ADVANCES IN FOREST FIRE RESEARCH

2022

Edited by
DOMINGOS XAVIER VIEGAS
LUÍS MÁRIO RIBEIRO

GAMBUT field experiment of peatland wildfires in Sumatra: infrared measurements of smouldering spread rate

Muhammad A. Santoso[1]; Eirik Christensen[1]; Hafiz M. F. Amin[1;5]; Pither Palamba[3]; Yuqi Hu[1;6]; Dwi M. J. Purnomo[1]; Wuquan Cui[1]; Agus Pamitran[2]; Franz Richter[1]; Thomas E. L. Smith[4]; Yulianto S. Nugroho[2]; Guillermo Rein*[1]

[1]Department of Mechanical Engineering, and Leverhulme Centre for Wildfires, Environment and Society, Imperial College London, London, SW7 2AZ, United Kingdom, {m.santoso16, e.christensen16, hafiz.amin, y.hu15, dwi.purnomo16, w.cui17, franz.richter11, g.rein}@imperial.ac.uk
[2]Department of Mechanical Engineering, Universitas Indonesia, 16424, West Java, Indonesia, {pamitran@eng.ui.ac.id, yulianto.nugroho@ui.ac.id}
[3]Department of Mechanical Engineering, Universitas Cenderawasih, Jayapura, Indonesia, {pither.palamba@yahoo.com}
[4]Department of Geography & Environment, London School of Economics & Political Science, United Kingdom, {t.e.l.smith@lse.ac.uk}
[5]School of Computing, Engineering & Digital Technologies, Teesside University, Middlesbrough, United Kingdom {H.Amin@tees.ac.uk}
[6]Sichuan Fire Research Institute of the Ministry of Emergency Management, Chengdu, China, {huyuqi@scfri.cn}

**Corresponding author*

Keywords

Peat, smouldering, fire, field, infrared

Abstract

Peatland wildfires present challenge to the mitigation of climate change due to the large amount of ancient carbon emission. Once ignited, the organic soils in peatland can burn for a long periods (weeks to months) and are difficult to extinguish. Peat fire is governed by smouldering combustion which is the slow, low temperature, flameless burning of charring porous fuel, and the most persistent type of combustion phenomena. The detection and monitoring of peatland wildfires are often conducted by remote sensing like satellite. However, there is currently a missing gap between spread of peat fires in the small laboratory scale and the large field scale. This work covers this gap by conducting field-scale controlled experiment of peatland wildfires. The experimental campaign, GAMBUT, was conducted in the peatland of Sumatra, Indonesia, covering an area of 408 m2. Smouldering spread rate was measured by infrared cameras and subsurface thermocouples. The smouldering sustained up to 10 days and nights, and survived against three rainfalls. Observation from infrared images show that horizontal smouldering spread rate fluctuates during propagation. However, no significant difference was found between average horizontal spread rates from the measurements of infrared camera and thermocouples, i.e. 0.3±0.13 cm/h to 0.8±0.2 cm/h. The spread rates here agree with the trend in the literature of laboratory experiments, fit within in the ranges of high moisture (MC) and inorganic (IC) contents of the soil (MC between 23 to 141% and IC between 49 to 72%). Even though slower, the fires thrived up to 10 days and against three rainfalls, demonstrating the persistency of smouldering peat fires and calling for a consideration of degraded peatland with high inorganic content to be consistently included in the mapping and monitoring of peatland area. GAMBUT presents a unique understanding of peatland wildfires at field conditions and aims to contribute to the better monitoring and mitigation acts.

1. Introduction

Peatlands contribute to the massive amount of carbon storage in the world, estimated to be up to 700 Gt (Yu 2012). In pristine conditions, the organic soil in peatland is protected from fires either due to the high moisture content, and the cold condition such as the case of permafrost in the Arctic region. However, recent increase of frequency of severe wildfires around the world, especially those of peatlands in the Arctic region, identifies that the ancient carbon that has been stored in peatlands for millennia is under threat to be released to the atmosphere

https://doi.org/10.14195/978-989-26-2298-9_133

(Young *et al.* 2016). Once ignited, the organic soil (peat) can burn for weeks to months and difficult to be extinguished, surviving against rainfalls and firefighting responses (Rein 2016).

