Is the residual ash method applicable to tropical peatlands? A case study from Brunei Darussalam

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SUMMARY

Tropical peatlands in Southeast Asia are a significant carbon sink, but are under major threat of fire resulting in significant carbon emissions. This study focused on the residual ash method, which has not been applied before for a tropical peatland, to determine the amount of carbon lost due to fire along two transects. To evaluate the method in a tropical peatland, we sampled peat cores to a depth of 150 cm along two transects in a drainage-affected peatland in Brunei Darussalam and analysed Landsat images to determine burn count at individual sampling locations between 1988 and 2020. The ash residue method indicated that the carbon release from the two transects was 3.61 ± 1.08 kg m^{-2} and 3.77 ± 0.80 kg m^{-2} respectively due to peat decomposition and fire. However, our results show that although some locations burned up to five times, the expected ash content (of at least 4 %) was not found in the surface peat. Therefore, the majority of the resulting ash from these fires must have been transported out of the peatland, possibly in smoke or washed away via ground and surface water transport. We conclude that the residual ash method to determine carbon loss is not a reliable method to determine carbon loss in degraded tropical peatlands.

KEY WORDS: ash content, Borneo, carbon emission, fire, peat swamp forest

INTRODUCTION

Intact peatlands are important carbon stores and are known for their ability to sequester large amounts of carbon. An estimated 500-700 Gt of organic carbon globally is stored in peatlands although peatlands (including forested peatlands) only occupy around 3 % of the global land area (Page *et al.* 2011, Scharlemann *et al.* 2014, Page & Hooijer 2016). Land management practices as well as weather conditions can significantly influence the overall carbon budget of peatlands (Rogiers *et al.* 2008). Recent research has shown that drainage as well as conversion into palm oil plantations have turned large areas of tropical peatlands from a net sink of CO_2 into a net source of soil-derived greenhouse gases (GHGs) (Leifeld *et al.* 2019).

Pristine tropical peatlands are formed under environmental conditions of high humidity and high water tables in which peat is constantly submerged leading to a slower rate of peat decomposition than the rate of peat formation (Page *et al.* 2006, Page & Hooijer 2016). This peat is composed of partially decomposed woody vegetation consisting of usually over 99 % organic matter (Andriesse 1964, Anderson 1983). Tropical peatlands have grown over thousands of years (Dommain *et al.* 2011). Bornean peat swamp forests dominated by Dark Red Meranti *Shorea albida* (also known as Alan bunga) can accumulate carbon at an average rate of 53.5 g m^{-2} y^{-1} over hundreds of years (Dommain *et al.* 2015). Recently, rainfall fluctuations have been shown to influence growth and subsidence of tropical peatlands (Cobb *et al.* 2017). These ecosystems are highly sensitive and easily disrupted (Page & Hooijer 2016), as their functioning depends on the water level (Cobb & Harvey 2019, Cole *et al.* 2019).

Recent predictions on the conservation of peatlands are grim. At the current rate of peat degradation, 98 % of tropical peatlands will have disappeared by 2100 (Leifeld *et al.* 2019). Drainage as well as secondary subsidence are key factors for peatland degradation in Southeast Asia (Hoyt *et al.* 2020). As a result of peat drainage, the water table declines exposing the peat to the atmosphere. This drainage introduces the peat to an aerobic environment by increasing oxygen levels, triggering peat decomposition (Couwenberg *et al.* 2010, Hooijer *et al.* 2012, Page & Hooijer 2016, Miettinen *et al.* 2017). Decomposition causes carbon to be released into the atmosphere as carbon dioxide (Jauhiainen *et al.* 2008, Carlson *et al.* 2015).

Fires, in particular smouldering fires, in peatlands constitute some of the largest fires on the planet (Rein 2015). Fire is a major cause for the rapid loss of peat swamp forests especially in Southeast Asia (Page *et al.* 2002, Certini 2005, Rein *et al.* 2008). Between 2001 and 2009, tropical peat fires contributed to 3 % of global fire emissions (van der Werf *et al.* 2010), while within Borneo, peat fires accounted for 75 % of burnt forest area and 81 % of fire hotspots in 2006 (Page *et al.* 2009). Anthropogenic peat fires are often the result of land clearance for agriculture, infrastructure development, deforestation as well as oil palm plantations (Page *et al.* 2002, Langner & Siegert 2009, Miettinen 2011, Miettinen *et al.* 2012, Kool *et al.* 2006, Cole *et al.* 2019). Peat fires release significant quantities of carbon into the atmosphere, and repeated peat fires significantly affect the peatland ecosystem and carbon dynamics (Lupascu *et al.* 2020) and can cause haze (Hu *et al.* 2018). Emission of fine particles (PM2.5) and associated trace metals such as aluminium and iron from peat fires are a major health concern (Betha *et al.* 2013). A recent study found that emission ratios of aerosol particles emitted from burning of ombrotrophic peat were highest for calcium and followed by elements such as iron and aluminium (Das *et al.* 2019).

Fires can burn as surface, shallow or deep peat fires. Shallow fires commonly burn up to a depth of 15 cm, whereas deep peat fires have been reported to burn up to 1 m deep (Zoltai *et al.* 1998). With the shallow fires being the most common, greater depth of burning, with depths of up to 25 cm and greater carbon losses, have been reported for drained peat plots compared to pristine peat plots (Turetsky *et al.* 2011, Hirano *et al.* 2014). During burning, steep temperature gradients exist in the soil and often no heating occurs beyond 20 to 30 cm depth (DeBano 2000). However, Page *et al.* (2002) estimated that in 1997, 51 ± 5 cm of peat was lost in fires in Central Kalimantan, whereas Ballhorn *et al.* (2009) estimated loss of 33 ± 18 cm of peat from fires in Central Kalimantan, Borneo in 2007. In particular, deeper peat fires affect soil carbon that has not been part of the active carbon cycle for centuries to millennia (Turetsky *et al.* 2015). The closer the groundwater table is to the surface of the peatland, the lower the fire risk. A groundwater level no more than 40 cm below the peat surface is recommended to prevent subsidence and fire (Wösten *et al.* 2008), and peat layers with high moisture content below the surface peat can act as a fire blockade (Taufik *et al.* 2020).

A number of methods exist to estimate the carbon loss from peatlands, of which long-term monitoring of subsidence rates, CO_2 flux measurements, and evaluation of changes in ash content are the most prominent (Grønlund *et al.* 2008, Rogiers *et al.* 2008, Leifeld *et al.* 2011, Couwenberg & Hooijer 2013). In order to calculate carbon changes in peat soils, dating of radiocarbon peat samples has been shown to be a reliable method (Krüger *et al.* 2015) but is expensive and can also have its pitfalls (Väliranta *et al.,* 2014). Krüger *et al.* (2016) applied this method for an ombrotrophic peatland in Finland and identified a net carbon gain (sink) for the site, whereas methods using differences in ash content identified a net carbon loss (source). These differences highlight the importance of site-specific conditions such as changing ash content vs. depth and the importance of a carefully selected natural reference site when using ash-based methods for the estimation of carbon lost to the atmosphere.

