Roles of fire history and rewetting in peatland restoration and vegetation recovery on the Merang peat dome, South Sumatra, Indonesia

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SUMMARY

In the restoration of drained and degraded tropical peat swamp forest (PSF) it is not well understood whether fire suppression on its own is sufficient to facilitate regeneration, or if rewetting plays a key role. We attempt to answer this question in the Merang area, a 23,000-ha peatland located in South Sumatra province, Indonesia. As with more than 90 % of PSF in Southeast Asia, the area has been largely degraded by logging and drainage canals, along with multiple fires. It has been designated and managed as an ecosystem restoration area since 2016, by which time only a single 254 ha patch of original PSF habitat remained. However, scattered remnant PSF trees (< 1 % cover) occurred throughout the area, along with seedlings of pioneer woody species in a landscape otherwise dominated by sedges and ferns. Peatland rehabilitation began with installation of 84 box dams in 2017, followed by 212 peat compaction dams mainly between late 2019 and early 2020. Since installation of the latter, the average water table depth (WTD) has decreased by 20–120 cm. In parallel with reduced WTD and fire prevention, regrowth has been vigorous, with total cover of woody plants increasing by almost a third, from 28.6 % in 2016 to 39.4 % in 2021. At the same time, changes in normalised difference vegetation index (NDVI) indicate a doubling in increase of woody vegetation cover between 2017–2020 and 2020–2021. Reduced WTD supports the recovery of woody vegetation cover, but Principal Component Analysis (PCA) strongly suggests that fire history determines the species composition of regenerated woody pioneer vegetation. *Melaleuca cajuputi* dominates where fires have been most frequent (on average > 4 fires), while *Macaranga pruinosa*, *Melicope glabra* and *Melicope lunu-ankenda* dominate in regenerating areas that have experienced 1–2 fires. While fire suppression is essential to prevent further loss of vegetation, effective rewetting is required before woody vegetation can recover.

KEY WORDS: compacted peat dams, *Macaranga*, *Melaleuca*, *Melicope*, peat swamp forest, pioneer species

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INTRODUCTION

Indonesia has 14.9–20.6 Mha of peatlands (Wahyunto *et al.* 2003, 2004, 2006; Page & Rieley 2016, Warren *et al.* 2017) including about 12.3 Mha in Sumatra and Kalimantan (Hooijer *et al.* 2010, Mietinnen e*t al.* 2012, Osaki *et al.* 2016). Most of these peatlands are located in coastal lowlands and have formed in the past 4,000–10,000 years as a consequence of the Holocene maximum in regional rainfall and stabilisation (Neuzil 1997, Dommain *et al*. 2011). Originally, these coastal lowland peatlands were dominated by tall peat swamp forest (PSF) (Page & Rieley 2016) and formed a habitat for unique biodiversity (Posa *et al.* 2011). In addition, Indonesian PSFs store globally significant amounts of carbon, regulate water across the landscape, and benefit local people by providing timber, hunting and fishing resources along with a variety of non-timber forest products that contribute to livelihoods (Hergoualc'h *et al.* 2018).

Since the 1980s, however, Southeast Asian PSFs have been intensively logged and large parts have been drained and converted to other land uses or are degraded and remain unused (Page *et al.* 2009, Miettinen *et al.* 2016, Giesen & Sari 2018). According to Dohong *et al.* (2017), the main drivers for peatland degradation in Southeast Asia are logging and conversion to industrial plantations. Conversion involves drainage, leading to recurrent fires, peat subsidence, flooding and further degradation (Wösten *et al.* 2006, Hooijer *et al.* 2012, Dohong *et al.* 2017). Oil palm and *Acacia* (pulp) plantations extended over 6.3 Mha of peatland on Sumatra and Kalimantan (Borneo) by 2015, with most of the remaining PSF on these islands being degraded (Miettinen *et al.* 2016).

During the severe 2015 El Niño drought about 850,000 ha of peatlands in Sumatra and Kalimantan were burnt and in that year 81 % of Indonesia's greenhouse gas emissions were estimated to originate from peatland fires (Pribadi & Kurata 2017). At the same time, economic losses in Indonesia were estimated to be at least USD 16 billion (World Bank 2016) and 1.3 Tg of carbon was released to the atmosphere (Huijnen *et al.* 2016). In response to these events, in January 2016 the Indonesian government established the National Peatland Restoration Agency by Presidential Decree (PerPres No. 1/2016) with a mandate to coordinate and facilitate the restoration of 2.49 Mha of degraded peatlands during the period 2016–2021 (Purnomo *et al.* 2018), under a peatland restoration programme that focused on rewetting, revegetation, and the revitalisation of livelihoods (the '3Rs approach').

Rewetting and improving the hydrological function of degraded peatland is expected to trigger faster natural regeneration of peatland vegetation (Jaenicke *et al.* 2011). While this seems an obvious course of action for peatlands that are drained and degraded, there are also risks, as drainage of peatland leads to soil subsidence and can potentially increase future flooding (e.g., Sumarga *et al.* 2016). A recent review of 94 replanting pilots and studies on degraded peat between 1988 and 2019 (Smith *et al.* 2022) indicates that rewetting significantly reduces survival rates of PSF seedlings although it does not affect the half-life of seedlings (as a measure of time until 50 % mortality) or relative growth rates. As explained by those authors, native PSF species are adapted to waterlogging (especially to root hypoxia), but seedlings can still die when full submergence leads to stomatal closure and reduced photosynthesis (Smith *et al.* 2022). Most of the 94 trials and studies are small-scale, however, and larger scale peatland restoration programs in Indonesia such as the 23,000 ha Sumatra Merang Peatland Project (SMPP) (targeting the Merang peat dome) in South Sumatra and the 149,800 ha Katingan Mentaya project in Central Kalimantan have so far not resulted in publications on the roles of rewetting and fire suppression in revegetation.

Fires obviously need to be prevented to avoid immediate loss of any recovering PSF vegetation (Page & Hoscilo 2016, Putra *et al.* 2018). However, is fire suppression on its own sufficient to facilitate PSF regeneration or does rewetting play a key role, in spite of indications that rewetting affects the survival of PSF seedlings? This article sets out to further clarify the roles of both fire (suppression) and rewetting on the recovery of woody peatland vegetation.

METHODS

Study site

Location and management

Our SMPP study site at Merang is a 22,922 ha peat dome located in the north-eastern part of South Sumatra province, Indonesia (coordinates of centre of SMPP area: 2° 01' 18.2" S, 104° 08' 28.6" E) (Figure 1) and extends to approximately 14 km (north–south) by 21 km (east–west). Peat depths vary from 2–3 m in the west to more than 7 m in the north-east, and the average peat depth is > 5 m (Forest Carbon 2019). Until the 1990s, the SMPP peatland still supported largely original PSF habitat typical for the peatlands of Sumatra and Kalimantan.

The study area was managed under a forestry concession and logged between 1989 and 2001. After this it was subjected to widespread illegal logging from 2001 to 2015, whereby many canals were excavated to ease the extraction of logs. By 2009 a total of 213 km of canals had been excavated (Barkah & Sidiq 2009), leading to lowering of the water table. From 2008 to 2011 the area was targeted by the Merang REDD Pilot Project (MRPP) (Rayan 2010), but illegal logging and burning continued nevertheless.

Based on our interpretation of 2016 Planetscope surface reflectance mosaic satellite images (https://www.planet.com/pulse/surface-reflectance-basemaps/), only one patch of about 254 ha of PSF vegetation remained at the SMPP site by 2016 (Figure 2). Closed canopy tree species in this small PSF remnant include *Campnosperma coriaceum*, *Carallia brachiata*, *Dacryodes costata*, *Durio carinatus*, *Ganua motleyana*, *Horsfieldia glabra*, *Mezzetium parviflora*, *Myristica iners*, *Palaquium burckii*, *Polyalthia sumatrana*, *Sindora bruggemanii*, *Syzygium acuminatissimum*, *Syzygium clavimyrtus*, *Vatica rassak* and *Xylopia altissima*. Emergent tree species include *Alstonia pneumatophora*, *Dyera polyphylla*, *Koompassia malaccensis*, *Shorea teysmanniana*, *Shorea uliginosa* and *Tetramerista glabra*. The understorey includes palms such as *Cyrtostachys renda*, *Eleiodoxa conferta*, *Licuala paludosa*, various rattan species (e.g., *Korthalsia* sp.) and the tall pandan *Pandanus atrocarpus* (Barkah

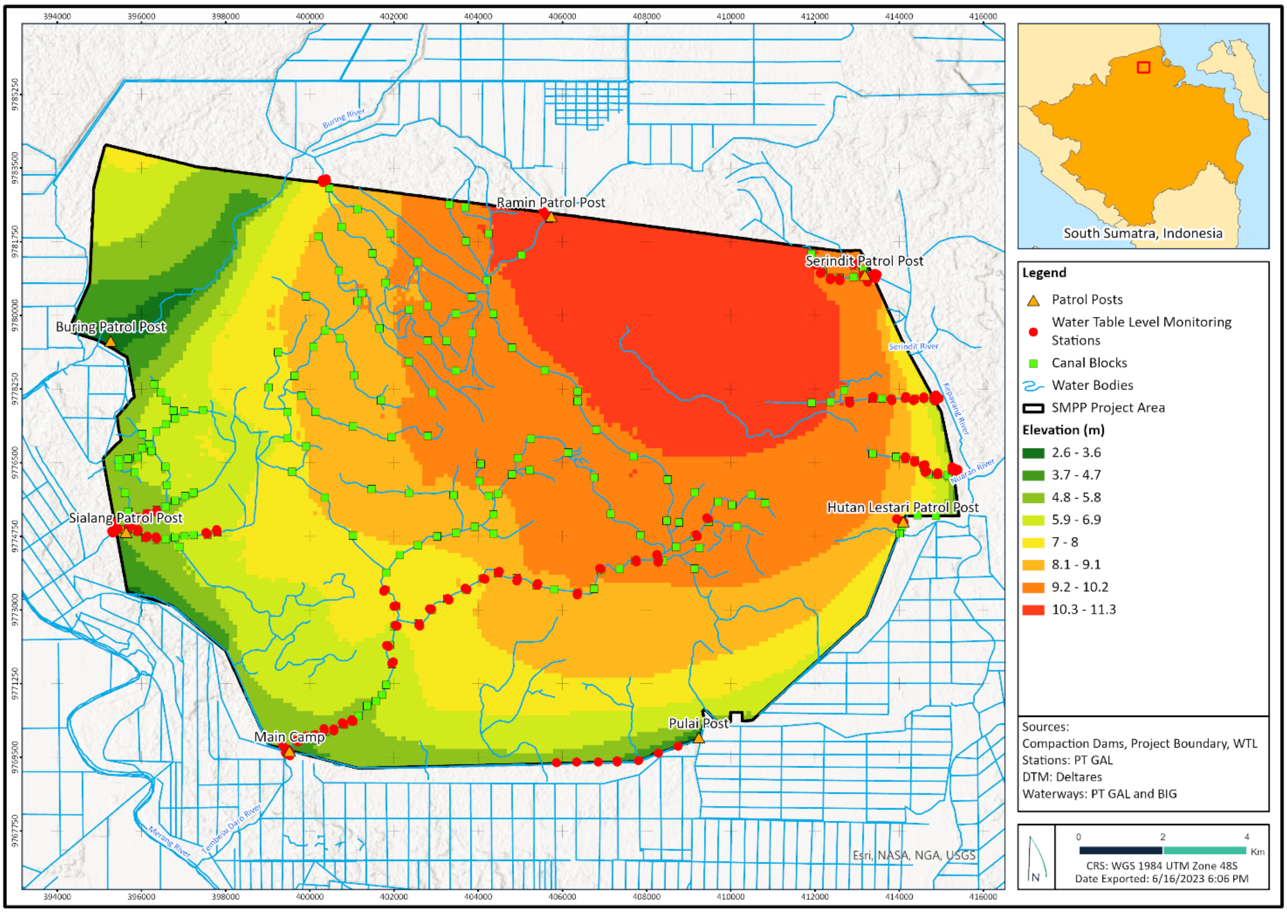

Figure 1. Digital Terrain Model (DTM) of the SMPP study area and 1 km adjacent area. Water bodies, dipwells, patrol posts and compacted peat canal blocks are shown. The DTM corresponds with peat depth, with 2–3 m peat depth in the west/south-west and depths of 7 m and more in the north-east. Peat depths are based on GIZ MRPP measurements in 2009–2010 (Forest Carbon 2019) from 132 boreholes with use of kriging for interpolation.

