will be used in the Discussion section.

261 **3. Results**

262 **3.1 Overview of meteorological conditions**

263 Figure 4 presents a time series of monthly environmental variables from 2004 to 2017. 264 Monthly precipitation ranged from 80, 82, and 82 mm in August to 341, 323, and 326 mm in December on average in 2004–2016 at the UF, DF, and DB sites respectively. 265 266 Similar seasonal variations in precipitation were seen at the all three sites, in which 267 precipitation started to decrease in May until August then started to increase in 268 September until November. Mean annual precipitation from 2005 to 2016 was 2663 \pm 269 479, 2623 ± 479 , and 2641 ± 473 mm (mean ± 1 standard deviation) at the UF, DF, and 270 DB sites respectively. Meanwhile, annual air temperature exhibited slight seasonal 271 fluctuation with bimodal peaks in May and October. Mean annual air temperatures from 2005 to 2016 were 26.1 \pm 0.5, 26.1 \pm 0.2, and 26.4 \pm 0.3 °C at the UF, DF, and DB sites 272 273 respectively. Variation in the GWL was synchronized with precipitation events. In the 274 wet season, GWL became positive (aboveground) at the UF and DB sites whereas it 275 remained negative (belowground) at the DF site. GWL at the DB site has decreased 276 since 2014 due to the drainage channel excavation activities nearby.

Albedos at the UF and DF sites had been increasing slightly with occasional rises. Conversely, albedo at the DB site increased gradually, with seasonal fluctuation throughout the observation period. Monthly BF data in the two cells were almost synchronized, although cell 2 had a higher BF than cell 1. BF in cell 2 was the highest, at 0.10, in September 2009, when the DB site was damaged severely by fire.

282

283 3.2 Seasonal variation in albedo

284 Figure 5 shows the monthly ensemble average of albedo at the three sites. Data plots 285 were classified using BF. Albedo generally increased with an increase in BF in the dry 286 season. Excluding the influence of haze (BF ≥ 0.005), monthly averages ranged from 287 0.092 in May to 0.096 in December at the UF site, from 0.087 in April to 0.098 in 288 December at the DF site, and from 0.087 in April to 0.109 in September at the DB site. 289 The mean monthly albedo with BF<0.005 over the entire observation period was 0.094 290 $\pm 0.005, 0.092 \pm 0.006, \text{ and } 0.099 \pm 0.017 \text{ (mean} \pm 1 \text{ standard deviation) at the UF, DF,}$ 291 and DB sites respectively, excluding the data during fires. There were significant 292 differences (p < 0.01) of albedo at DB site with those at UF and DF sites from the whole 293 study period. Figure 6 illustrates the inter-site differences in monthly albedo with 95% 294 confidence intervals determined using the bootstrap method with 1000 repetitions. From 295 February to August, the albedo at the DF site was significantly lower than that at the UF 296 site (p < 0.05). Albedo at the DB site was significantly greater (p < 0.05) than the albedo at 297 the UF site in July, September, and October, and that at the DF site from July to October. 298 All monthly albedo values at each site are listed in the Appendix.

299

300 **3.3 Inter-annual variation in albedo**

Albedo at the DB site increased annually since observations began (Fig. 4c). At the end of 2016 the albedo recorded was 0.131, exceeding those at the UF and DF sites by more than 0.02. Figure 7 illustrates the inter-annual variation in albedo at the three sites. Annual increments in albedo were calculated by applying linear regression to the data only in April–June to eliminate the influence of fire and to use the entire datasets at all the sites. BF in April–June was below 0.005 throughout the observation period (Fig. 7). The increasing rate at the DB site was the highest (0.0044 year⁻¹, $R^2 = 0.76$, p < 0.01), followed by the DF site (0.0013 year⁻¹, $R^2 = 0.74$, p < 0.01) and UF site (0.0007 year⁻¹, $R^2 = 0.50$, p < 0.01).