The aim of this study was to quantify the amount of carbon loss from fire events using ash contents. The ash residue method has been used to estimate subsidence in northern peatlands (e.g. Krüger *et al.* 2016, Wüst-Galley *et al.* 2016), because it is much cheaper than other methods such as using radiocarbon dates or monitoring subsidence manually. However, for the ash residue method to work, its assumptions must be satisfied: most importantly, that mineral content remains in place in the surface peat after the organic matter has decomposed or burned (Laiho & Pearson 2016).

Subsidence and fire are major problems in tropical peatlands, and carbon loss estimates are needed to predict their future carbon balance. In this study, we tested the ash residue method in a tropical peatland to evaluate whether this simple, intuitive and cheap method is reliable in these settings. We found that a large majority of the ash released by decomposition and fire could not be found in surface peat, suggesting that the ash residual method cannot be used reliably for degraded peats around drainage channels, and raising questions about the fate of the mineral content liberated by peat degradation.

METHODS

Study area

Located in Northwest Borneo, Brunei is not excluded from the threat of wildfires with forest fire events having risen almost three-fold over the past three years (Brunei Fire and Rescue Department, 2020). Major causes of fire ignition were anthropogenic-driven due to illegal farming and fishing, coupled with a prolonged dry season.

The research site (Figure 1) is situated along Jalan Badas road at the Badas peat dome around 85 km from Bandar Seri Begawan, Brunei. Brunei has a

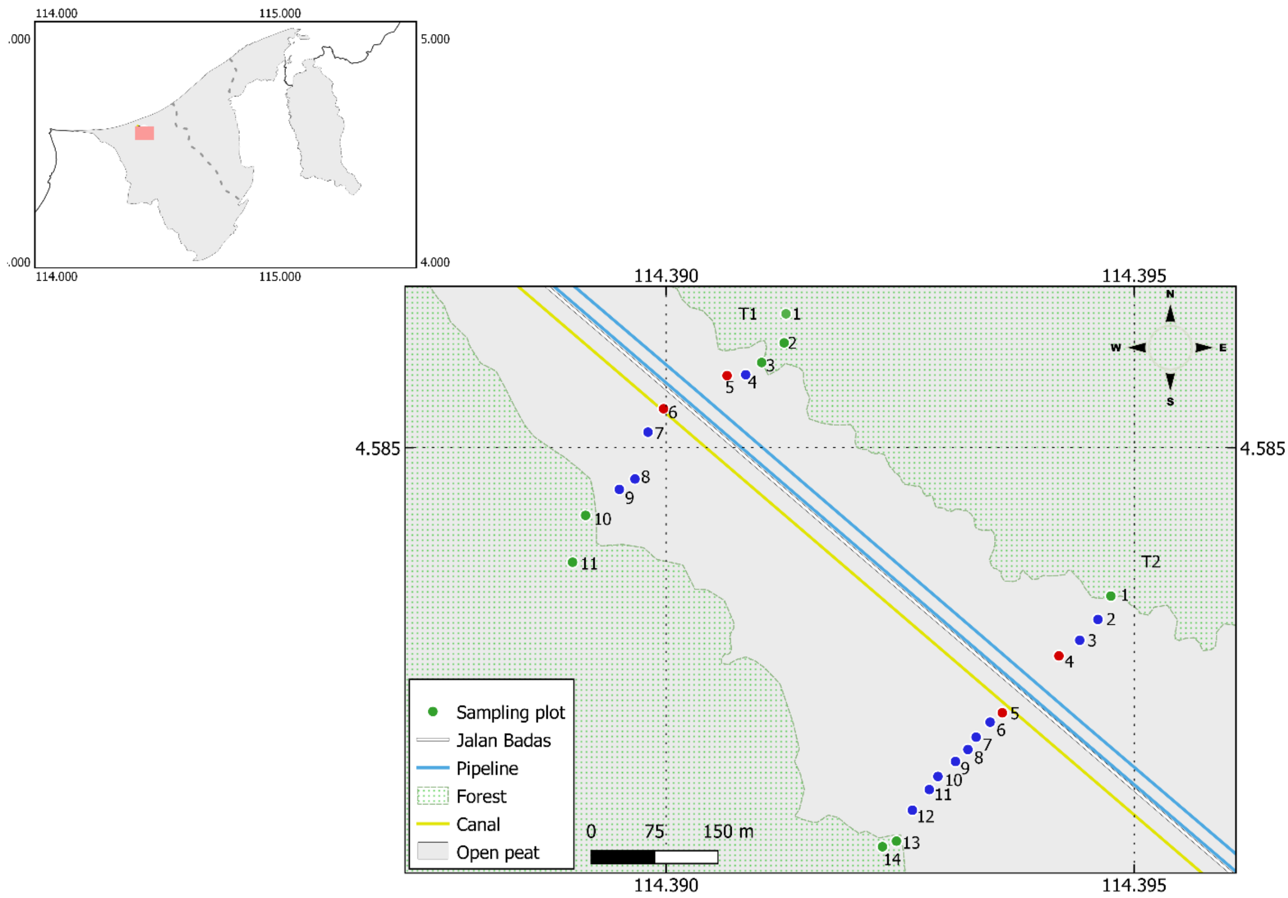

Figure 1. Map showing the location of the study sites in Badas (left). Sampling plots are colour coded along two transects (Transect 1 and Transect 2). Forest peat samples are denoted by green dots, peat samples nearest to the road are represented by red dots and the rest of the plots are marked with blue dots.

tropical climate, with rainfall showing a seasonal pattern with two maxima and two minima. The first maximum occurs during the period October to January with December being the wettest month and the second maximum from May to July with May generally being the wettest month (Brunei Darussalam Meteorological Department, 2017). The lowest total monthly rainfall occurs in February and the second minimum period occurs during June to August. The average annual rainfall from 2014 to 2017 was 2676 mm (Brunei Darussalam Meteorological Department, 2017) measured at Brunei International Airport.