2009, Giesen 2018). Outside the 254-ha remnant forest, isolated mature trees of the original PSF occur scattered throughout the degraded peatland of the study area, albeit at very low densities (cover < 1 %), along with seedlings of pioneer tree and shrub species that are found at higher densities (Giesen 2018). This degraded peat landscape is otherwise dominated by sedges and ferns.

Since 2016, the Merang peatland has been designated as a carbon storage and sequestration licensed area (*Izin Usaha Pemanfaatan Penyerapan Karbon dan/atau Penyimpanan Karbon* or PAN/RAP) (Buergin 2016) - the Sumatra Merang Peatland Project (SMPP) - and has been under active management in a 47-year licence including sustainable forest management, conservation forest management and biodiversity protection (see *prinsip penyelenggaraan karbon hutan* in: Ministry of Forestry 2012). The area remains uninhabited apart from SMPP staff based at a main camp and five additional patrol posts, all located on the edge of the SMPP peatland (Figure 1). The SMPP area borders on oil palm and *Acacia crassicarpa* plantations to the west and south, the Kepayang village forest to the east and a High Conservation Value (HCV) forest (managed by a plantation concession) to the north.

The eastern boundary of the SMPP area lies 4–5 km from Berbak-Sembilang National Park, a 360,000 ha peatland and mangrove area designated Indonesia's first Ramsar wetland of international importance, and the core of the larger Berbak-Sembilang UNESCO Biosphere Reserve (Silvius *et al.* 2016). The SMPP area provides a corridor between the National Park to the east and the surrounding HCV areas, and its use is confirmed (via camera trapping among other means) by the occurrence of key species such as Sumatran tiger (*Panthera tigris* ssp. *sumatrae*) and Malayan sun bear (*Helarctos malayanus*), numbers of which have been rising since 2016 (Forest Carbon 2021).

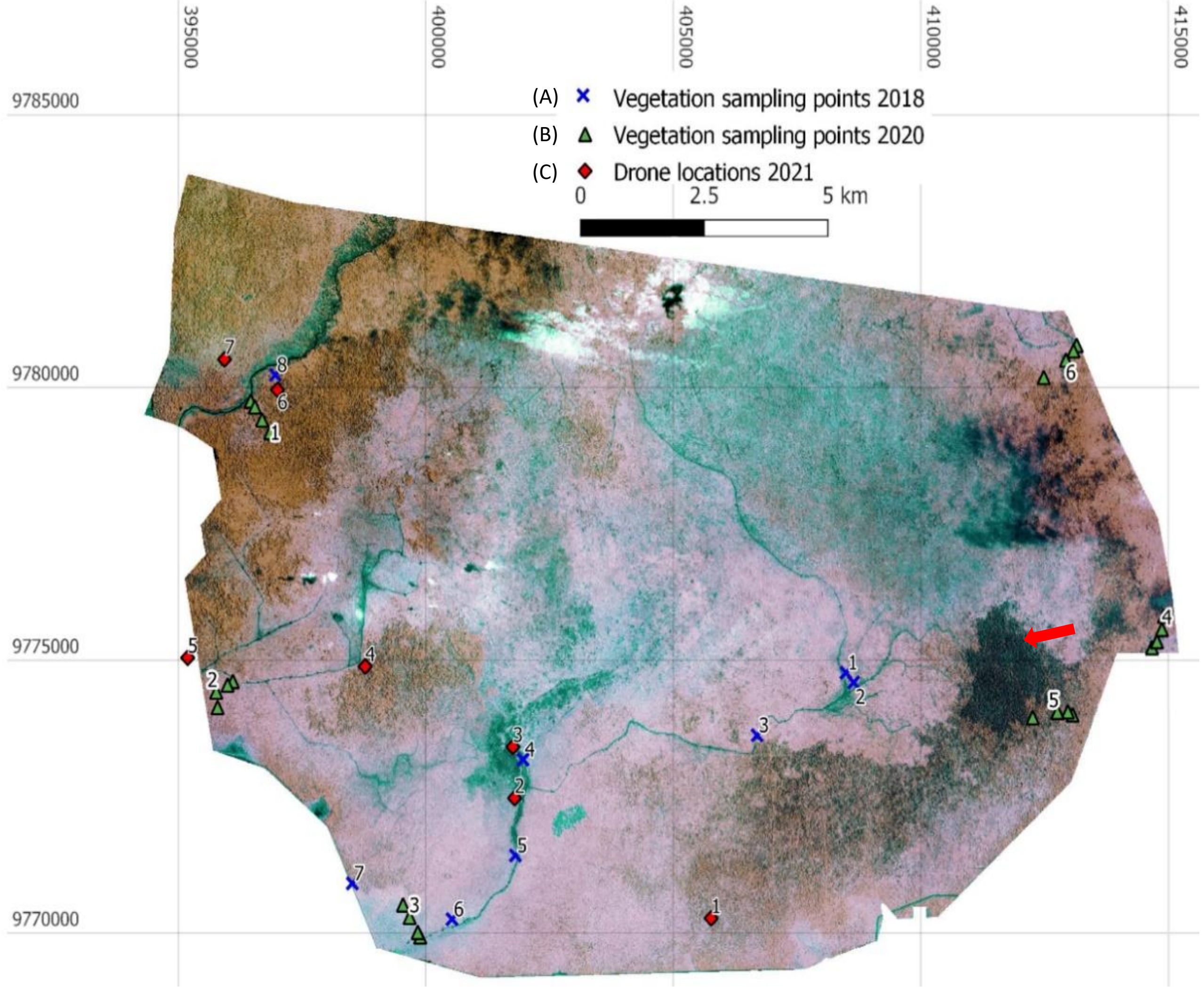

Figure 2. Locations of SMPP sampling points 2018–2021. These are projected onto the Planetscope mosaic satellite image of 2020. Sample points are selected in areas where recovery of woody vegetation is apparent (dark reddish-brown or dark bluish-green, with coarse structure). Note the contiguous 254 ha patch of remnant original PSF (dark green, indicated by red arrow) in the eastern part of the study area. Field sampling: (A) 2018 = field records of species occurrence along 5 m × 50 m transects; (B) 2020 = 24 plots at six locations, using 2 m × 2 m plots for herbaceous vegetation and 8 m × 8 m, 16 m × 16 m or 32 m × 32 m plots for woody vegetation; (C) 2021 = drone imagery, taken from a height of 10–30 m.

Fires and rewetting

Tree felling and canal excavation created circumstances that led to wildfires affecting about 1,000 ha of the SMPP area in 2005 and 9,000 ha during the El Niño drought of 2007/8. During the devastating El Niño of 2015 about 17,500 ha was burned, leaving unaffected only the 254 ha pocket of remnant PSF described earlier and an area of a few thousand hectares along the central Tembesu Daro River, which had burned in previous years. Since 2015, fires have not occurred at Merang apart from a small fire of < 10 ha in 2019 that was quickly suppressed. Table 1 summarises the fire history of SMPP, while details are provided in Appendix 1.

To reduce fire risk and allow vegetation recovery in the SMPP area, a programme of rewetting was undertaken focusing on blocking the 213-km canal system to reduce drainage of the area. Rewetting has occurred in three stages. In 2010, four ‘box dams’ (i.e., wooden frames filled with bags of earth or peat; see Appendix 2 for an example of a box dam) were constructed as initial trials. In 2017–2018, 84 box dams were constructed, and subsequently 212 compacted peat dams (see Appendix 2 for example compacted peat dams) were completed from December 2019 to early 2022 (Figure 1 and the map in Appendix 2; note that 188 out of 212 had been completed by March 2020). Details of dam

Table 1. Fire history at the SMPP study area, 2001–2015 (there were no significant fires after 2015). Landsat 7 true colour satellite images from 2001 to 2015 were used to determine the number of fires that had occurred at each of the 21 vegetation sample point locations. Burn scars can be readily detected on these images because they stand out as bright red or brown scars in an otherwise green landscape (Appendix 1). Burnt areas (ha) were determined by superimposing a grid, while number of fires per sampling location was determined by simply superimposing these sites on the satellite imagery and counting the number of times the location was affected by fires.

Date of imagery	Location	Burnt area (ha)	# burnt sampling points
06 Sep 2001	Along the Buring river and canal in far north-east	25	0
18 Jun 2004	Along the Buring and Tembesu Daro rivers, patch in middle-west, small scattered patches in north-east.	150	1
20 May 2005	Large central area along Tembesu Daro (750–2000 ha) plus area in north-east (200 ha) and along south-west border (20 ha).	1,100	3
12 May 2008	About 40 % of total area, especially in north, north-east and central area, but also in the south-west.	9,000	4
31 May 2009	Small scattered fires along Tembesu Daro (< 199 ha), mid-north (20 ha), mid-west (50 ha) and mid-south (50 ha).	200	2
09 Oct 2010	Fires along/around Tembesu Daro (250 ha) and scattered mid-south-west (100 ha) and south (150 ha).	500	3
27 Jun 2013	Broad zone along the entire Tembesu Daro, along many canals in south-west and central area burned during 2005 fires.	2,500	7
10 Aug 2015	Large patch in north-west, not near Buring or Tembeu Daro	350	0
05 Sep 2015	Same patch as previously but expanded (500 ha), and along Buring river (200 ha) and mid-north (120 ha).	820	11
05 Jul 2016	Most of the SMPP area burned in previous year, except for central area along Tembesu Daro, some patches in far north and 200+ ha in far south-east which escaped burning in 2015. No recent (2016) fires visible.	17,500	20

construction are provided in Appendix 2. Canals at SMPP are 2–6 m wide and 1.3–1.5 m deep, and the respective widths of the 212 compacted peat dams are 7 m (n = 179), 9 m (n = 31) and 11 m (n = 2). On average, the dams have been constructed to a height of 128 cm (range is 105–170 cm) above the field level. These compacted peat dams have proved durable and only one had required replacement by 2021, although most have developed minor spillways around the edges, meaning that the water level is at or near the surface of the peat.