Peat fire is dominantly governed by smouldering combustion, which is the slow, low temperature, flameless burning of charring porous fuel, and the most persistent type of combustion phenomena. Smouldering peat fire spreads in both horizontal and vertical direction (in-depth into the subsurface layer). Recent laboratory studies have been conducted to understand both directions of smouldering spreads (Huang *et al.* 2016; Huang and Rein 2017; Christensen *et al.* 2020), and reveal the heat transfer effect on the faster spread in the subsurface layer than the surface layer. This phenomena can cause an overhang formation in which the surface layer stays unburned while the subsurface continues to propagate (Huang *et al.* 2016).

Currently, there is limited controlled experiment in the field to explain the different smouldering behaviour between surface and subsurface layers to improve the monitoring and mitigation of peatland wildfires in the field scale. Most studies in the field were conducted forensically such as the measurements were conducted on actual peatland wildfires with minimum control on the ignition methods, measurements location, and fire spread area (Page *et al.* 2002; Usup *et al.* 2004; See *et al.* 2007; Simpson *et al.* 2016; Smith *et al.* 2018). Pastor et al. (Pastor *et al.* 2017) conducted systematic peat fire experiment in the peatland of Peruvian Andes with each experimental area of 50×50 cm, and 1 out of 18 tests show temperatures up to 400°C and 3 show temperature above 100°C. This work aims to add to the previous field studies, contribute to the systematic methodology of peatland wildfires experiment in the field, and better understanding of surface peat fires spread in the field scale.

2. Methodology

The experimental campaign, GAMBUT, was conducted in Rokan Hilir regency, Sumatra, Indonesia, from 19 to 29 August 2019 (Santoso 2021). More detailed discussion of the study area can be found in Santoso (2021). The site in this study is in a tropical wet climate with a mean annual rainfall of 2,080 mm (Badan Pusat Statistik Kabupaten Rokan Hilir 2015); mostly covered by palm trees, ferns, and sedges; and closely located with an artificial reservoir (water pond) (Figure 1). The experiments were conducted in 12 days across changing precipitations. Three rainfall events equated to 4.8 mm of water column height occurred in the afternoon of day 6, 1.4 mm in the night of day 6, and 2.5 mm in the night of day 9 (Santoso 2021).

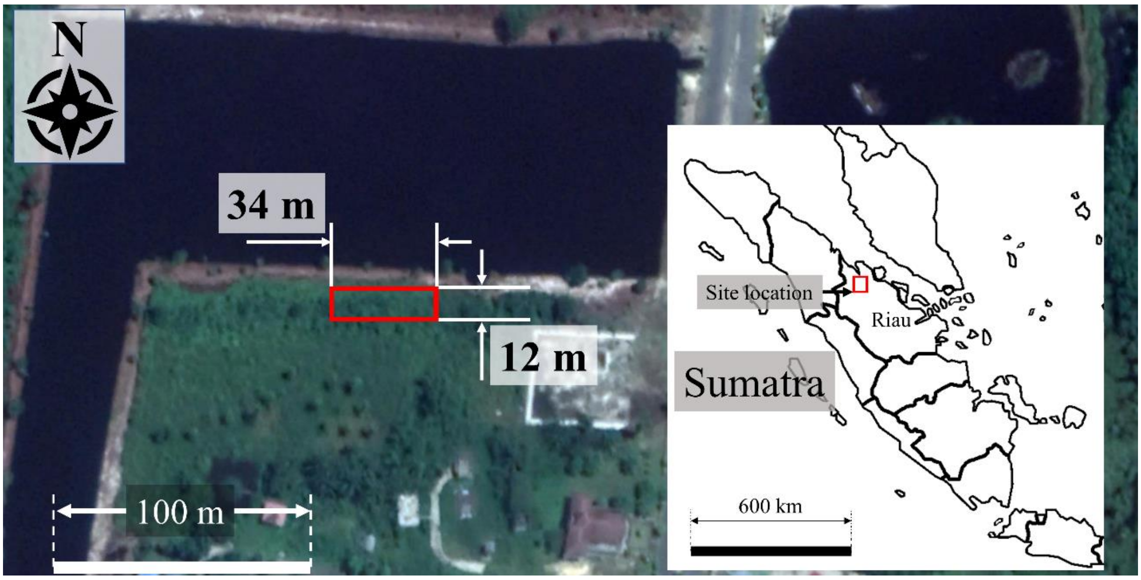


Figure 1- Top view of the site for GAMBUT experiment near a reservoir (Google Earth, 2021). The experiment area is indicated by the red rectangle. The site is a secondary peat swamp forest in Rokan Hilir, Sumatra, Indonesia (1°36'17.1"N 100°58'30.5"E). Inset picture shows Sumatra Island in which the site is indicated by a red rectangle (Golbez, 2021, CC BY) (Santoso 2021).