At the study site in Badas, the construction of two water pipelines in the early 1970s resulted in drainage and peat subsidence (Suhip *et al.* 2020). Both pipelines are located approximately 10 and 20 m away from the road (Jalan Badas) to the northeast. A canal of around 1 m depth runs parallel to the road to the southwest. Two transects (Transect 1 and Transect 2) 500 m apart from each other were set up, crossing Jalan Badas from one edge of the peat swamp forest to the peat swamp forest on the other side (Figure 1). Transects were used instead of random sampling in order to cover in a consistent manner sampling points in the peat swamp forest, in the open non-forested peat, as well as peat close to the road. The elevation of the peat at the forest ranges from around 2 m to 9 m above sea level (m a.s.l.). The open peat towards the east of the road has a 1 m to 3 m higher elevation than the peat towards the western site of the road, based on the 2014 Digital Terrain Model (DTM) data from the Shuttle Radar Topography Mission (SRTM). The average groundwater table at the Badas peat dome site, determined using seismic refraction (Azhar *et al.* 2019), lies at around 0.4 m below the surface with peat depths of more than 9 m (Suhip *et al.* 2020). Degraded and previously burnt peat at the study site are commonly dominated by ferns and other common pioneer species (Hirano *et al.* 2012), while the intact peat swamp forests are dominated by pure *Shorea albida* stands (Anderson 1964, Stoneman 1997). Frequent fire events occur at major hotspots along the

Seria By-Pass road, located within 3 km of our study site, and a larger fire event occurred in Badas during the 2016 dry season.

Peat sampling

Peat coring was conducted at eleven sampling points along Transect 1 and fourteen sampling points along Transect 2 (Figure 1). Transect 2 is the longer transect as the edges of the forest are slightly further apart than at Transect 1. Three peat cores were taken at each sampling point using a Russian peat corer (Eijkelkamp peat sampler). Peat cores were taken at 50 cm, 100 cm and 150 cm depth. The peat cores were transferred into 50 cm long PVC pipes cut in half, with 5.08 cm inner diameter, and wrapped with plastic before being transported to the laboratory at Universiti Brunei Darussalam for analysis.

Bulk density, ash content and carbon loss determination

In the laboratory each peat core was divided into four subsamples measuring 12.5 cm length. Bulk density measurements were carried out on subsamples of fresh peat immediately after sampling in order to avoid the peat from drying out and becoming compacted. Samples were put into 18 cm round aluminium trays and were left to dry in an oven for 48 hours at 70 °C. After cooling, they were weighed and dry bulk density (*DBD*, g cm^{-3}) was calculated as follows:

$$DBD = \frac{Mass\ of\ dry\ soil}{Volume\ of\ corer\ sample\ chamber} \qquad [1]$$

The core length was measured using a ruler, while the corer cross-sectional area was calculated from the sample chamber volume (530 ml) and length (50 cm).

The remaining fresh peat samples were air-dried for 24 hours. Air-dried peat samples were then finely ground and homogenised using pestle and mortar. Approximately 10 g of finely ground samples were placed in individual 50 ml crucibles, which were then oven-dried for 24 hours at 105 °C. After oven-drying, the individual samples were reweighed and placed into a Gallenkamp Muffle Furnace Size 2 for 2 hours at 550 °C. After 2 hours, the samples were transferred to a desiccator to cool completely prior to re-weighing.

The ash content (%) of each sample was determined as follows (Allen *et al.* 1989):

$$Ash = \frac{Mass\ of\ ash}{Mass\ of\ oven\ dried\ soil} \times 100 \qquad [2]$$

Determination of carbon loss of peat through ash was calculated following Turetsky & Wieder (2001). This method has been applied in northern peatlands (e.g., Glukhova & Sirin 2018) but has not been applied yet in tropical peatlands. In order to determine the amount of carbon lost, it is critical to evaluate the results against a reference site which has not experienced fire events. In our case, the ash content from peat at a depth of 1.5 m was taken as reference ash content, as the ash content there was similar to what has been found at nearby undrained sites (Gandois *et al.* 2013, Dommain *et al.* 2015). We utilised the top 50 cm of the peat core which has experienced burning and the bottom unburned part of the peat core (135 cm to 150 cm depth), to calculate ash content, dry mass and burned organic matter.

In order to calculate the amount of ash in the top, burned peat section not associated with combustion processes (*TUA*, top unburned ash), the total organic matter of the top peat portion was multiplied by the quotient of ash and organic matter of the bottom unburned peat portion:

$$TUA = (TM \times TOMC) \times \left(\frac{BAC}{BOMC}\right) \qquad [3]$$

where *TUA* = top unburned ash not associated with combustion processes (mg), *TM* = top dry mass (mg), *TOMC* = top organic matter concentration (mg g^{-1}), *BAC* = bottom ash concentration (mg g^{-1}), *BOMC* = bottom organic matter concentration (mg g^{-1}).

The top organic matter concentration was calculated through:

$$TOMC = 1000 - TAC \qquad [4]$$

where *TAC* equals the top ash concentration (mg g^{-1}).

The bottom organic matter concentration was calculated using the equation:

$$BOMC = 1000 - BAC \qquad [5]$$

Then, *TUA* was subtracted from the total ash in the top portion in order to calculate the amount of ash left behind after fire (*EA*, excess ash) in the top portion:

$$EA = (TM \times TAC) - TUA \qquad [6]$$

Lastly, in order to calculate the amount of burned organic matter (*BOM*, mg) that produced the excess ash at the peat surface, *EA* was multiplied by the organic/ash ratio of the bottom portion of unburned peat:

$$BOM = EA \times \left(\frac{BOMC}{BAC}\right) \qquad [7]$$

All initial calculations are based on a 10 cm diameter core with subsequent extrapolation to a per square metre basis. We assumed 55 % carbon content by mass to estimate the quantity of carbon that has been lost into the atmosphere owing to fire events based on results at a nearby site (Dommain *et al*. 2011) and the small range of carbon content values in other Southeast Asian ombrogenous peatlands (Shimada *et al.* 2001, Warren *et al.* 2012).

Statistical analyses

Differences in % ash content between forest and open sampling locations and between transects were analysed using two-way ANOVA without interaction effects. Transects were included as factor in order to determine if the ash content difference is significant between transects. Separate two-way ANOVA were conducted for all sampling depths combined, and for selected sampling depths (12.5 cm, 62.5 cm, 100 cm and 150 cm). Differences in % ash content between the four selected sampling depths were analysed for forest locations, and for open locations, separately using one-way ANOVA. All values of ash content were arcsine-transformed prior to ANOVA. All ANOVA calculations were conducted using R version 3.4.1 (R Core Team, 2017).