Rainfall in the SMPP area was measured daily with standard raingauges installed in the six patrol posts surrounding the project area (Figure 1). Annual rainfall in 2021 was 2,049 mm. The long-term average annual rainfall from 1970 to 2000 was 2,547 mm (Fick & Hijmans 2017), with drier months usually from June to September. This shows the same pattern as in Jambi City (Sultan Thaha Airport; 1° 38' 10'' S, 103° 38' 31'' E, operated by the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG)) located 50 km from the SMPP main camp. However, SMPP average annual rainfall is 17 % lower than Jambi City's 44-year long-term average of 2903 mm. The patrol post weather stations indicate that in 2020 SMPP rainfall was only 0.5 % lower than the long-term average (2,380 mm), while 2019 was 25 % drier (1,820 mm).

Survey methods

Hydrology

Each of the six patrol posts (which includes main camp) is equipped with a weather station consisting of a thermometer, a hydrometer, a raingauge, and five dipwells set along a 200 m transect perpendicular to the nearest canal with daily water table depth (WTD = ground level *minus* water table level) measurements. The dipwells are PVC tubes (diameter 10 cm) with many small holes drilled through their walls, that sit vertically in the peat so that WTD can be measured (manually). In addition to the 30 patrol post dipwells there are 251 dipwells that are measured at monthly intervals. These are mainly located along rivers and canals at distances of up to 2 km from the SMPP border; an exception is the series of 26 dipwells along the 15 km length of the Tembesu Daro River. The daily patrol post WTD data covers 2019 and 2020.

Spatially explicit assessment of the effect of canal blocks on WTD was conducted using the observed WTDs and weather measurements. For our statistical approach we use the pre- and post-dam WTDs and weather measurements to try to separate out the effect of the dams on WTD. This simple setup imposes two key restrictions on what the dataset can be used for. On the one hand, WTD data are needed both before and after dam placement. On the other hand, precise weather measurements are required. Only the data from three patrol posts fulfil these requirements. The rest of the dipwells do not have weather station measurements, do not have a dam nearby, or do not have data from before installation of the dams.

The two main weather variables affecting the water balance of tropical peatlands are rainfall and evapotranspiration which, in turn, affect the WTD. Compared to rainfall, which can vary by up to 150 mm from day to day (Lee 2015), evapotranspiration (daily range up to 3–6 mm; see Hirano *et al*. (2015) and Wati *et al.* (2018)) can be considered constant for our purposes. Therefore, our simple statistical model uses only rainfall.

There is a delay between a rainfall event and its effect on WTD. For this reason, we used a rolling window of 10 days' cumulative rainfall prior to the WTD measurement (10*dayCumP*). Our baseline model of WTD in the absence of dams (WTD_b) is expressed by the following linear regression:

$$WTD_b = a + b \times 10dayCumP \qquad [1]$$

where a and b are constants. We calculated WTD_b separately for each dipwell in all three transects for the period following the installation of canal blocks, compared the result with WTD measured post-dams (WTD_{pd}), and all differences (ΔWTD_{dams}) were attributed to the effect of the dams:

$$\Delta WTD_{dams} = WTD_{pd} - WTD_b \qquad [2]$$

Annual averages of ΔWTD_{dams}, calculated using Equation 2 for each dipwell, were plotted against distance from the dipwell to the nearest dam.

Vegetation assessment

Vegetation was assessed using two approaches: i) field sampling/assessments and analysis, and ii) analysis of satellite imagery. The field data were then subject to a Principal Component Analysis (PCA) (Abdi & Williams 2010) using the Plotly open-source module of the programming language Python that is used for data visualisation and support (https://plotly.com/python/pca-visualization/). The PCA was limited to the 18 most common tree species because it is difficult to conduct a reliable assessment of herbaceous vegetation and small shrubs using drones (see sub-section iC. below), especially where they are obscured by trees.

Field sampling focused on degraded peatland in the SMPP area and served to identify plant species and their relative abundance. All identification of plant species was carried out by the same person and follows Giesen *et al.* (2018) with taxonomy according to WFO (https://worldfloraonline.org/). Three rounds of field sampling (iA, iB, iC) were carried out during the period 2018–2021 at the locations indicated in Figure 2.

iA. Random stratified sampling of vegetation at eight locations, along transects of 5 m × 50 m (24–26 April 2018). The locations were selected using the Land Use Land Cover (LULC) map produced by Forest Carbon in 2017 on the basis of a Sentinel 2A image (06 July 2017) and a Landsat 8 OLI image path/row 125/61 (23 May 2016) (Giesen 2018). This LULC map recognised vegetation types based on broad physiognomics: remnant PSF, young secondary scrub, mature secondary scrub, flooded scrub, open water, and *Melaleuca* secondary scrub. Sampling was carried out in all types except open water (no observable vegetation) and flooded scrub (which was inaccessible). The presence of all tree and shrub species was recorded, regardless of specimen size.

iB. Detailed ground truthing in 24 plots at six locations, 2 m × 2 m for the herbaceous layer and 8 m × 8 m, 16 m × 16 m or 32 m × 32 m for woody vegetation, were conducted by Forest Carbon field teams at six locations in August–September 2020. These locations were selected using remote sensing (RS) imagery (Planetscope mosaics based on annual data with 4.77 m spatial resolution, 4 band (red, green, blue, near-infrared) spectral resolution) obtained for 2016–2021. Locations were selected so that they occurred in areas with woody vegetation (as visible on imagery) and spatially complemented the 2018 sampling (see iA). Data recorded in the plots were: all plant species involved, an estimate of cover/density; and for woody species the number of individuals, diameter at breast height (DBH) and height. Photos were taken at all locations so that plant species identification could be verified.

iC. Drone fly-over ID of vegetation types. Locations where the most vigorous recovery of woody vegetation had occurred were identified by comparing 2016 and 2020 RS Planetscope surface reflectance mosaic images; this resulted in the identification of seven target locations. As negative WTDs severely restricted field access, full colour photos, with a ground sampling distance of 3 cm per pixel, were taken at these seven locations between 24 February and 01 March 2021 with a Hasselblad L1D-20c camera[1] from low altitude (10–30 m above the vegetation) using a DJI Mavic Pro 2 drone. Key woody species and their relative abundance were then identified based on physical characteristics. During the 2018 field surveys (see A), drone imagery was also taken while in the field, and used later to confirm identification on the 2021 drone surveys in areas that had become inaccessible due to rewetting.

Satellite imagery (Planetscope annual mosaics; see iiB) was analysed using the normalised difference vegetation index (NDVI) and a grid analysis of woody vegetation cover.

iiA. NDVI analysis. NDVI is a relatively simple graphical indicator based on ‘greenness’ of a landscape based on a calculation of individual spectral measurements:

$$NDVI = \frac{(NIR-VIS)}{(NIR+VIS)} \qquad [3]$$

where VIS and NIR stand for the spectral reflectance measurements acquired in the visible (red) and near-infrared regions, respectively (Defries & Townshend 1994, Hartoyo *et al.* 2021). By design, NDVI varies from -1.0 to +1.0. It should be noted that NDVI is functionally, but not linearly, equivalent to the simple infrared/red ratio (NIR/VIS). Differences in NDVI (ΔNDVI) therefore reflect changes in greenness and hence changes in vegetation, and a positive NDVI represents an increase in cover/density. In practice, difference in NDVI is mainly related to changes in tree cover (Hartoyo *et al.* 2021). An attempt was made to perform an annual NDVI analysis using Planetscope surface reflectance mosaic images from 2016–2021. However, a cloud/thin cloud haze cover on images from 2016, 2018 and 2019 caused interference that prevented NDVI analysis for these years and hence NDVI analysis was limited to a comparison between 2021, 2020 (for which year the effects of several clouds and shade had to be removed manually) and 2017, which was the least cloud-affected image prior to the SMPP canal blocking programme.

iiB. Grid analysis of cover of woody vegetation. A transparent grid, whereby approximately 500 grid blocks covered the SMPP project area, was overlaid onto annual Planetscope images from 2016–2021. For each grid block the percentage cover of woody vegetation was visually assessed on an enlarged image. To limit bias, each assessment was repeated twice by the same assessor and averaged.

RESULTS

The hydrological data are displayed in Figure 3, and Table 2 summarises the WTD and rainfall statistics at the patrol posts before and after the installation of compacted peat dams. WTD was significantly less (i.e., the water table was higher) after the dams were built, while the average rainfall increased at two of the three patrol posts and remained similar at the third. Figure 4a shows the WTD measurements at the patrol posts before dam installation, and Figure 4b shows the measurements after dam installation (WTD_{pd}). The baseline WTD (WTD_b) calculated using Equation 1 is shown in both of these Figures for comparison. ΔWTD_{dams} (Equation 2) corresponds to the distance between the regression line and the points in Figure 4b. Thus, the simple hydrological model applied to the period 2019–2020 indicated that the dams in the canal network reduced the annually averaged WTD by an amount in the range 20–120 cm (Figure 5), compared to the situation before the compacted peat dams were installed. This effect was most pronounced close to the dams. Measurements concentrated close to the dams and the canal network indicated a slightly greater change in WTD (up to 120 cm, Figure 5).

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[1] The camera contains a 1" CMOS sensor with 20 MP (megapixel) effective pixels, a lens with FOV (field of view) 77°, focal length 35 mm (28 mm format equivalent), aperture f/2.8–f/11, and focus distance (auto focus) 1 m to ∞. Raw images are stored as RGB mode (3:2 aspect ratio; 5472 × 3648 pixels) in JPEG format.