The experiments in this study were conducted in three plots of land, each with dimensions of 10 by 10 m (Figure 2a). Firebreaks were made around the perimeter of each plot by digging trenches of 50 cm wide and 50 cm deep which were filled with sand to prevent fires from spreading beyond these plots. From the left to right of Figure

2, the plots are indicated as Plot 1, Plot 2, and Plot 3. In each plot, two peat fire experiments were conducted (Figure 2b). In Plot 1, these two peat fire experiments are indicated as fire area of Plot 1 North (P1N) and Plot 1 South (P1S). In Plot 2, the fire area are Plot 2 North (P2N) and Plot 2 South (P2S), while the fire area in Plot 3 are Plot 3 North (P3N) and Plot 3 South (P3S). In total, six peat fire experiments were conducted during this field experiment campaign. In this study, fires in the north and south sides of the plots were well separated and did not spread into each other. Ignition was conducted by slash-and-burn and ember ignition. Slash-burn ignition was conducted by burning piles of dried surface vegetation of a dimension of 8 m length, 1 m wide, and 50 cm high, while ember ignition was conducted by filling an ignition pit shown in Figure 2b with smouldering charcoals. Details of ignition methods can be seen in (Santoso 2021).

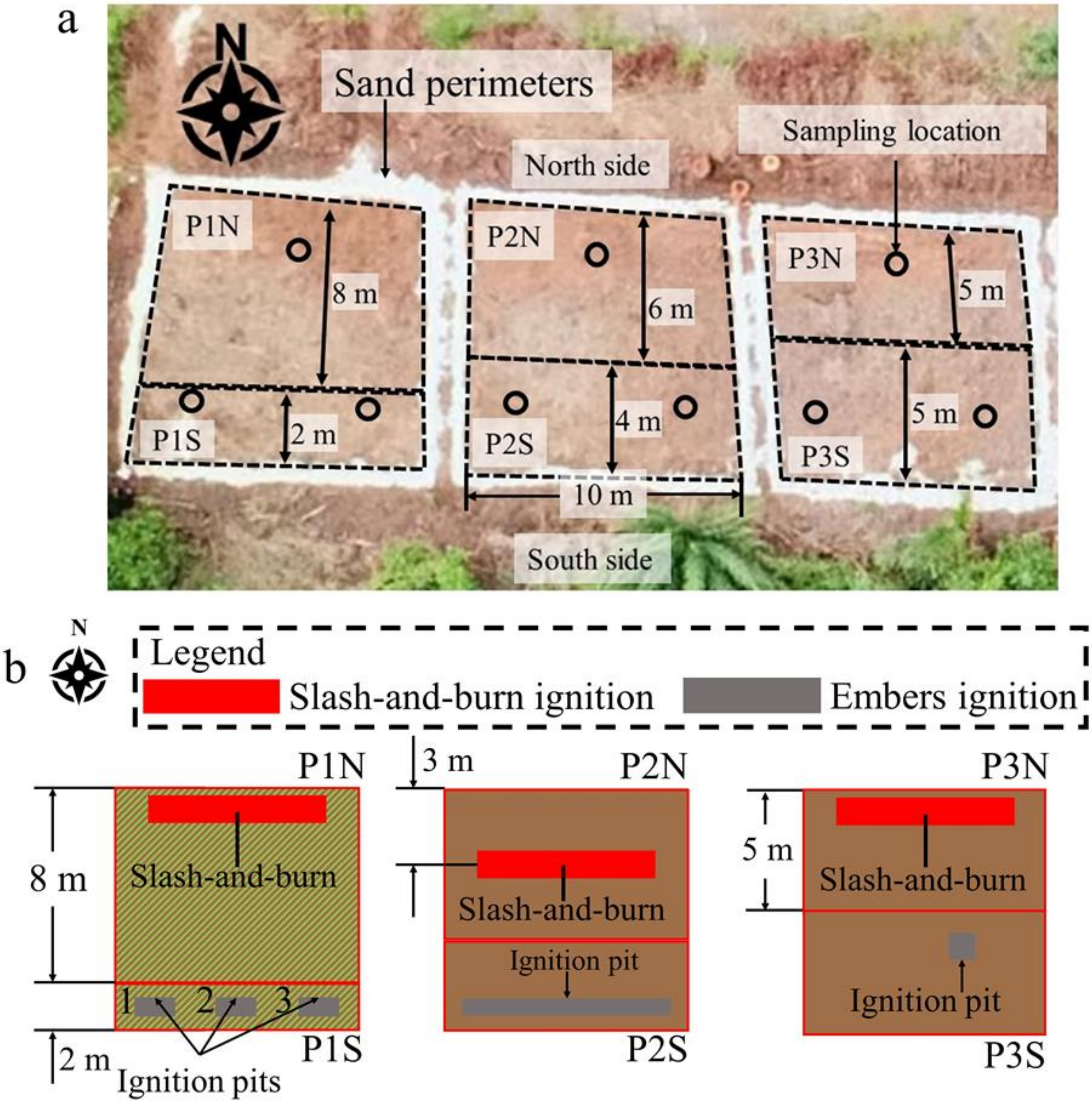


Figure 2- a) Top view of the 12 × 39 m of experimental area after surface vegetation treatment (Nugroho, 2018, CC BY). Black circles represent peat sampling locations for measurements of bulk density, moisture content (MC), inorganic content (IC), and elemental content. b) Schematic of the fire areas and different ignition methods. Red and grey rectangles refer to slash-and-burn and ember