Fire occurrence and forest loss scoring in Landsat images

To explore the occurrence of fire and the retreat of forest along the sample transects, we examined Landsat imagery of the site to distinguish forest cover, burned areas, and open land / low vegetation. The advantage of using Landsat imagery over medium-resolution (MODIS) burnt area mapping is that small scale shifting fires can be detected (e.g. Miettinen *et al*. 2007). We first searched for Landsat Collection 2 Level-2 Science Products using EarthExplorer (https://earthexplorer.usgs.gov/) to find Landsat 4-5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8-9 Operational Land Imager (OLI) images of Badas with no more than 40 % cloud cover, then manually eliminated images in which Badas was obscured by clouds. The resulting imagery dates were:

- for Landsat 4-5 TM: 1988-12-21, 1990-06-18, 1991-04-18, 1994-11-20, 1996-09-22, 1998-01-15, 2000-03-09, 2005-07-29, 2007-07-03, 2009-04-03 and 2011-08-15;

- for Landsat 7 ETM+, 1999-11-26, 2000-11-12, 2001-07-10, 2002-06-27, 2008-06-27, 2012-08-09, 2017-07-06 and 2019-03-06;

- for Landsat OLI, 2015-03-19, 2015-08-10, 2017-07-30, 2018-08-18, 2020-05-19, 2020-05-19 and 2020-07-06.

For each image, we assembled RGB composite images using the short-wave infrared, near infrared and red bands respectively (TM and ETM+ bands 7, 4, and 3; OLI bands 7, 5 and 4), after Miettinen & Liew (2010) and Miettinen *et al.* (2016). For information on forest cover prior to the first TM image (1988-12-21), we also searched for imagery from the Landsat 1-5 Multispectral Scanner (MSS), Collection 2 Level 1, which yielded a single useful image, from 1972-10-15. Because Landsat 1-5 MSS did not measure in the short-wave infrared, we assembled a composite image using data from the two near infrared bands and the red band (Landsat 1 MSS bands 7, 6 and 5 as red, green and blue). The Landsat 1 MSS image has a spatial resolution of 60 m; the TM, ETM+ and OLI images have a resolution of 30 m.

We then scored each sample location based on the Landsat imagery. In each image, each sample location was scored as forest, open land / low vegetation, recently burned, or undetermined (e.g., when the sample location was obscured by clouds or cloud shadows, or data were missing because of the Scan Line Detector failure on Landsat 7). Scoring was performed independently by three of the authors. From the raw score data, we then computed the number of years since the site was last seen to be forested according to each scorer; for locations that were identified as open in the Landsat 1 MSS image from 1972, we assumed forest cover in the now open peat was lost after July 1, 1965. In addition, we computed the number of images in which each scorer identified a location as having recently burned. We then computed the mean years since forest cover and the mean number of images scoring each location as burned across all three scorers.

RESULTS

Variation in bulk density, ash content and burned organic matter content

Bulk density values from both transects showed large variability with densities only slightly decreasing with depth (Figure 2).

The mean ash content for both transects generally decreased with depth (Figure 3). The ash content results showed that mean ash contents for the surface peat reached values of more than 2 % for Transect 1 and Transect 2 (Figure 3). The southwestern side of each transect (side where the drainage canal is

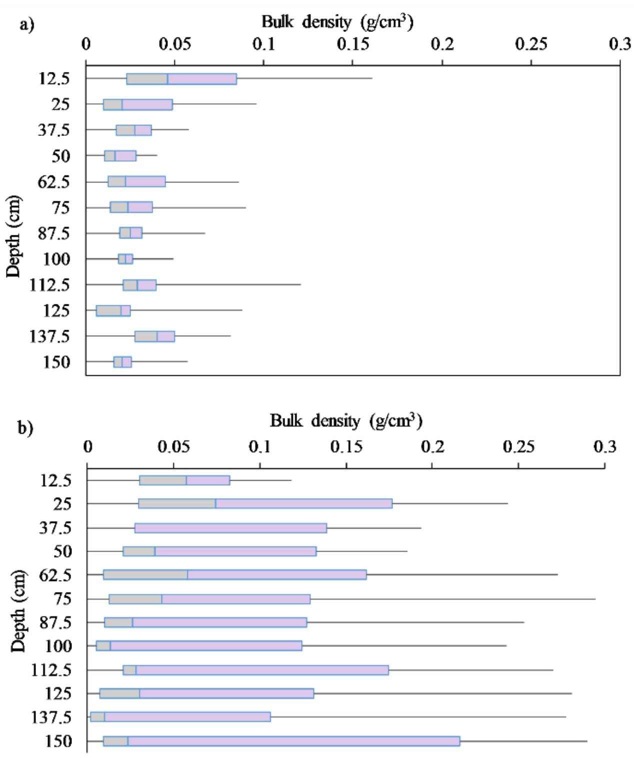

Figure 2. Boxplot of bulk density values versus depth for (a) Transect 1 and (b) Transect 2.

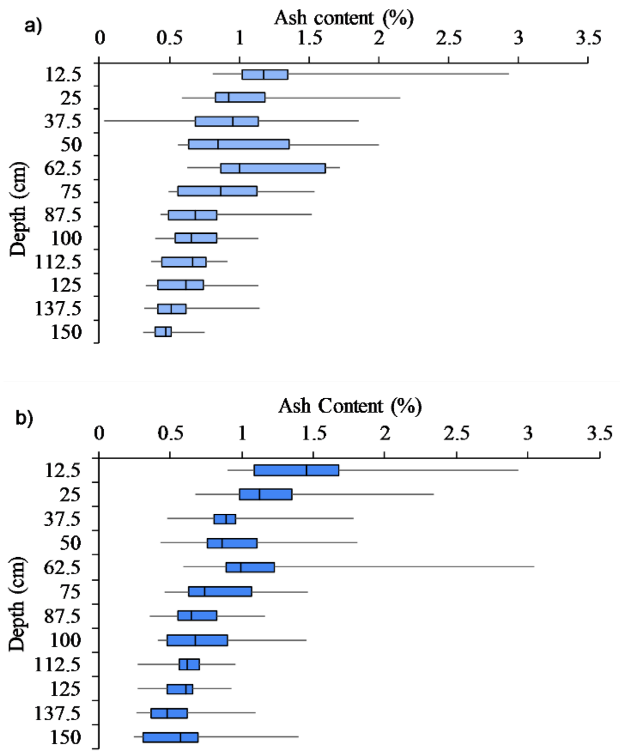

Figure 3. Boxplot of ash content versus depth for (a) Transect 1 and Transect 2 northeastern section and (b) Transect 1 and Transect 2 southwestern section.

running) generally showed a higher ash content and greater variability in ash concentrations than the northeastern side in particular for the top 25 cm of peat. While the ash content generally decreased with depth, at a depth of around 60 cm the ash content was higher than at the previous shallower depth. This anomaly was observed for both transects. With ash contents ranging between 0.8 % to 2.9 % for depths from 0 to 1 m, at depths of 1.5 m the ash content for both transects converged significantly, varying on average between 0.5 % to 0.6 %. In comparison, ash contents at these depths for sampling points in the forest with ash contents between 0.3 % and 0.4 % were slightly lower than sampling points in the open peat.
Mean ash content did not significantly differ between forest and open sampling locations, either when all sampling depths were combined, or at the selected sampling depths of 12.5 cm, 62.5 cm, 100 cm and 150 cm (Table 1). In contrast, mean ash content differed significantly between the two transects, particularly at 12.5 cm depth.