310

311 **3.4 Influence of environmental conditions**

Generally, the timing of positive peaks of albedo in the dry season corresponded to negative peaks of GWL and positive peaks of BF and AOD, especially in 2006, 2009, and 2015 (Fig. 4b–e). In 2015 the maximum albedo levels were 0.156, 0.162, and 0.183 at the UF, DF, and DB sites, respectively. In addition, BF had positive peaks of 0.042 in cell 1 and 0.087 in cell 2, and AOD reached 3.79. In contrast, although BF and AOD had their positive spikes in 2012, no clear sharp spikes of albedo were observed.

318 The influence of water conditions on light reflection characteristics was examined. 319 The relationship between albedo and GWL is illustrated in Figure 8. Daily average data 320 were classified by AOD. High albedo (below around -1.0 m) was observed at low GWL 321 ranges at all sites. Generally, albedo increased with an increase in AOD. Some plots 322 with AOD ≥ 0.5 were also observed at relatively high GWLs from September to 323 October 2012, during which time GWL did not decrease markedly, while AOD peaked (Fig. 4). Excluding the AOD ≥ 0.5 data, albedo showed a significant negative 324 325 relationship with GWL at the UF and DF sites. Conversely, the albedo at the DB site 326 was not significantly correlated with GWL when GWL < 0 m. When groundwater rose 327 above ground (GWL ≥ 0 m), albedo seemed to be lower than the estimated value by the 328 fitted line for GWL<0 at the DB site but not at the UF site.

329 Figure 9 illustrates the relationship between albedo and VPD. Data with $AOD \ge 1.0$

330 were generally greater than data with AOD < 0.5. Albedo increased slightly at the

331 lowest and highest VPD ranges (VPD<ca.10 and VPD≥ca.25 hPa) at the UF and DF

sites. For the AOD < 0.5 data, the quadratic relationships were significant (p < 0.05). On the other hand, linear and quadratic fittings were roughly overlapped each other and both fitting lines showed increasing trend of albedo with VPD within the observed range at DB site.

336

337

338 **4. Discussion**

4.1 Comparison with other studies

340 Table 3 provides a range of literature values from this study and previous studies. The 341 mean observed albedo values (0.092–0.099) at BF < 0.005 at the sites were lower than 342 those in other tropical forests: 0.114-0.12 in an Amazonia forest (Cescatti et al., 2012; 343 Oliveira et al., 2019). Peat swamp forests might have canopy structures similar to those of Amazonian forests, forming dense crown canopies of evergreen broadleaf trees. 344 345 However, in our study area a few small canopy gaps were generated by tree fall 346 especially at the DF site. The reduction in upward reflection due to the resulting uneven canopy could be the reason for the lower albedo at our forest sites. In addition, the 347 348 albedo observed in the present study was much lower than that in treeless peatlands: 349 0.132 at a Finnish peat bog in summer (Gao et al., 2014); 0.137 at an open mesotrophic 350 fen on a Finnish peat soil in July (Lohila et al., 2010); and 0.140 at an open Finnish 351 peatland in summer (Kuusinen et al., 2013). Bright-colored short vegetation dominating 352 the ground surface could be the reason for the higher albedo in treeless peatlands.

353

4.2 Influence of land cover change

355 Compared with that at the forest sites (UF and DF), albedo at the burned site (DB)

356 was higher after a severe fire in 2009, when the ground was mostly covered with 357 vegetation mainly comprising ferns (Fig. 4c). Many studies have reported an increasing 358 albedo following deforestation in the tropics. For example, albedo increased by 0.027 359 and 0.032 following the conversion of tropical forests into pasture and agricultural land 360 respectively in southwestern Amazonia (Oliveira et al., 2019). Berbet and Costa (2003) reported that the albedo increased by 0.043 following the replacement of a tropical 361 362 forest with pasture in Amazonia. In addition, Sabajo et al. (2017) reported that the 363 albedo of clear-cut areas was 0.02 higher than that of forests in Sumatra, Indonesia. 364 However, the albedo of the DB site was lower than those of the UF and DF sites until 365 the middle of 2009 (Fig. 4c), potentially because relatively dark colored bare peat was 366 still largely exposed. In contrast, Thompson et al. (2015) reported that albedo at a 367 burned peat bog was higher than that at an unburned site over a two-year period 368 following a wildfire, with no clear difference detected after four years. They explained 369 that the higher albedo at the burned site was due to the immediate recovery of 370 Sphagnum moss over the peat soil.