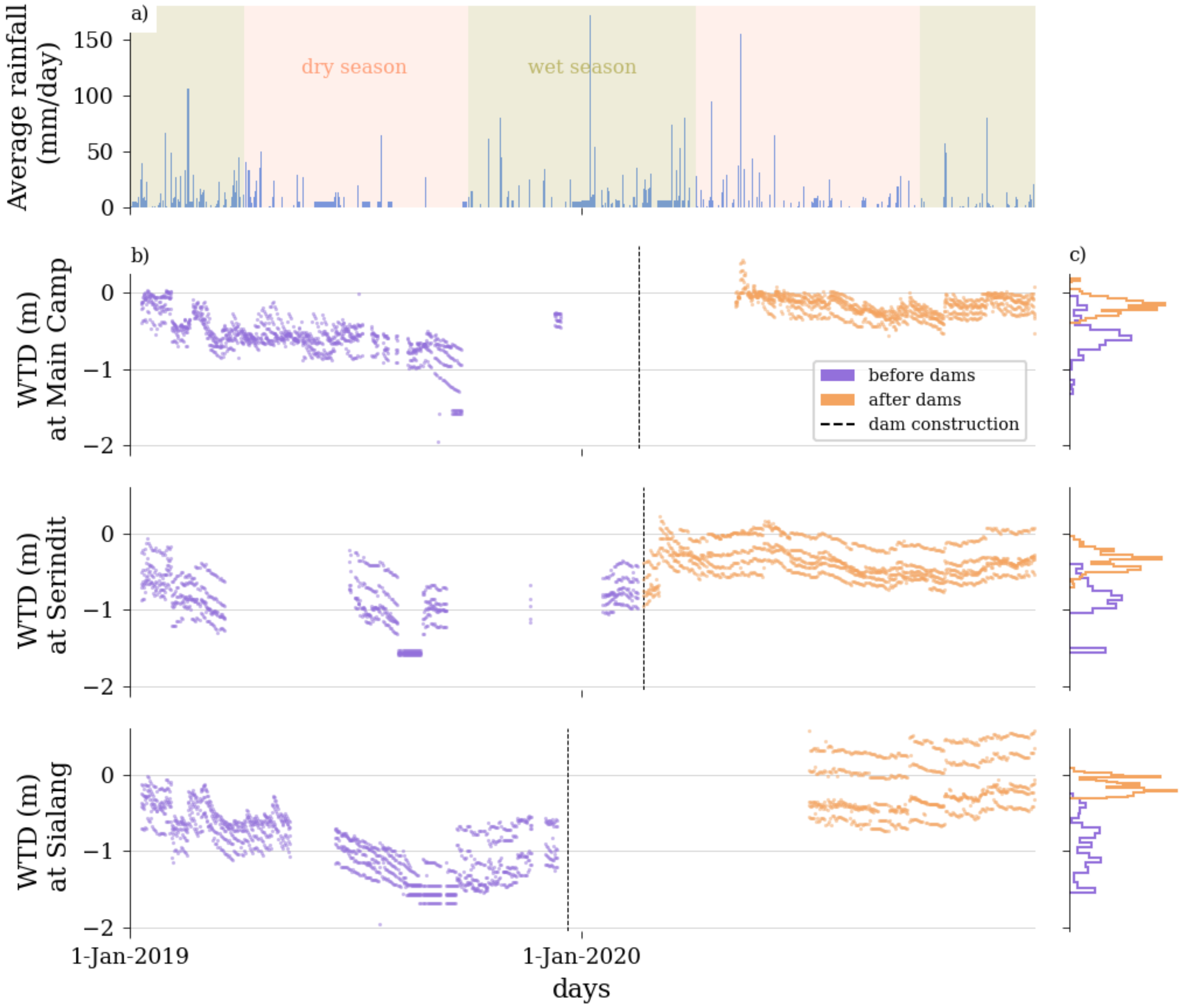

Figure 3. Summary of hydrological data for the years 2019 and 2020. a) Daily rainfall, averaged over patrol posts (blue bars), with wet and dry seasons indicated by the shaded areas. b) Water table depth (WTD) at the patrol post transect dipwells (5 dipwells per transect). WTD data collected before and after dam construction are shown in purple and orange, respectively. The dam construction date is indicated by a black dashed line. c) Normalised histograms of WTD values from b).

Table 2. Hydrological information from the SMPP patrol posts. “Main Camp”, “Serindit” and “Sialang” are the names of the patrol posts (refer to Figure 1 for locations). WTD and Rainfall values are averages of all available readings (five dipwells, one raingauge) at each transect; values in (brackets) are standard deviations.

	Main Camp	Serindit	Sialang
Before installation of canal block:			
Average daily WTD (m)	-0.54 (0.24)	-0.88 (0.28)	-0.93 (0.34)
Average daily rainfall (mm)	5.9 (12.3)	5.5 (13.4)	6.0 (14.2)
Installation date of nearby canal block	16 Feb 2020	20 Feb 2020	20 Dec 2019
After installation of canal block:			
Average daily WTD (m)	-0.15 (0.11)	-0.35 (0.12)	-0.18 (0.09)
Average daily rainfall, (mm)	5.4 (15.0)	6.3 (14.8)	7.7 (18.7)

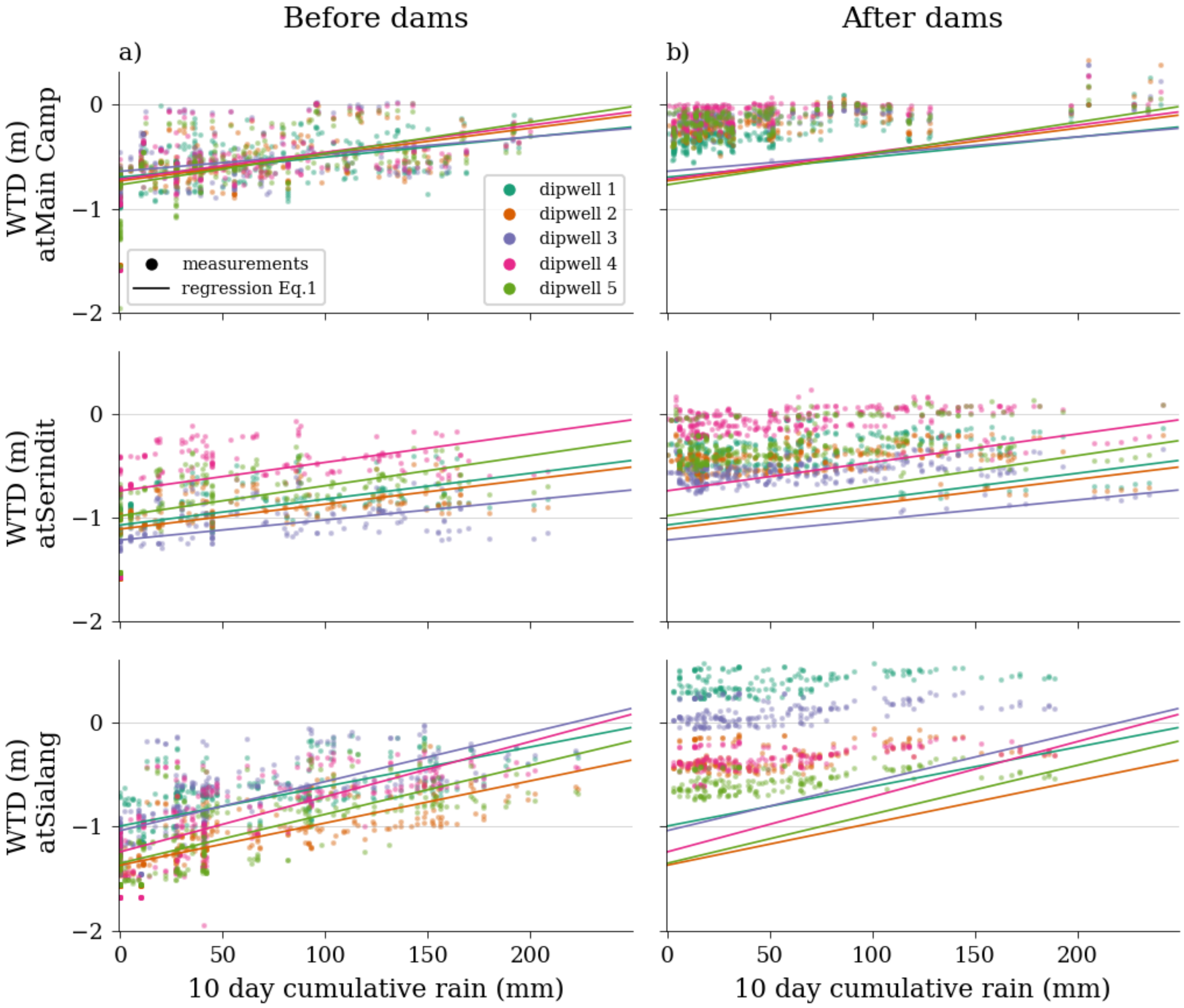

Figure 4. Dipwell measured WTD (coloured dots) and the linear regressions of Equation 1 for the five dipwells along the transect near each patrol post (lines) a) before, and b) after the dams were installed. The linear regressions were constructed using WTD data collected before the installation of compacted peat dams. The same linear regressions are plotted again in b) for reference. 'Main Camp', 'Serindit' and 'Sialang' are the names given to the patrol posts (refer to Figure 1 for locations). Each colour represents the data from one dipwell in the patrol post transect.

Vegetation

The total number of plant species identified in the 21 field survey sampling sites (combined; Figure 2) was 71, of which 58 were identified to species level, ten to genus level, one to family level and two to local name only (Appendix 3). The herbaceous layer of these degraded peatland areas is dominated by sedges and ferns that often establish a cover of 75–100 %. Fern species include *Blechnum indicum*, *Nephrolepis biserrata*, *Pteridium aquilinum* and *Stenochlaena palustris*, while the dominant sedge is *Scleria sumatrensis*, with some *Scleria terrestris*. The tall wild ginger *Alpinia mutica* forms dense stands at a few locations. The main tree species recorded (i.e., species recorded more than once; Table 3) are *Archidendron clypearia*, *Dyera polyphylla*, *Macaranga pruinosa*, *Melaleuca cajuputi*, *Melicope glabra* and *Melicope lunu-ankenda*. These are indigenous PSF species, and all are pioneer species except swamp jelutung *D. polyphylla* which is also characteristic of mature PSF (Middleton 2007). Other common tree species are *Campnosperma coriaceum*, *Cratoxylum arborescens*, *Gymnacranthera farquhariana*, *Syzygium palembanicum* and *Trema orientalis*, along with the two palm species *Cyrtostachys renda* (red sealing-wax palm) and *Eleiodoxa conferta* (edible swamp *salak* or *asam paya*).

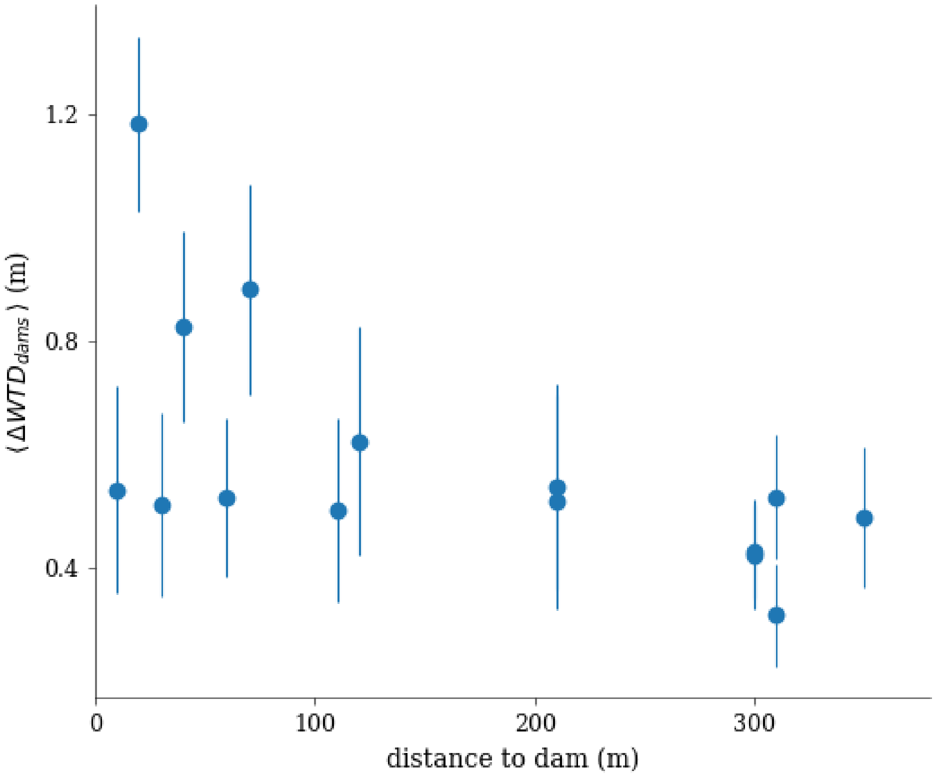

Figure 5. Changes in WTD attributed to the effect of the compacted peat dams at SMPP, plotted against the distance from each dipwell to the nearest dam. The dots show annual means of ΔWTD_{dams} (Equation 2) and the bars extend over the standard deviations.