Within forest and open sampling locations, respectively, the deepest peat at 100 cm depth and 150 cm depth showed significantly lower ash content than the surface peat portion at 12.5 cm depth (Figure 4). Ash content at 62.5 cm depth for forest and open sampling locations were also significantly higher than at 150 cm depth.

Mean ash contents for sampling points closest to the road were higher than the adjacent sampling points to the east and west. Ash content values for Transect 1 were generally higher in the open peat compared to the forested peat. For Transect 2, the differences in ash content between open and forested peat were smaller except for the previously mentioned high surface ash content at sampling sites northeast of the road (Figure 1). The spatial surface profiles of ash contents up to a depth of 25 cm (Figure 5) reveal that ash content was higher in the open peat, notably near the perimeter of the road, and lower toward the forest in both NE and SW directions.

The burned organic matter values calculated from ash content following Turetsky & Wieder (2001) range between 1.88 kg m^{-2} to 17.52 kg m^{-2} for SW parts of transects and 0.54 kg m^{-2} to 24.25 kg m^{-2} for NE parts of transects. Estimates of burned organic matter from ash content for Transect 1 were almost double those for Transect 2 (Table 2).

The average estimated burned organic matter of the East and West side for both transects were 6.57 ± 1.97 kg m^{-2} and 6.86 ± 1.45 kg m^{-2}, respectively.

Table 1. The effects of area (Forest vs Open) and transects (Transect 1 vs. Transect 2) on ash content, for all sampling depths combined, and for selected sampling depths (12.5 cm, 62.5 cm, 100 cm and 150 cm), analysed using two-way ANOVA. Ash content values (%) were arcsine-transformed prior to ANOVA, conducted at α = 0.05. Significant p-values are highlighted in bold.

Depth	Factor	df	F	p-value
All sampling depths combined	Area	1	0.1	NS
	Transect	1	10.3	**<0.01**
12.5 cm	Area	1	2.0	NS
	Transect	1	15.0	**<0.001**
62. 5 cm	Area	1	0.3	NS
	Transect	1	0.1	NS
100 cm	Area	1	1.6	NS
	Transect	1	2.4	NS
150 cm	Area	1	3.9	NS
	Transect	1	1.5	NS

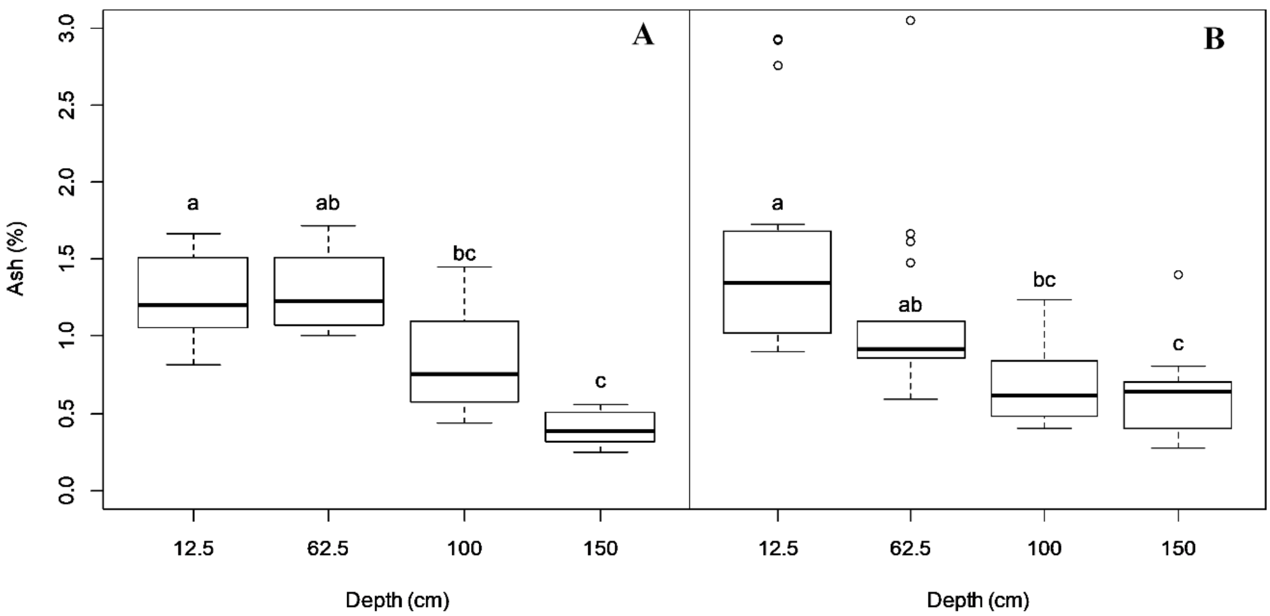

Figure 4. Variation in ash content (%) at (a) Forest and (b) Open areas at four selected sampling depths (12.5 cm, 62.5 cm, 100 cm and 150 cm). Ash content values (%) were arcsine-transformed prior to ANOVA, conducted at α = 0.05. Superscripts with different letters (a, b, c) within a panel indicate significant differences. Thick black line in boxplot represents median value. Hollow circles represent outliers.