371 The albedo of the DB site exhibited an increasing trend up to 0.131 at an annual rate of 0.0044 year⁻¹ until 2016 (Fig. 7c). An increase in albedo after fire, which represented 372 373 a 0.08 increase over the first decade, was also observed in burned boreal forests (Amiro 374 et al., 2006). The albedo of 0.131 was generally lower than that observed in shrubland, 375 savanna, grassland, and cropland (e.g., Myhre et al., 2005; He et al., 2018; Ge et al., 376 2019). The comparison of albedo at DB site with those at reference sites mentioned 377 above and Figure 7c suggest that albedo continued to increase at the DB site as long as 378 the existing light-colored herbaceous plants was expanding. Page et al. (2009) reported 379 that a high-intensity fire prevents transition of non-forest vegetation or bare peat into

forest and replaces the plant community with ferns and sedges with few or no trees. Over the last few decades, fire has occurred so frequently that DB sites have become dominated by ferns and no change in this condition is expected. Therefore, observations at short term intervals are essential to capture such dynamic variation and to make precise estimates of albedo.

The annual albedo of forest sites has also been increasing gradually (Fig. 7), although 385 the annual rates of 0.0007 year⁻¹ at the UF site and 0.0013 year⁻¹ at the DF site were 386 387 lower than 30% of the rate observed at the DB site. Increasing albedo could reflect 388 subtle changes in canopy structure with gradual tree growth. For example, canopy gaps 389 were changing following the termination of selective logging in the late 1990s. Tree 390 growth resulting in filling of canopy gaps would smooth the forest canopy and thus, 391 increase albedo. Canopy recovery after tower construction might be another reason for 392 the inter-annual increase.

393

394 **4.3 Seasonal variation in albedo**

395 The larger seasonal fluctuation in albedo observed at the DB site as compared with 396 the fluctuations at the UF and DF sites (Figs. 4 and 5) could be due to the greater 397 seasonal fluctuation in ground conditions at the DB site, including exposure of peat soil 398 and growth of ferns. The bare ground at the DB site, was much more exposed due to 399 sparsely distributed vegetation. Basically, peat soil turns dark in the wet season and light 400 in the dry season, depending on the GWL. At the UF and DF sites, however, the ground 401 surface was almost entirely covered by a dense canopy. In addition, ferns dominating 402 the DB site lightened leaf color in the dry season because of the decrease of leaf water 403 content. Therefore, the albedo at the DB site increased in the dry season.

The annual amplitudes of albedo at the forest sites (0.004 at the UF site and 0.011 at the DF site, on average) were lower than those at other tropical forests (0.025; Berbet and Costa, 2003). The larger annual amplitudes were due to decreasing LAI in the dry period, resulting in higher albedo. Myneni et al. (2007) reported that the Amazon rainforest exhibits notable LAI seasonality with an annual amplitude of 25%. Our smaller annual range would indicate weaker LAI phenology.

410

411 **4.4 Influence of fire smoke**

The AOD was similar in magnitude and seasonal variation to those in Amazonian forests. Oliveira et al. (2007) reported that AOD exceeded 3.0 during the dry season due to biomass burning events. Schafer et al. (2008) showed that AOD at 440 nm peaked in the dry season when fire occurred. Generally, AOD is a reliable index for fire smoke.