The results of the Principal Component Analysis (PCA) between woody species are depicted in Figure 6 for three principal components (PCs). These results show that the three PCs together accounted for 74.8 % of the total variance in the dataset, with 51.1 % of variance being accounted for by PC1, 15.5 % by PC2 and 8.2 % by PC3.

With regard to PC1, most woody species have negative or near-neutral loadings, while *Melicope lunu-ankenda* and *Macaranga pruinosa* have strong positive loadings (9.0 and 7.3, respectively) and *Melicope glabra* has a moderate positive loading (1.2). PC2 has strong positive loadings (+5.3) for *Melaleuca cajuputi*, while the loadings for the other woody species vary from +2 to -2.5. PC3 has moderately positive loadings (+1.8 to 2.4) for *Archidendron clypearia* and *Melastoma malabathricum*, while the loadings for other woody species range between -1.6 and +1.0.

In terms of fire history (from 2001 to 2015), most of the study area has been burned at least once, and the 21 points sampled in 2018–2021 have burned 2.5 times on average (based on analysis of Landsat 7 satellite images 2001–2015; Table 1). Fifteen sample sites had 1–2 fires only, while the remaining six sites had 3–8 fires. Areas along the Buring River (north-west SMPP) and Tembesu Daro canal (mid-south-southwest SMPP) appear to have burned most often.

Figure 7 shows the NDVI differences (ΔNDVI values) for 2017–2020 and 2017–2021. ΔNDVI 2017–2020 shows a positive value (signifying an increase in woody vegetation) for most areas except for the central and mid-northern part of SMPP. On average, the NDVI increase is +0.0226 with a standard deviation of 0.0244. ΔNDVI 2017–2021 shows a positive value of +0.0431 with a standard deviation of 0.0229 for the entire SMPP area except for about 20 small patches (each < 1ha) with negative ΔNDVI that dot the area. The calculated ΔNDVI for 2020–2021 is +0.0206, which means that the increase in NDVI from 2020 to 2021 is almost equal to that during the period 2017–2020.

The increase in woody vegetation is also evident from the grid analysis of Planetscope imagery from 2016–2021 (Figure 8), which shows an increase in cover from 28.6 ± 1.4 % in 2016 to 39.4 ± 1.8 % in 2021. This increase is not linear, but hovers around or under 30 % from 2016 to 2019 then increases rapidly to 40.6 ± 3.3 % from 2019 to 2020, levelling off at 39.4 ± 1.8 %) from 2020 to 2021. This represents a 38 % increase in cover of woody vegetation from 2016 to 2021.

Table 3. Key trees and palms of recovering degraded peatland at the SMPP. In 2018, only presence was recorded (as •); in 2020, number of individuals per plot was recorded; in 2021, species were recorded at densities + = present, ++ = common, +++ = very common. Locations of sampling points are indicated in Figure 2.

No.	Family	Species	Local name	2018 sampling points								2020 sampling points						2021 sampling points						
				1	2	3	4	5	6	7	8	1	2	3	4	5	6	1	2	3	4	5	6	7
1	Anacardiaceae	*Campnosperma coriaceum* (Jack) Hallier	terentang													1		+		++	+	+		
2	Apocynaceae	*Dyera polyphylla* (Miq.) Steenis	jelutung	•	•	•	•	•	•		•						2				+			
3	Arecaceae	*Cyrtostachys renda* Blume	palem merah	•	•	•																		
4	Arecaceae	*Eleiodoxa conferta* (Griff.) Burret	asam payau															+				+	+	
5	Cannabaceae	*Trema orientalis* (L.) Blume	bangkirai							•								+				+		
6	Dipterocarpaceae	*Shorea uliginosa* Foxw.	meranti rawa													1		+						
7	Ebenaceae	*Diospyros maingayi* (Hiern) Bakh.	beluluk													4	1							
8	Euphorbiaceae	*Blumeodendron tokbrai* (Blume) Kurz	kayu tukulan										1			2								
9	Euphorbiaceae	*Macaranga pruinosa* (Miq.) Müll.Arg.	mahang	•		•		•				33	5		37	6	6	++			+++	+++	+++	+++
10	Hypericaceae	*Cratoxylum arborescens* (Vahl) Blume	geronggang			•	•	•	•		•													
11	Mimosaceae	*Archidendron clypearia* (Jack) Nielsen	petai belalang			•				•		10	4					++				+		
12	Myristicaceae	*Gymnacranthera farquhariana* (Hook.f. & Thomson) Warb.	dara-dara										1			6	3							
13	Myrtaceae	*Melaleuca cajuputi* Powell	gelam				•		•							1			+++	+++				++
14	Myrtaceae	*Syzygium palembanicum* Miq.	kayu kelat										1		1	5	2							
15	Pandanaceae	*Pandanus atrocarpus* Griff.	selingsing		•	•																		
16	Rutaceae	*Melicope glabra* (Blume) T.G. Hartley	bangun-bangun	•	•			•					3	1	1	1					+		++	
17	Rutaceae	*Melicope lunu-ankenda* (Gaertn.) T.G. Hartley	sepongol	•	•	•	•	•	•	•	•	5	1		24	33	5	+++			++	+++	++	++
18	Tetrameristaceae	*Tetramerista glabra* Miq	punak													2	1							

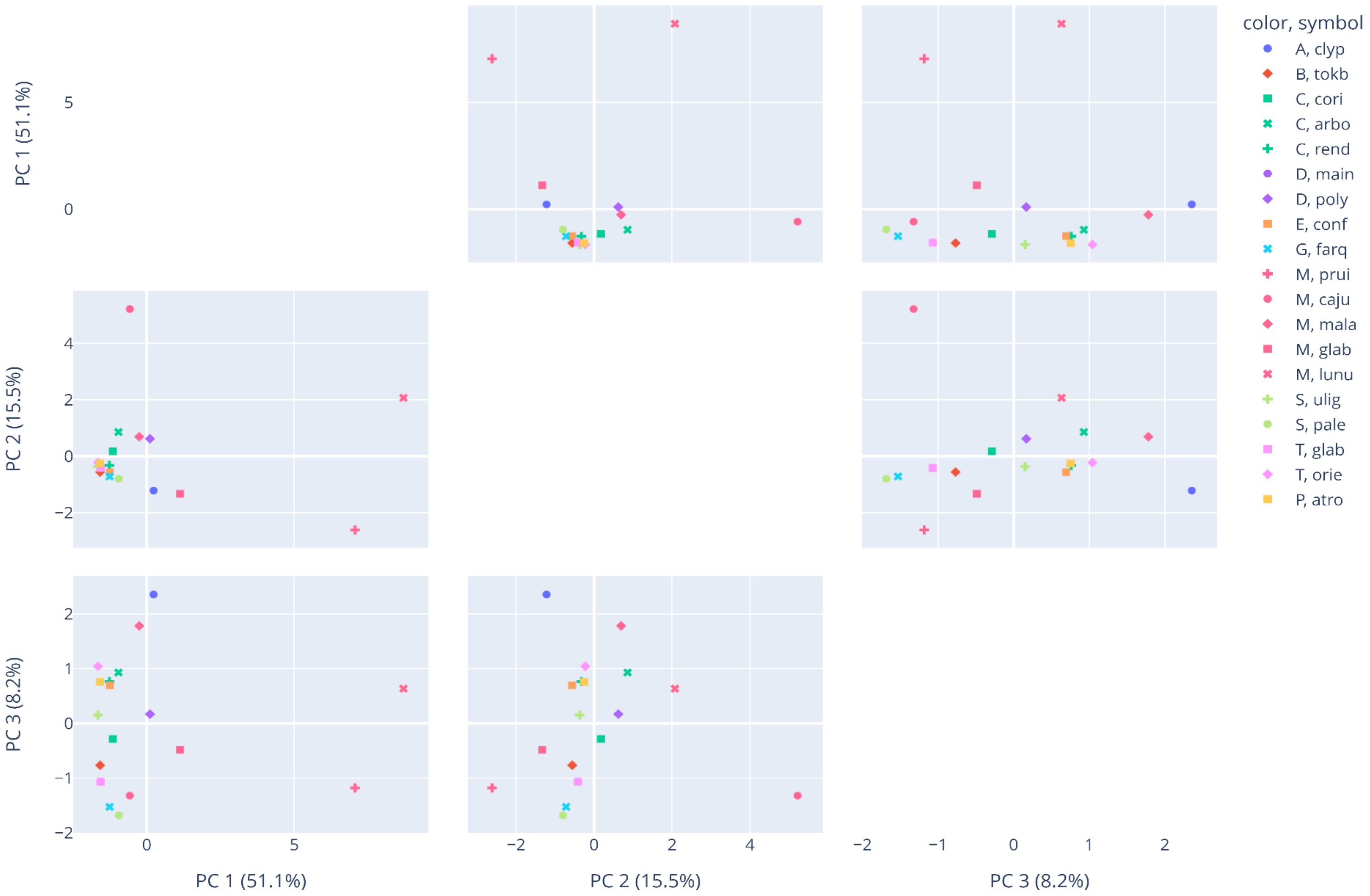

Figure 6. Principal Component Analysis (PCA) plot of SMPP trees and shrubs, in three components. Species abbreviations: *A.clyp = Archidendron clypearia; B.tokb = Blumeodendron tokbrai; C.cori = Campnosperma coriaceum; C.arbo = Cratoxylum arborescens; C.rend = Cyrtostachys renda; D.main = Diospyros maingayi; D.poly = Dyera polyphylla; E.conf = Eleiodoxa conferta; G.farq = Gymnacranthera farquhariana; M.prui = Macaranga pruinosa; M.caju = Melaleuca cajuputi; M.mala = Melastoma malabathricum; M.glab = Melicope glabra; M.lunu =Melicope lunu-ankenda; P.atro = Pandanus atrocarpus; S.ulig = Shorea uliginosa; S.pale = Syzygium palembanicum; T.orie = Trema orientalis; T.glab = Tetramerista glabra.*