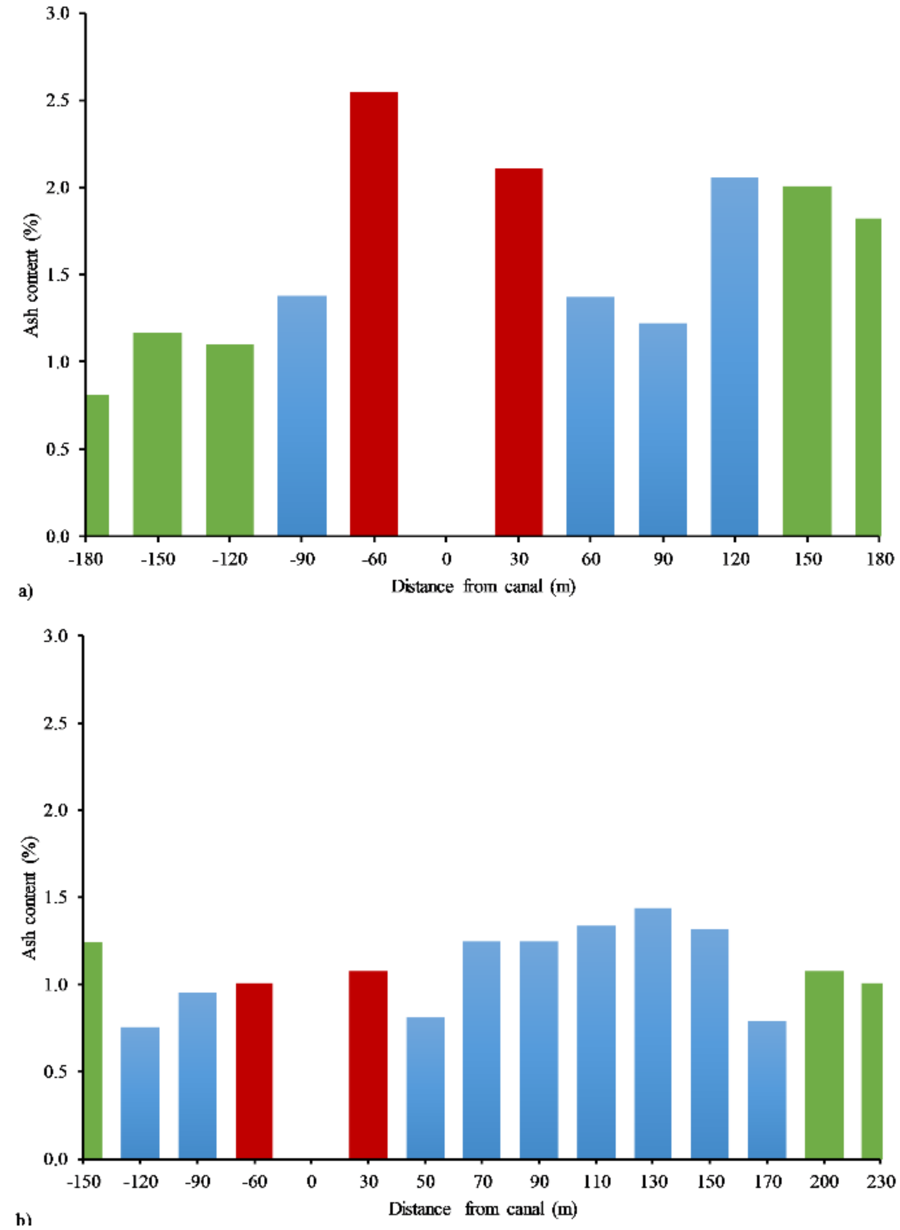

Figure 5. The spatial distribution of surface ash in (a) Transect 1 and (b) Transect 2 (green represents peat swamp forest; blue represents open peat; red represents peat nearest to the road).

Applying a carbon value for peat of 55 %, the average carbon lost for the northeastern sections of both transects is estimated to be 3.61 ± 1.08 kg m^{-2} and 3.77 ± 0.80 kg m^{-2} for the southwestern sections of both transects based on the residual ash method.

Fire occurrence and forest loss scoring from Landsat images

Examination of Landsat images showed the progressive retreat of the forest along the two transects, and repeated fires, with more frequent fires closer to the canal (Figures A1 and A3 in the Appendix). The time since forest cover varied from more than 50 years immediately adjacent to the canal (where open land adjacent to the water pipelines was apparent in the Landsat MSS image from October 15, 1972), to the still-forested locations at the end of Transect 1. There were some differences among the three scorers but spatial patterns were similar (Figure A1). Five of the sample locations (T1–6, T2–3, T2–4, T2–5 and T2–6) were identified as having recently burned on at least three Landsat image dates, and over half (14/25, 58 %) were identified as having recently burned on more than one date. Most of the sample locations (16/25, 64 %) were last seen with forest cover over 20 years ago.

Table 2. *TAC* - Top Ash Content, *BAC* - Bottom Ash Content, *TM* - Top Mass, *BOM* - Burned Organic Matter, SE - Standard Error.

Sampling point		*TAC* (mg g^{-1})	*BAC* (mg g^{-1})	*TM* (g)	*BOM* (kg m^{-2})
T1-NE	1	8.16	4.21	9.56	4.42
	2	11.44	4.97	4.28	2.76
	3	12.65	5.10	2.61	1.91
	4	14.10	3.10	10.00	17.52
	5	29.28	7.56	10.01	14.18
	Mean ± SE				8.16 ± 3.21
T1-SW	6	16.68	2.82	10.01	24.25
	7	16.70	5.60	8.20	8.02
	8	27.62	13.98	6.01	2.89
	9	15.30	2.92	6.01	12.61
	10	16.82	7.00	6.01	4.16
	11	29.31	5.83	6.00	11.95
	Mean ± SE				10.65 ± 3.16
T2-NE	1	11.79	6.70	5.00	1.88
	2	10.23	4.00	5.08	3.91
	3	9.17	4.80	5.13	2.31
	4	13.49	3.53	7.34	10.22
	Mean ± SE				4.58 ± 1.93
T2-SW	5	11.92	8.06	6.04	1.43
	6	8.98	7.59	6.01	0.54
	7	11.29	6.76	6.03	1.99
	8	13.46	6.88	6.02	2.84
	9	15.59	6.41	6.16	4.36
	10	17.27	4.61	6.08	8.25
	11	9.82	3.19	6.01	6.18
	12	9.07	2.73	6.07	6.96
	13	11.07	3.43	5.06	5.55
	14	10.12	2.47	5.04	7.71
	Mean ± SE				4.58 ± 0.87

DISCUSSION

The method of calculating carbon loss from ash contents relies on the concept that peat decomposition and fire remove organic matter, leaving inorganic/mineral material behind. The ash residue method assumes that mineral content of peat remains in place in the surface peat, when peat decomposes or burns. A study by Laiho & Pearson (2016) found a strong variability of ash content with depth and time, with a greater variability of ash contents for minerotrophic peatland than for ombrotrophic peatland. It was found that several factors such as variation in ash and element concentrations between peatlands, vertical distribution of ash concentrations and physical and biological processes can affect the ash content. For certain horizons, ash content actually seemed to decrease or was steady over a 50-year time frame (Laiho & Pearson 2016).

At Badas, both transects show a similar trend in ash content with depth, with Transect 1 having a higher top ash content than Transect 2. The burn count for both transects show that Transect 2 shows a higher burn count compared to Transect 1 (Figure A1). This explains the greater retreat of forest at Transect 2 compared to Transect 1. However, despite the greater burn count and retreat of forest at Transect 2, the top ash content is lower compared to Transect 1.

Our research site has been affected by drainage and subsidence due to canal and road construction for decades. After rapid subsidence due to shrinkage and compaction in the first few years after drainage, the main driver of further subsidence is peat decomposition and fire (Andriesse 1988, Wösten *et al.* 1997, Hooijer *et al.* 2012; Figure A4). Although we do not know the exact date of canal construction, imagery shows that it was dug before 1972. Therefore, we assume that the area around the ditch has been subsiding from the canal for at least 50 years. Thus, based on an average decomposition-driven subsidence rate of 2.2 cm y^{-1}, determined in 2.7 MHa of drained peatlands in Sumatra and Borneo over 2007 to 2011 (Hoyt *et al.* 2020), we would expect approximately 2.2 cm y^{-1} x 50 y = 110 cm of oxidative peat loss from subsidence alone.