416 To examine the reliability of the albedo data measured directly with radiometers 417 under the most severe haze conditions in the present study with an AOD of 3 at the DF 418 site, we calculated α_{obs} using Eq. 3 for comparison with the observed α_{obs} . By assuming 419 $\alpha_{obs} \approx \alpha_{cano}$ at BF<0.005 and applying the mean albedo (0.092) for α_{cano} with $\beta = 0.086$ 420 and $\lambda = 0.89$ to Eq. 3, α_{obs} was calculated to be 0.160. This value was comparable to the 421 observed values (0.14 \pm 0.02, mean \pm 1 standard deviation) at AOD \geq 3 in Figs. 8b and 422 9b; α_{obs} is 174 % of α_{cano} . That is, 74 % of overestimation was caused by haze. When x_v 423 is a half (250 m) or double (1000 m) the distance of 500 m, α_{obs} is calculated to be 0.221 424 and 0.126, respectively. Similarly, when x_L is a half (7.3 m) or double (29.2 m) the 425 actual distance (14.6 m), α_{obs} is calculated to be 0.126 and 0.221 respectively, with $x_v =$ 426 500 m.

427 The calculated values above clearly indicate that severe haze causes the

428 overestimation of surface albedo and that albedo strongly depends on the distance 429 between the observation height and the vegetation height. Therefore, distinctly high 430 albedo during fire events must have resulted from the haze layers below the radiometer 431 and not from sharp responses of vegetation. It is quite challenging to determine canopy 432 albedo using single-point observations above the canopy under severe haze conditions. 433 The degree of the haze effect on albedo was quantitatively demonstrated using 434 equations 2 and 3.

435

436 **4.5 The response of albedo to GWL and VPD**

437 First, we explain the variation in GWL at the DB site because GWL remained high 438 until 2014 despite the drainage. The high GWL was partly caused by ground lowering 439 due to the loss of surface peat by repeated fires. For example, surface peat was burned 440 by 0.22 m in thickness in 2002 at DB site (Hirano et al., 2014). Another reason for the 441 high GWL would be lower evapotranspiration due to low tree density (Hirano et al., 442 2015). However, GWL has decreased since 2014 because of channel excavation nearby. 443 Albedo clearly decreased at the DB site when GWL was positive (Fig. 8). Generally, 444 the albedo of open water is lower than that of soil. Thus, the appearance of open water 445 on the ground surface at the DB site, where some small puddles were exposed to the sky 446 in the wet season, could have contributed to the decrease in albedo. In contrast, such a 447 decrease in albedo was not observed even during flooding at the UF site because the soil 448 surface was mostly covered with canopy. Loarie et al. (2011) reported a similar result,

449 where flooding decreased forest albedo in South America.

In the forest sites in the present study, defoliation increased slightly in October–
December (data not shown). In addition negative GWL peaks were regularly observed

452 in September–October. Leaf color turns brighter due to drying during the dry season 453 with a slight corresponding decrease in LAI. Therefore, albedo had a negative 454 relationship with GWL (Fig. 8) at the UF and DF sites. Sanchez-Mejia et al. (2014) 455 have also investigated the relationship between albedo and GWL in a semiarid 456 shrubland. They reported that albedo increased by about 0.03 in a closed canopy site 457 and by about 0.05 in an open site with a lowering of GWL 0 to -0.6 m. The rates of 458 increase are higher than those observed at our sites: 0.006 (UF), 0.005 (DF), and 0.001 459 (DB), following the lowering of GWL by 0.6 m (Fig. 8).

An increase in albedo with a lowering of GWL seems to be inconsistent as in this study in which the albedo at the DF site was not greater than that at the UF site. Although the differences between the UF and DF sites in canopy structure, tree species and phenology are potential reasons for the discrepancy, further investigations are required to establish robust evidence to explain this inconsistency.