ignitions, respectively. Green diagonal lines refer to the surface litter that is kept intact on plot 1. Fire areas indicated by P1N, P2N, P3N, P1S, P2S, and P3S are Plot 1 North, Plot 2 North, Plot 3 North, Plot 1 South, Plot 2 South, and Plot 3 South, respectively (Santoso 2021).

Plot surfaces were cleaned from palm trees, ferns, sedges, and surface litter vegetation, except plot 1 where surface litter vegetation was kept intact (Figure 2b) to obverse its effect on the effectiveness of slash-and-burn ignition. The visual difference from above as shown by Figure 2a is not obvious since the litter vegetation left on Plot 1 have been significantly dried naturally, thus the colour of the vegetation have turned brownish, similar to the surface of dried peat in Plot 2 and Plot 3.

Infrared (IR) images were recorded using a FLIR Duo-R camera, mounted on a crane with an angle-adjustable hand to adjust the field of view of the camera. This crane was mounted on a rail to allow convenient IR image measurement along the plots, on both the north and south sides (Figure 3). Active fire area on the surface was obtained by analysing the acquired IR images. For the analysis of IR images, a similar approach used in (Amin *et al.* 2020) was adopted and a threshold value of camera intensity well above the surrounding area (0.1) was chosen. The images were converted to greyscale and the pixels where the normalized intensity increases above the intensity threshold were marked (subset in Figure 3). The area inside the marked perimeter line was then calculated to be the active fire area. The scaling from pixel dimension to physical length was possible by using a geo-reference plate with a dimension of 0.17 × 0.14 m, also shown in the subset of Figure 3.