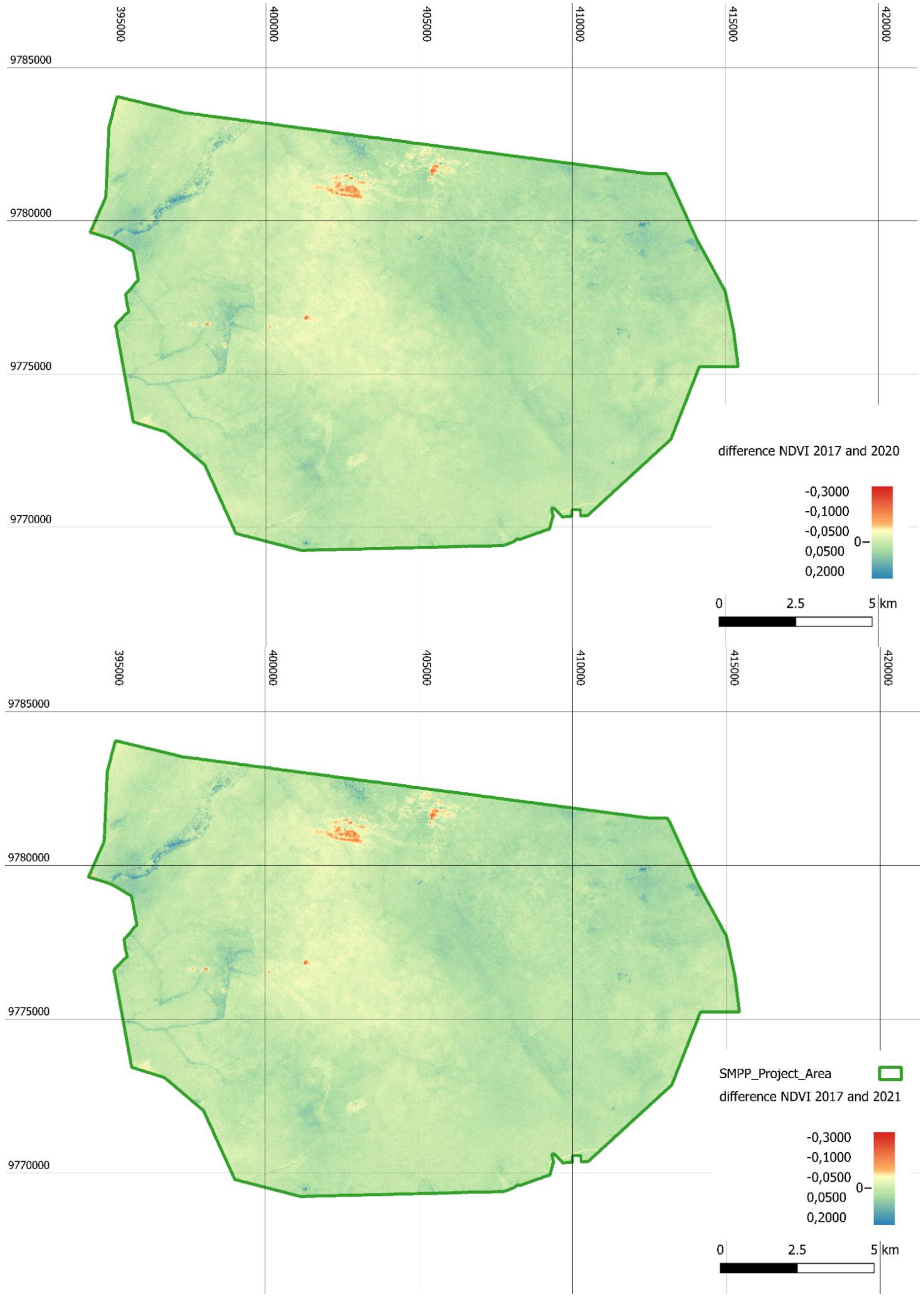

Figure 7. NDVI differences at SMPP for 2017–2020 (top) and 2017–2021 (bottom).

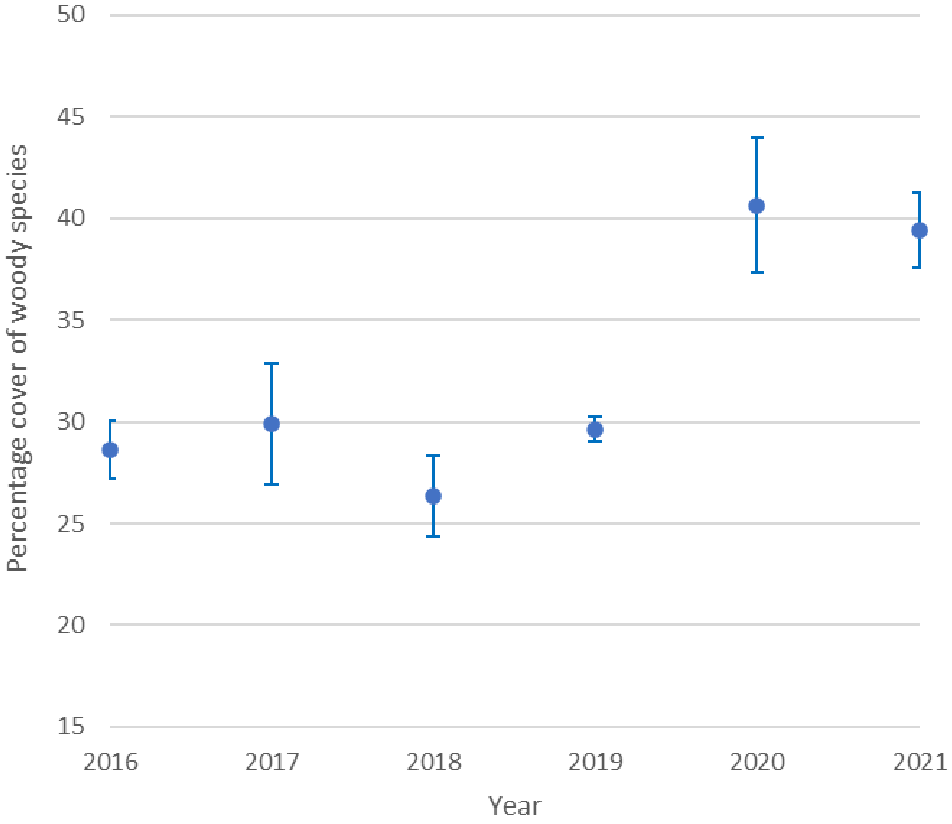

Figure 8. Changes in cover of woody vegetation at SMPP, 2016–2021. Dots shows the annual means, while error bars indicate standard deviations.

DISCUSSION

Hydrology

Several conclusions can be drawn from the basic hydrological statistics for the patrol posts during the periods before and after dam installation shown in Table 2. First, WTD was smaller (i.e., the water table was higher) at all patrol posts - even the one where rainfall decreased - after installing the dams. Secondly, the smaller standard deviation after the dams were built indicates that the dams may have had a regularising effect on WTD. These observations are indicative of some influence of the dams on the measured WTD although, without any further analysis, it would be difficult to separate it from the effect of rainfall on WTD.

The change in WTD caused by the dams is the main background information needed for the vegetation analysis. Hydrological processes are dynamic and change quickly according to rainfall and local conditions such as proximity to canals, canal conditions and damming, and topography. The measurement setup is concentrated close to canals and dams. Because the effect of canals decreases with distance (Evans *et al*. 2019), analysis of the measured data alone would lead to over-estimation of the dam effect on WTD. Therefore, upscaling of the measurements using a hydrological model for the whole Merang area was required.

While the data and the available resources did not support using a full scale physically-based hydrological model (Cobb *et al*. 2017, Urzainqui *et al*. 2020), we constructed a two-component statistical hydrological model to capture the dam effect and to separate it from the changes caused by varying rainfall. Good-quality on-site rainfall data were available, which is important because rainfall has a high inter- and intra-annual variability, and is considered to be the major driver of hydrology in the area (Page *et al*. 2009, Takahashi *et al*. 2021). In the first component we established the connection between rainfall and WTD in selected measurement transects, and in the second component the connection between WTD change and distance to the dams was created. While the simple model captures the temporal changes in WTD, it cannot describe either interactions between the dams or the inhomogeneous changes in WTD arising from the direction of water flow in the canal network.

The network of 203 compacted peat dams has been sufficient to reduce WTD by at least 20 cm at the observation points and by up to 120 cm near the dams (Figure 5). From Figure 3b, two things can be observed. First, the water table rose after dam construction and, secondly, the variation in WTD decreased, indicating that the number of days when the water table was more than 40 cm below the surface decreased after the dam construction (purple and orange marginal distributions in Figure 3c).

The reduction of WTDs by 20–30 cm on average compares favourably with the results of canal blocking at Sebangau National Park in Central Kalimantan in 2013–2015, where WTDs were raised on average by a modest 7.5 cm (Kasih *et al.* 2016). The difference may be partially explained by the types of dams used for canal blocking. At Sebangau, box dams (with spillways) were installed, and these appear to have been much less effective than compacted peat dams at SMPP. Results at SMPP are similar to canal blocking trials at Tanjung Leban, Bengkalis Regency, Riau Province, Sumatra, where canal blocking in 2018 raised the water level in the canal by about 70 cm and reduced WTD in the peatland by about 30 cm at a distance of 60 m from the canal and by 20 cm at a distance of 210 m (Sutikno *et al.* 2020).

Vegetation

Recovery of woody species cover

Although fires were absent at SMPP from 2016 onwards, the cover of woody vegetation was more or less stable during 2016–2019, based on the analysis of tree cover. One may therefore conclude that while the absence of fire is important to prevent dramatic loss of woody vegetation, this alone probably does not lead directly to the recovery of woody species in degraded tropical peatland over a period of at least 4–5 years. The subsequent sharp increase in cover of woody species in 2020–2021 coincides with the reduction of WTD, by 50–120 cm near canal blocks and by at least 20–30 cm over greater distances, after the installation of compacted peat dams. Conversely, the installation of temporary box dams in 2017–2018 does not appear to have led to an increase in woody vegetation cover (Figure 8).

The relationship between recovery of woody vegetation and WTD is supported by the NDVI analyses. The observed changes in NDVI indicate an overall net increase in cover of woody vegetation between 2017 and 2020, but with a decline in the central and central-northern part of the SMPP area. The net increase of NDVI from 2020 to 2021 is almost equal to the NDVI increase of 2017–2020, indicating an increase in the recovery rate of woody vegetation that coincides with canal blocking using compacted peat dams and the associated reduction of WTD. In addition to the small areas of NDVI decline in the central and central-northern part of the SMPP area, decline was visible in about 20 small patches (each < 1ha) with negative ΔNDVI that dot the area. Direct human disturbance (after 2017) seems highly unlikely as the cause because these locations are generally remote. However, the negative NDVI indicates a very local decline in woody vegetation, perhaps due to locally unfavourable conditions such as insect attack or plant disease.

In their systematic review of 94 replanting pilots and studies on degraded peatland between 1988 and 2019, Smith *et al.* (2022) found that rewetting had a negative effect on survival, although not on half-life and relative growth rates. Indigenous PSF species are tolerant to flooding, but severe flooding above the height of tree seedlings can result in hypoxia and increased seedling mortality rates (Giesen 2004, van Eijk *et al*. 2009, Rotinsulu *et al.* 2016). Smith *et al.* (2022) conclude that, because survival and growth rates of seedlings were lower in rewetted compared to drained peatlands, the dual aims of rewetting and revegetation may struggle to be achieved simultaneously. Our study suggests that timing is probably essential in determining the outcome of rewetting. While the reduction of WTD in 2020 due to blocking of canals is likely to have triggered flowering, fruiting and seedling establishment, it is unlikely that this also led to the observed significant increase in vegetation cover in the same year (from 28.6 % cover in 2019 to 40.6 % in 2020), as newly established seedlings are unlikely to result in such a peak until at least several years later. Hence, the increase in woody vegetation density at our study site probably does not reflect seed germination and seedling growth and is more likely to reflect an increase in size of already established and less vulnerable larger seedlings, saplings and small trees, boosted by higher and more stable WTD. The water table rose above the peat surface after canal blocking, and this may have been detrimental to seedling survival but ultimately have had an overall positive effect on already well-established woody plants.

Species composition of recovering woody vegetation

On average, 4.6 woody species (range 1–11) were recorded per sample site, with 18 woody species being recorded in total (Table 3). If all herbaceous and vine species are included, the average number of species recorded per sample location is 11.4 (range 4–40), with a total of 71 species (Appendix 3). The numbers are lower for the drone surveys (average 7.4, range 4–12), as herbaceous species are difficult to assess in this way, and hence further analysis focused on the data for woody species. Note that these surveys were conducted only in degraded areas, which are the focus of this study, and if surveys had been carried out in the remnant PSF this would have resulted in many more species and probably more than doubled the total list of species (Barkah 2009, Giesen 2018).