465 In the present study the albedo increased at the lowest VPD range (VPD<ca.10 hPa) 466 at the UF and DF sites. Water droplet might increase reflection of incoming solar 467 radiation. Some water droplets might have remained on the leaf surfaces at the UF and 468 DF sites even more than an hour after the rainfall under low VPD conditions whereas 469 water droplets easily evaporated at the DB site. This could be because of the difference 470 in vegetation height and structure between the forest and burned sites. Conversely, 471 albedo increased at the highest VPD range (VPD 2 ca. 25 hPa) at all three sites, 472 potentially because leaf surfaces become lighter and reflection on leaf surfaces is 473 enhanced to facilitate adaptation to water deficit under dry atmospheric conditions (e.g., 474 Yu et al., 2000). Therefore, changes in pedospheric and atmospheric moisture (or 475 dryness) influenced albedo via vegetation responses, especially those of leaves.

477

478 **5.** Conclusions

479 Our continuous long-term field observations revealed the impact of fire and water 480 conditions (GWL and VPD) on albedo in tropical peat ecosystems. Fire decreased land 481 surface albedo by exposing the dark-colored peat soil. Subsequently, ferns regenerated immediately and expanded over the ground surface. Conversely, intensive fire 482 483 sometimes caused severe haze. Apparent albedo sharply increased under such hazy 484 conditions because the haze layer between the radiometer and canopy increased 485 reflection of incoming downward radiation. Hence, the albedo of vegetation cannot be 486 measured under such hazy conditions. Nevertheless, decreasing GWL slightly increased 487 the albedo in both the undrained and drained forests. At the highest VPD range 488 (VPD 2ca.25 hPa), the albedo increased at all sites. Therefore, both pedospheric and 489 atmospheric dryness increased albedo. When the soil surface was water-saturated (GWL 490 ≥ 0 m), albedo at the burned site decreased because the ground was dotted with exposed 491 puddles. In contrast, no decrease was observed in the undrained forest because open 492 water with low albedo was covered by the forest canopy.

We observed several environmental changes in response to rapidly shifting land surface characteristics. Therefore, short-interval measurements are required for the accurate evaluation of change in albedo. Our study also explored changes in albedo under heterogeneous environments. The expansion of the target area to the entire Southeast Asia and observation of trends under diverse meteorological conditions over different land cover types, including oil palm and acacia plantations, would be insightful. In addition, long-term continuous field observations before and after land conversion 500 would reveal impacts with a high temporal resolution.

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- 502

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664 **Figure legends**

- 666 Fig. 1 Map of the study area.
- ⁶⁶⁷ Fig. 2 Canopy photos of (a) UF, (b) DF and (c, d) DB sites.
- Fig. 3 Schematic diagram of the partitioning of incoming shortwave radiation under
 severe haze conditions.
- Fig. 4 Monthly variations in (a) precipitation, (b) GWL, (c) albedo, (d) BF, and (e) AOD. Precipitation shown in panel (a) was observed at the DF site. Month with BF > 0.02 in either cell was shown by shading in panel (b)-(e) as indicating fire event. Beginning month of canal construction in the vicinity of DB site is marked with an arrow in panel (b).
- Fig. 5 Seasonal variations in monthly mean albedo at (a) UF, (b) DF, and (c) DB sites. Plots are classified into five categories by BF: BF<0.005, $0.005 \le BF$ <0.01, $0.01 \le BF$ <0.02, $0.02 < BF \le 0.03$, and $0.03 \le BF$. The polyline connects the monthly average with BF<0.005. Grey bars show the 95% confidence interval determined by a bootstrap method with 1000 replications.
- Fig. 6 Inter-site differences in monthly albedo. The mean (plots) and 95% confidence
 interval (bars) were determined by the bootstrap method with 1000 replications.
- Fig. 7 Inter-annual variation in albedo at (a) UF, (b) DF, and (c) DB sites. Monthly data
 for only April–June are shown to exclude the influence of fire.
- Fig. 8 Relationship between albedo and GWL at (a) UF, (b) DF, and (c) DB sites. Plots were classified into five categories by AOD: AOD<0.5, $0.5 \le AOD < 1$, $1 \le AOD < 2$, $2 \le AOD < 3$, and $3 \le AOD$. Data with $AOD \ge 0.5$ in September–October 2012 were
- 687 marked with crosses. A line was fitted to the data with AOD<0.5. In panel (c),
 - 30