Furthermore, our scoring of Landsat imagery indicates that most of the sampling locations had burned more than once since 1972. Page *et al.* (2002) estimated that in 1997, 51 ± 5 cm of peat was lost in fires in Central Kalimantan, whereas Ballhorn *et al.* (2009) estimated loss of 33 ± 18 cm of peat from fires in Central Kalimantan, Borneo in 2007. With these magnitudes, we would expect the loss of at least 33 cm of peat. This might not be additive with oxidation from subsidence, so to be conservative we use 110 cm as an estimate of the magnitude of peat loss at the site, which is consistent with observation of subsidence around pilings at the site (Figure A2).

Finally, as the forest at the site was not removed by logging but instead was lost to fire at the site, if mineral content from fire remained in situ, we would expect the forest mineral content to be found in the surface peat at the site. Nguyen *et al.* (2016) estimated biomass-carbon of the same forest type (with adjustment for hollow trees) of 217.7 x 10^3 kg ha^{-1}, which corresponds to 21.77 kg m^{-2}. Based on peat carbon content from Dommain *et al.* (2015) of 39.168 kg m^{-3} (based on a mean dry bulk density of 0.072 g cm^{-3} and carbon concentration of 54.4 %) and considering that most of the sampling locations support little vegetation, we estimate that the forest biomass lost to senescence and fire is equivalent to roughly 50 cm of peat.

These data suggest that the ash from the equivalent of ~50 cm (from vegetation) plus ~100 cm (from fire and decomposition) should be distributed in the surface peat. If this ash remained within the top 50 cm of the peat, we would expect that this layer would have an ash content that is roughly four times its original value, from addition of the mineral content from the burned and decomposed forest and peat to the original mineral content in that layer. As the mean ash content of deeper peat at this site is 1 % to 2 %, we would thus expect 4 to 8 % ash content in surface peat at Badas, at least in the more degraded sampling locations.

Instead, we measure ash contents that are mostly lower than those of surface peats at nearby sites (1.56 % at a pristine site, and 2.21 % at a deforested but not drained site; Gandois *et al.* 2013) or in a 350 cm core from a pristine site supporting the original forest type at Badas (1.9 ± 1.4 %; Dommain *et al.* 2015) (Table 3). We infer that a large majority of the ash content released by fire and decomposition at the site has not remained in situ but instead has been removed either in smoke (Das *et al.* 2019), as dust, or in ground- and surface water. In particular, frequent flooding of the site has occurred due to the lowering of the peat surface from subsidence and fire, as observed around canals and ditches in other degraded tropical peatlands (Page *et al.* 2008, Ritzema *et al.* 2014), and may have removed much of the residual mineral content in dissolved or particulate form. Flooding events have been observed by the authors since 2009 during the wetter periods of most years, such as the period from November to February.

The aim of this research was to evaluate the residual ash method for estimating carbon loss along two transects at the Badas peat dome, Brunei Darussalam. Based on our calculations as well as reported ash contents from drained and undrained peat forests, we expected ash contents between 4 % to 8 %, however we only found ash contents ranging between 1 to 2 %. We therefore conclude that the ash residue method is not a reliable method for estimating carbon loss from fire and subsidence in degraded Southeast Asian peatlands. This implies that most of the mineral content released by decomposition and fire has been exported from Badas, and thus could be an important source of mineral content deposited in benthic or marine environments, from the atmosphere (from smoke), or transported via ground and surface water. Further research to investigate the fate of this mineral content is warranted.

Table 3. Ash contents from tropical peatlands in Borneo.

Description	Ash content (%)	Reference
Samples from coastal and inland peatlands in West Kalimantan:		
- acrotelm (top 100 cm)	4.18 % ± 6.295 (n = 163)	Anshari *et al.* (2010)
- catotelm (below 100 cm)	3.54 % ± 5.518 (n = 107)	
- undrained peat forest	4.10 % ± 9.17 (n = 39)	
- drained peat	4.21 % ± 5.813 (n = 159)	
North Selangor peat swamp forest:		
- forest	4.9 % ± 0.99	Cooper *et al.* (2020)
- drained	7.5 % ± 0.83	
Peat swamp forest in Brunei:		
- Mendaram	0.4 – 2.8 %, overall mean 1.56 % (n = 3)	Gandois *et al*. (2013)
- Damit	0.7 – 5.2 %, overall mean 2.21 % (n = 3)	

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AUTHOR CONTRIBUTIONS

ARC conceptualised the study; ARC, RSS, SHG developed the methodology of the research; AAA, SHG, ARC, SI, collected the data; AAA, ARC, SI, SKT, SMJ, SHG and RSS analysed the data; AAA wrote the first draft of the manuscript and all authors revised, reviewed and gave critical freedback. All authors contributed to final editing of the manuscript and approved the final version.