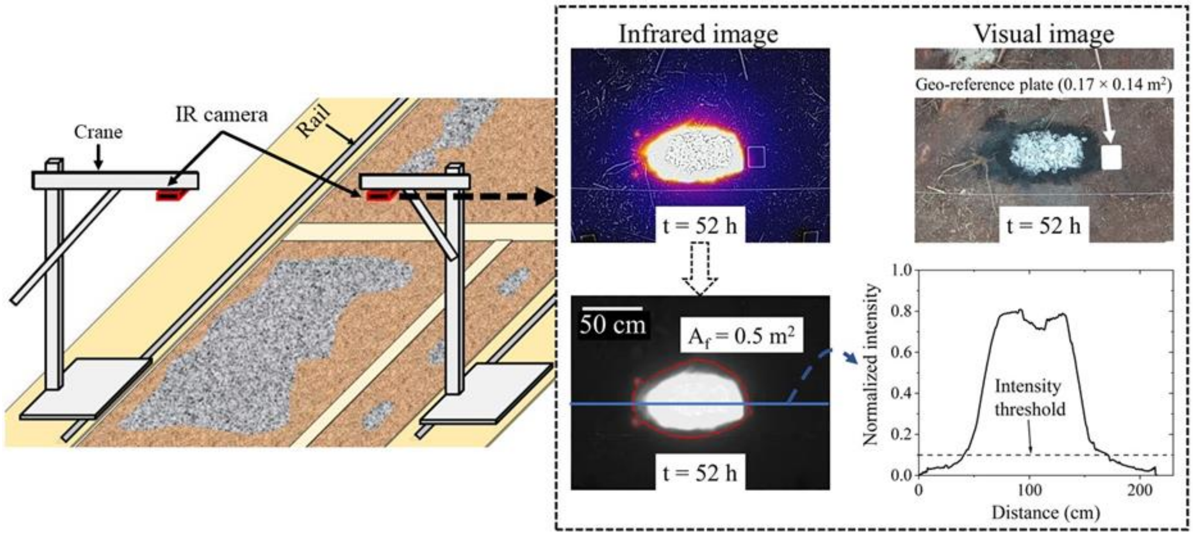


Figure 3. Infrared imaging setup and analysis to measure smouldering spread and area. The normalized pixel intensity threshold is chosen to be 0.1 to represent the point at which the intensity started to steeply increase, indicating the outer perimeter of the peat fire area. A_f and t are the active fire area and time since ignition, respectively (Santoso 2021).

Thermocouples were used to smouldering spread rate at the subsurface level. Due to the uncertain peat fire propagation direction, thermocouples were placed at certain points based on the visual observation and the likelihood of propagation direction. To obtain spread rate data, two thermocouple points were located at a known distance, 15 cm. The spread rate is then calculated from the known distance (15 cm) and the time-lapse of the two consecutive thermocouples reached maximum temperature or 300°C which is above peat char oxidation temperature (230°C). Each thermocouple point contains two K-type thermocouples at 10 cm (shallow layer) with probe diameter of 1.5 mm, and at 30 cm depth (deep layer) with probe diameter of 3 mm. Details of thermocouple placement can be seen in (Santoso 2021). As peat fires progressed and passed a thermocouple point, the thermocouples were then moved to a new location, if the thermocouples were not burnt. Continuous MC measurements were also conducted in P2N fire area by placing module soil moisture sensors at 4 different depths (10, 20, 30, and 40 cm) below the slash-and-burn location (Figure 2b). This live measurement of MC adding to the spread rate measurements by the thermocouples.

3. Results

Figure 4 shows horizontal spread rates analysed from series of infrared images on fires in P1S and P3S. Smouldering spread rate on the surface can be seen to fluctuating during propagation. Rainfalls can also be seen to have minimum impact on both the fluctuations and the average spread rate. In this work, horizontal spread rate measured from infrared images is ranged from 0.1 to 0.5 cm/h. The spread rate in this work is smaller than the values in the literatures (Prat-Guitart *et al.* 2016; Huang *et al.* 2016; Hu *et al.* 2019; Amin *et al.* 2020; Christensen *et al.* 2020), mainly because both the MC and IC in the field here is higher than the soil conditions in the literatures. Figure 5 shows that the spread rate in this work agree with the trend in the literatures, fit within the ranges of high MC and IC soil conditions. No significant difference between horizontal spread rate measured by IR camera (0.3±0.1 cm/h) and subsurface thermocouples (0.8±0.2 cm/h).