- 688 line fitting was separately applied to two GWL ranges: GWL<0 and GWL≥0.
- 689 Fig. 9 Relationship between albedo and VPD at (a) UF, (b) DF, and (c) DB sites. Plots
- are classified into five categories by AOD, as shown in Fig. 8.
- 691
- 692

693 Figure 1





Location of observation towers

694

696 Figure 2



(b) DF site



(c) DB site in a dry condition



(d) DB site in a wet condition



699 Figure 3

















Table 1

732 Site information

733

Site		UF	DF	DB
Geographical position		2.32°S, 113.90°E	2.35°S, 114.04°E	2.34°S, 114.04°E
Observation period		July 2004–June 2017	November 2001–June 2017	April 2004–February 2017
Canopy heig	ht (m)	23	26	0.2–1.8
Radiometer		36.3	40.6	3.3 (Apr 2004–Mar2012)
measurement height (m)				6.8 (Mar 2012–Dec 2013)
				13.6 (Dec 2013–Feb 2017)
Air	temperature	36.0	41.7	1.5
measurement height (m)				

735 Table 2

736 Nomenclature

Notation	Unit	Definition
GWL	m	Groundwater level
Su	$W m^{-2}$	Upward shortwave radiation
S_d	W m ⁻²	Downward shortwave radiation
BF		Burned fraction
VPD	hPa	Vapor pressure deficit
AOD		Aerosol optical depth
Hobs	m	Observation height
Hcano	m	Canopy height
β		Reflectance of the haze layer
γ		Absorbance of the haze layer
λ		Transmittance of the haze layer
α_{cano}		Albedo at the canopy
α_{obs}		Albedo at the observation height
x_L	m	Distance between observation height and canopy height
b _{ext}		Extinction coefficient
x_{v}	m	Visibility distance

Table 3

738 Comparison of albedo from forest and peatland sites.

Site type	Albedo	Reference
Tropical peatland	0.092–0.099	This study
Amazonia forest	0.114–0.115	Cescatti et al., 2012
Amazonia forest	0.12	Oliveira et al., 2019
Finnish peat bog	0.132	Gao et al., 2014
Open mesotrophic fen	0.137	Lohila et al., 2010
Open Finnish peatland	0.140	Kuusinen et al., 2013

742 Appendix

	UF	DF	DB
Jan	0.0968 ± 0.0030	0.0944 ± 0.0046	0.1000 ± 0.0166
Feb	0.0950 ± 0.0033	0.0909 ± 0.0049	0.0973 ± 0.0185
Mar	0.0942 ± 0.0025	0.0890 ± 0.0043	0.0940 ± 0.0174
Apr	0.0927 ± 0.0024	0.0863 ± 0.0057	0.0873 ± 0.0208
May	0.0922 ± 0.0034	0.0874 ± 0.0063	0.0929 ± 0.0185
Jun	0.0944 ± 0.0038	0.0892 ± 0.0055	0.0974 ± 0.0176
Jul	0.0951 ± 0.0044	0.0910 ± 0.0053	0.1028 ± 0.0127
Aug	0.0953 ± 0.0034	0.0906 ± 0.0043	0.1021 ± 0.0114
Sep	0.0961 ± 0.0032	0.0938 ± 0.0039	0.1090 ± 0.0086
Oct	0.0947 ± 0.0055	0.0901 ± 0.0053	0.1063 ± 0.0111
Nov	0.0944 ± 0.0060	0.0919 ± 0.0059	0.1032 ± 0.0154
Dec	0.0962 ± 0.0049	0.0967 ± 0.0056	0.1022 ± 0.0216

744 Monthly albedo (mean ± 1 standard deviation)