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Appendix

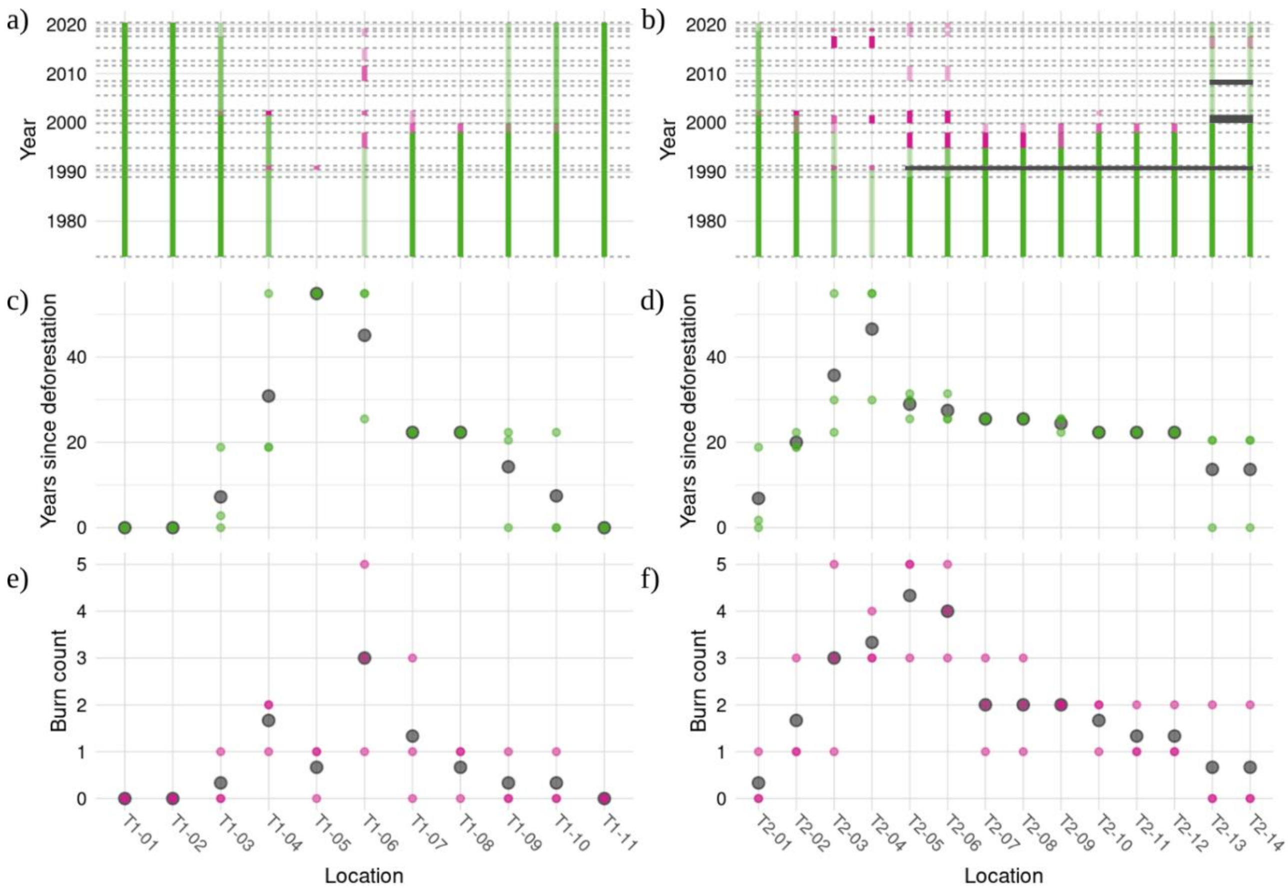

Figure A1. Fire occurrence and forest loss at Badas. (a, b) Scoring of each sample location on transects 1 (a) and 2 (b) as forest (dark green) or burned (red), vs. open land, based on Landsat images (imagery dates indicated by dashed horizontal lines). Data gaps due to cloud cover or the scan line detector failure on Landsat 7 are marked with gray boxes. Opacity indicates the proportion of scorers designating the location as forest or burned. (c, d) Years since deforestation of each sample location on transect 1 (c) and 2 (d) based on scoring (means: black points; individual scores: small green points). Locations scored as open in the first Landsat image (1972-10-15) were assumed to have been cleared on 1965-07-01. (e, f) Number of Landsat images showing each sample location as burned according to scores (mean: black points; individual scores: small red points).

Figure A2. Pilings supporting water pipelines along Jalan Badas. Piles are exposed under pile caps due to peat subsidence.

Figure A3. A smouldering peat fire along Jalan Badas, 02 February 2016.

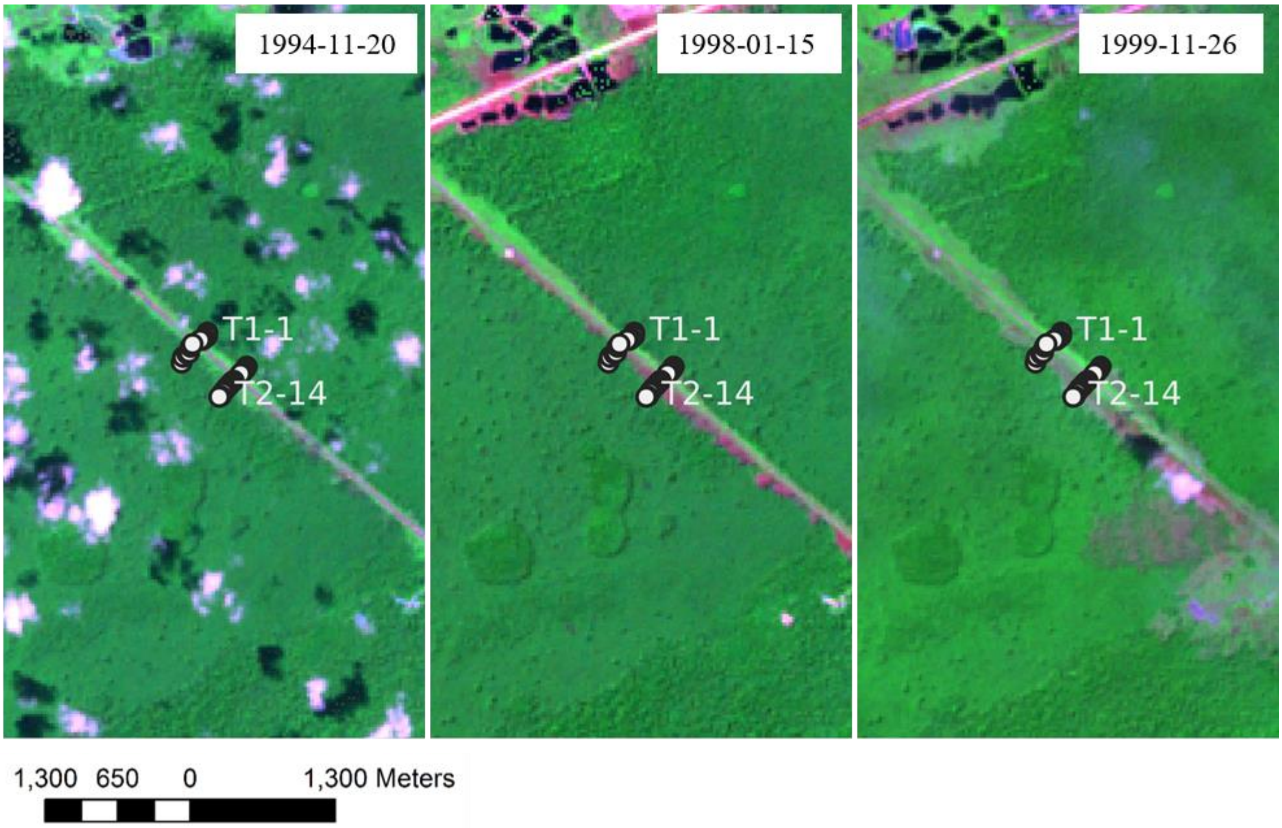

Figure A4. Sample Landsat images used for scoring (red band: short-wave infrared; green: near infrared; blue: red). Forest appears in shades of dark green, recently burned areas are pink, purple or red, and clear areas (low vegetation) appear light green.