The results of the PCA analysis show that, for PC1, most woody species have negative or near-neutral loadings while *Melicope lunu-ankenda* and *Macaranga pruinosa* have strong positive loadings and *Melicope glabra* has a moderate positive loading. These three species were found at locations where, generally, only 1–2 fires had occurred, therefore PC1 seems to be positively correlated to a relatively low fire incidence. *M. pruinosa*, *M. glabra* and *M. lunu-ankenda* have fruits that are dispersed by animals, notably birds and squirrels (Blackham *et al.* 2013), and repeated fires are likely to have a greater impact on species dispersed by animals than on species dispersed by wind or water.

PC2 has strong positive loadings for *Melaleuca cajuputi*, while the other woody species vary in loading values. At SMPP, *M. cajuputi* is found in areas that have had 4–5 fires, and with its characteristic peeling, papery bark it is known to be fire resistant and to recover well after fires (Tomita *et al.* 2000). Fruits of *M. cajuputi* are opened by high temperatures, such as those occurring during fires, and the seeds are dispersed easily by wind; hence, it is not surprising that this species is a dominant pioneer following repeated fires (Nuyim 1998). At the other end of the spectrum of PC2, *Macaranga pruinosa* (PC2 value of -2.5) is known to be fire sensitive and is suspected to be unable to cope with subsequent deep flooding (of 1–2 m) (van Eijk *et al.* 2009). Therefore, PC2 seems to be positively correlated with a higher incidence of fires.

PC3 has moderate positive loadings for *Archidendron clypearia* and *Melastoma malabathricum* while the loadings for other woody species range widely along a spectrum from -1.6 to +1.0. PC3, which describes 8.2 % of variance, therefore seems to be only weakly linked to any particular environmental factor.

Combined, PC1 (correlated with lower fire incidence) and PC2 (correlated to higher fire incidence) account for 66.6 % of variance in woody species composition. Hence, fire history seems to be the single most important factor in determining the woody species composition at a given location. This relationship agrees with observations of the effects of fire on vegetation in degraded peatland described by van Kostermans (1958) and Giesen (1990) for Kalimantan, where fire-affected vegetation is dominated by *Melaleuca*, *Shorea balangeran* and *Combretocarpus rotundatus*, with a final degradation stage dominated by sedges, grasses and ferns in areas subject to multiple burns. Similarly, at Berbak National Park in Jambi, Sumatra, multiple burn areas are usually dominated by ferns, sedges and pandans, while species such as *Macaranga pruinosa* occur where only single burns have occurred (van Eijk *et al.* 2009). Peatland fires and drainage lead to peat subsidence and subsequent flooding, and increased flooding may also play a role in determining the outcome of regeneration. As mentioned above, *M. pruinosa* was found not to recover in deeply (1–2 m) flooded parts of regenerating degraded peatland in Berbak NP in Jambi, Sumatra (van Eijk *et al*. 2009).

One may therefore conclude that, in our study area, reduction of WTDs leads to recovery of woody vegetation but fire frequency determines the species composition outcome of regeneration. *Melaleuca cajuputi* dominates where fires have been most frequent (i.e., > 4 fires on average), while *Macaranga pruinosa*, *Melicope glabra* and *Melicope lunu-ankenda* dominate in regenerating areas that have experienced only 1–2 fires. Overall, while fire suppression is essential to prevent further catastrophic loss of vegetation, in tropical peatland restoration programmes it must be combined with effective rewetting for woody vegetation to recover. Emphasising fire suppression without consideration of effective rewetting means that, in the long term, such areas will remain fire prone and likely to spiral into further degradation.

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AUTHOR CONTRIBUTIONS

WBJTG conducted botanical field work in 2018, is mainly responsible for the vegetation analyses, wrote the first draft and is the main author; SP, DW, JLC, Y-HOW, PM and RYN provided baseline information about the study area, organised additional botanical and other field studies, and provided feedback on draft versions; IU and AL are responsible for the hydrological assessments, modelling and drafting of the sections on hydrology; and PTG carried out the NDVI and PCA assessments.

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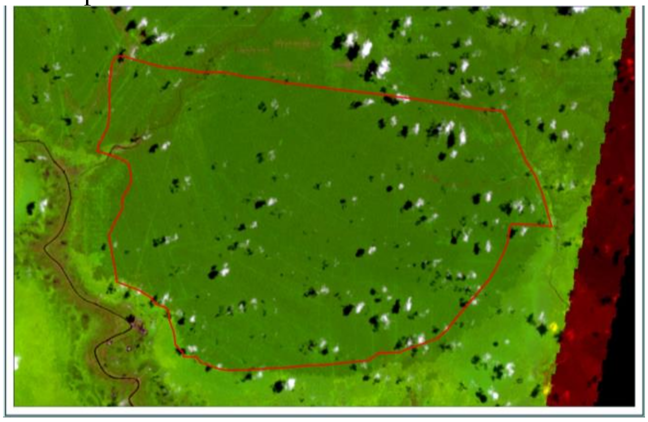
Appendix 1

Fire scars in the SMPP area visible on Landsat 7 images 2001–2016

The red line on each of the images below is the approximate boundary of the SMPP site. Dark greens indicate (predominantly) forested areas, light greens are secondary scrub and herbaceous vegetation, while reddish-brown and brown areas are recently cleared and/or burnt. The image from 2001 shows a logged peatland that is largely unaffected by burning. All of the later images show the scars of major fires that occurred in the SMPP area: 2005 1,100 ha burnt; 2008 9,000 ha burnt; 2013 2,500 ha burnt; 2015 820 ha burnt (fires and smoke visible in north-west); and 2016 17,500 ha burnt. Note that the latest image dates from 05 July 2016 and the scars visible on this image are from fires that occurred in late 2015. The red circle on the 2016 image indicates the 254 ha remnant of PSF in the south-eastern part of the SMPP area that has escaped burning. For information on Landsat 7 satellite imagery, refer to the US Geological Survey website: https://www.usgs.gov/landsat-missions/landsat-7.

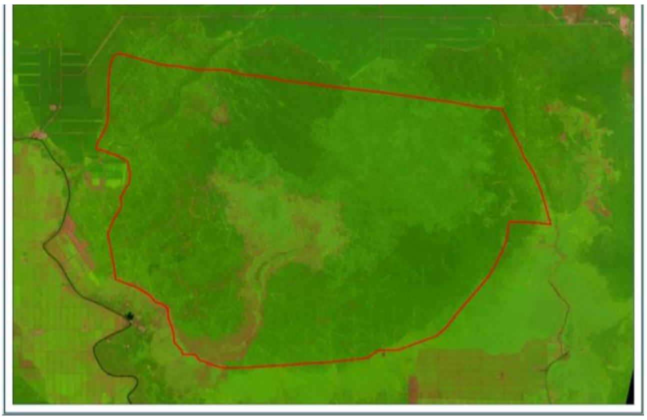
06 September 2001



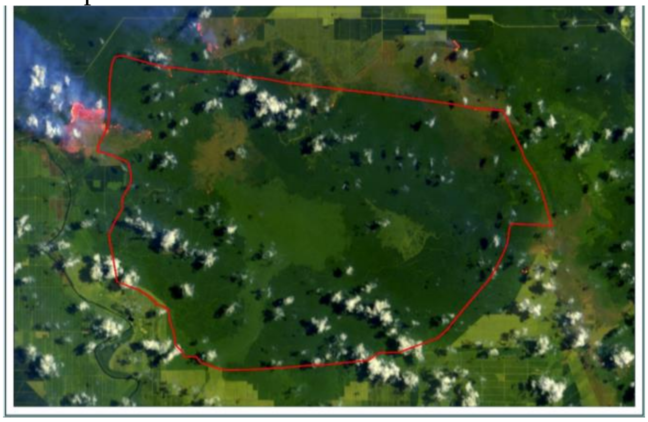
20 May 2005

12 May 2008

27 June 2013



05 September 2015



05 July 2016

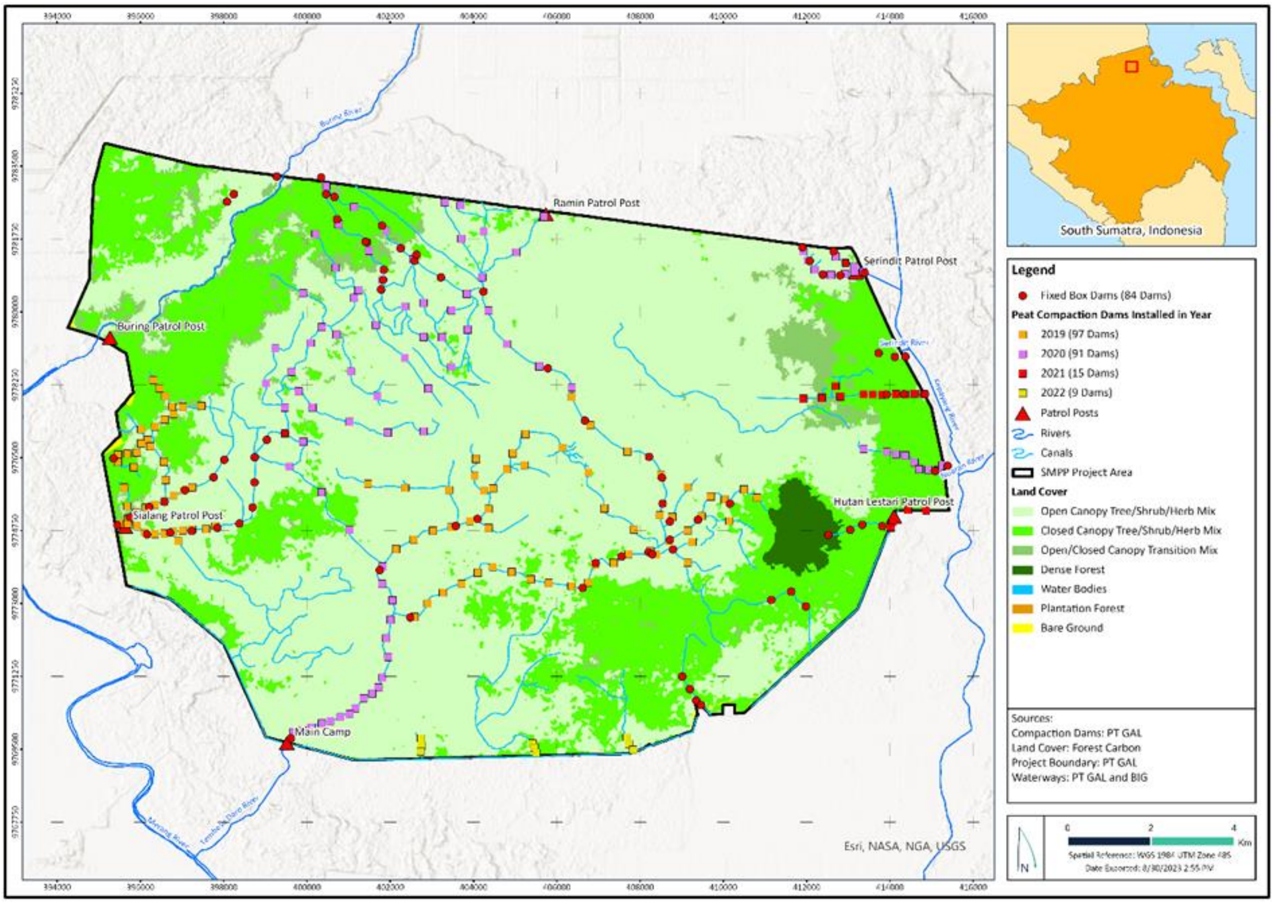
Appendix 2

Dam construction at SMPP

The map below illustrates the history of dam construction by the SMPP. The 84 so-called ‘box dams’ (see photographs below) were constructed in Q4 (Oct–Dec) 2017 (61 %) and Q1 2018 (30 %), with the remainder completed later in 2018. It soon became apparent that these dams required a lot of maintenance, and they were supplemented (and sometimes replaced) from 2019 onwards by compacted peat dams.

Compacted peat dams were constructed using field teams supported by logistics teams, each with an excavator working on clusters of canal blocks, and always starting on the farthest upstream dam and working down the incline. Peat for the compacted peat dams was excavated from borrow pits established at least 15 m from the site of the dam. Depending on local conditions, 0.2–0.5 m of topsoil was first removed from the borrow pit site. A foundation for the dam was excavated to a depth of 1.5 m in the canal bed, and fill material was placed in layers, with compaction carried out by rolling the excavators over the peat layers. On average, the dams were constructed to a height of 1.28 m (range is 1.05–1.70 m) above the field level, and they extend on each side (i.e. perpendicular to the canal) about 2 m beyond the width of the canal. After construction, photographs were taken of the dam, along with measurements of its dimensions and a GPS record of exact location.

A total of 212 compacted peat dams were constructed, mainly in Q4 2019 and Q1 2020 (29 November 2019 to 02 March 2020), when 188 (97 and 91) dams were completed. The remaining 24 were completed in 2021 (15) and 2022 (9). Canals at SMPP are 2–6 m wide and 1.3–1.5 m deep, and the respective widths of the 212 compacted peat dams are 7 m (n = 179), 9 m (n = 31) and 11 m (n = 2).



Examples of box dams at SMPP

KBG26 on Sei Tembesu Daro in the mid-southern part of SMPP; UTM: X408522/Y9776023. Constructed Sep 2017, photo Apr 2018 by W. Giesen for SMPP. As with most box dams the outer construction is of timber and the centre filled with bags of soil/peat, with a spillway in the middle to facilitate boat access upstream.

Box dam on upper Sungai Buring, near Buring patrol post in the north-western part of SMPP. Constructed in late 2017, photo by W. Giesen on 26 April 2018, by which time the dam had been overtopped and damaged. More details on box dam construction are provided by Dohong *et al.* (2018).

Examples of compacted peat dams at SMPP

Dam 292, cluster 7 near Sialang patrol post, western end of SMPP; UTM: X397034/Y9775702. Constructed Dec 2019, photo 25 Dec 2019 by W. Boissevain for SMPP. The canal is 2.2m wide but the compacted peat dam (constructed using an excavator) is several times this width and is raised to 128 cm (range 105–170 cm) above the field level.

Dam 270, also near Sialang patrol post; UTM: X396303/Y9774668. Constructed Feb 2020, photo 21 Feb 2020 by P. Richardson for SMPP. The canal is almost 3 m wide. More details on compacted peat dam construction are provided by Dohong *et al.* (2018).

Appendix 3: Plant species of sampling points 2018–2021 at SMPP. Locations are indicated in Figure 2. In 2018, only presence was recorded (as •); in 2020, number of individuals per plot was recorded for tree species, while other species were recorded at densities: + = present, ++ = common, +++ = very common; in 2021, only characteristic species were recorded at (the same) densities.

No.	Family	Species	Local name	Life form	2018 sampling points								2020 sampling points						2021 sampling points						
					1	2	3	4	5	6	7	8	1	2	3	4	5	6	1	2	3	4	5	6	7
1	Anacardiaceae	*Campnosperma coriaceum* (Jack) Hallier	terentang	tree													1		+		++	+	+		
2		*Gluta wallichii* (Hook.f.) Ding Hou	rengas	tree										1											
3	Annonaceae	*Artabotrys suaveolens* Blume	akar kekait	climber	•		•		•	•															
4	Apocynaceae	*Dyera polyphylla* (Miq.) Steenis	jelutung	tree	•	•	•	•	•	•		•						2				+			
5	Aquifoliaceae	*Ilex cymosa* Blume	?	tree													1								
6	Araceae	*Alocasia longiloba* Miq.	?	herb													++								
7		*Rhaphidophora montana* (Blume) Schott	?	climbing herb			•																		
8	Arecaceae	*Cyrtostachys renda* Blume	?	palm	•	•	•																		
9		*Eleiodoxa conferta* (Griff.) Burret	asam payau	shrubby palm															+				+	+	
10	Asteraceae	*Mikania cordata* (Burm.f.) B.L.Rob.	?	climbing herb						•			++				+++								
11	Blechnaceae	*Blechnum indicum* Burm. f.	pakis	herb	•		•			•	•	•	+++		+++	+++	+++		++	+++	+++	+++	++	+++	+++
12		*Stenochlaena palustris* (Burm. f.) Bedd.	pakis	herb	•	•	•	•	•	•	•	•	+++	+++	+++	+++	+++	+++	+	++	+++	++		+++	+++
13	Caesalpiniaceae	?	busur laut	tree													1								
14	Ctenolophonaceae	*Ctenolophon parvifolius* Oliver	?	tree													1								
15	Cyperaceae	*Fimbristylis schoenoides* (Retz.) Vahl	?	herb				•				•													
16		*Scleria sumatrensis* Retz	?	herb	•	•		•	•	•	•	•	+++		+++	+++	++	+++	++	++	++	+++			+
17	Davalliaceae	*Nephrolepis biserrata* (Sw.) Schott.	pakis	herb	•								+++	+++	+++	+++	+++	+++							
18	Dennstaedtiaceae	*Pteridium aquilinum* (L) Kuhn	pakis	herb	•				•	•		•	++	++	++	++	++	++							
19	Dilleniaceae	*Dillenia excelsa* (Jack) Gilg.	simpur	tree													2								
20	Dipterocarpaceae	*Shorea pauciflora* King	?	tree													1								
21		*Shorea uliginosa* Foxw.	meranti rawa	tree													1		+						
22		*Shorea* sp.	?	tree													7								
23	Ebenaceae	*Diospyros foxworthyi* Bakh.	?	tree													1								
24		*Diospyros maingayi* (Hiern) Bakh.	beluluk	tree													4	1							
25	Elaeocarpaceae	*Elaeocarpus petiolatus* (Jacq.) Wall.	?	tree			•																		
26	Euphorbiaceae	*Blumeodendron tokbrai* (Blume) Kurz.	kayu tukulan	tree										1			2								
27		*Endospermum diadenum* (Miq.) Airy Shaw	kayu labu	tree												3									
28		*Macaranga pruinosa* (Miq.) Müll.Arg.	mahang	tree	•		•		•				33	5		37	6	6	++			+++	+++	+++	+++
29	Fabaceae	*Derris trifoliata* Lour.	?	climber		•																			
30	Fagaceae	*Lithocarpus* sp. ('*lucidus*')	?	tree													1								
31	Geraniaceae	*Fagraea fragrans* Roxb.	tembesu	tree								•													
32	Hypericaceae	*Cratoxylum arborescens* (Vahl) Blume	geronggang	tree			•	•	•	•		•													
33	Ixonanthaceae	*Ixonanthes reticulata* Jack	?	tree													4								
34	Lauraceae	*Actinodaphne macrophylla* (Blume) Nees	?	tree													1								
35		*Litsea machilifolia* Gamble	nyamuk nyamuk	tree										1											

No.	Family	Species	Local name	Life form	2018 sampling points								2020 sampling points						2021 sampling points						
					1	2	3	4	5	6	7	8	1	2	3	4	5	6	1	2	3	4	5	6	7
36	Leeaceae	*Leea indica* (Burm.f.) Merr.	mamali	tree							●														
37	Lentibulariaceae	*Utricularia aurea* Lour	?	floating herb	●																				
38	Melastomataceae	*Melastoma malabathricum* L.	senduduk	shrub	●			●	●	●	●	●	++												
39		*Melastoma* sp.	belidang	shrub																					
40	Meliaceae	*Dysoxylum* sp.	?	tree															+			+			
41	Meliaceae	*Aglaia* sp.	?	tree													1								
42	Mimosaceae	*Archidendron clypearia* (Jack) Nielsen	petaibelalang	small tree			●				●		10	4					++				+		
43	Moraceae	*Artocarpus* sp.	?	tree													1								
44		*Ficus* sp.	arah	shrub			●																		
45		*Ficus sumatrana* (Miq.) Miq.	arah	straggling shrub								●													
46		*Ficus sundaica* Blume	arah	tree													1								
47	Myristicaceae	*Gymnacranthera farquhariana* (Hook.f. & Thomson) Warb.	dara-dara	tree										1			6	3							
48		*Horsfieldia irya* (Gaertn.) Warb.	?	tree													1								
49	Myrtaceae	*Melaleuca cajuputi* Powell	gelam	tree				●		●							1			+++	+++				++
50		*Syzygium palembanicum* Miq	kayu kelat	tree										1		1	5	2							
51		*Syzygium* sp.	kelat jambu	tree												1									
52	Nepenthaceae	*Nepenthes rafflesiana* Jack	kantong semar	climber		●																			
53	Pandanaceae	*Pandanus atrocarpus* Griff.	selingsing	tree		●	●																		
54		*Pandanus helicopus* Kurz ex Miq	rasau	tree	●																				
55	Rubiaceae	*Uncaria lanosa var. glabrata* (Blume) Ridsdale	kekait	climber	●		●	●			●		+		+		+					++	+		+
56	Rutaceae	*Melicope glabra* (Blume) T.G. Hartley	bangun-bangun	tree	●	●			●					3	1	1	1					+		++	
57		*Melicope lunu-ankenda* (Gaertn.) T.G. Hartley	sepongol	small tree	●	●	●	●	●	●	●	●	5	1		24	33	5	+++			++	+++	++	++
58	Sapotaceae	*Madhuca motleyana* (de Vriese) J.F.Macbr.	katio	tree													4								
60		*Payena* sp.	?	tree													2								
61	Schizaceae	*Lygodium flexuosum* (L.) Sw.	pakis	climbing fern	●					●															
62	Simaroubaceae	*Quassia borneensis* Nooteboom	kayu pait	tree												1									
63	Smilaceae	*Smilax myosotifolia* A.DC.	?	climber							●	●													
64	Stemonuraceae	*Stemonurus scorpiodes* Beccari	?	tree													7								
65		*Stemonurus secundiflorus* Blume	?	tree													5								
66		*Gomphandra* sp. ?	malasiro	tree													15								
67	Tetrameristaceae	*Tetramerista glabra* Miq	punak	tree													2	1							
68	Thymelaeaceae	*Gonystylus bancanus* (Miq.) Kurz.	ramin	tree													1								
69	Ulmaceae	*Trema orientalis* (L.) Blume	?	tree							●								+						
70	Zingiberaceae	*Alpinia mutica* Roxb.	?	herb							●								+++			++			
71	?	*?*	makai putih	tree														1							