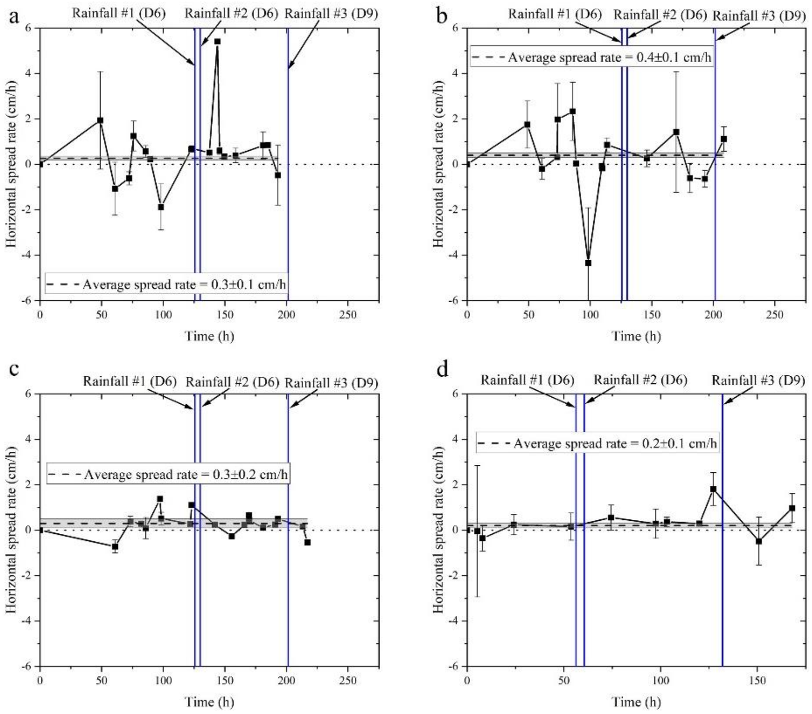
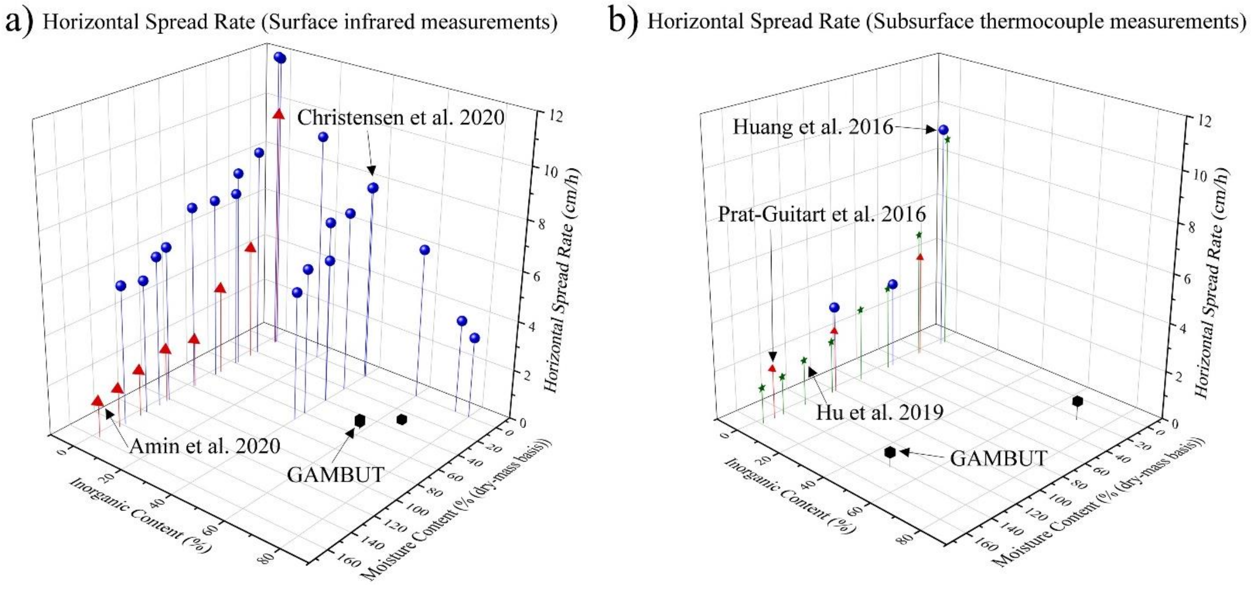


Figure 4- Horizontal spread rate from infrared camera images for a) pit 1 of P1S, b) pit 2 of P1S, c) pit 3 of P1S, d) P3S. The precipitation of the three rainfalls are 4.8 mm in the afternoon of day 6, 1.4 mm in the night of day 6, and 2.5 mm in the night of day 9. Details of weather conditions during GAMBUT can be seen in (Santoso 2021).


a) Horizontal Spread Rate (Surface infrared measurements)

b) Horizontal Spread Rate (Subsurface thermocouple measurements)

Figure 5- Horizontal spread rates from GAMBUT and literatures (Prat-Guitart et al. 2016; Huang et al. 2016; Hu et al. 2019; Amin et al. 2020; Christensen et al. 2020). a) Horizontal spread rate based on infrared images and b) based on subsurface thermocouple measurement at level more than 2 cm below surface up to 20 cm deep.

4. Conclusions

Here, we report horizontal spread rate measurements from GAMBUT field experiment of peatland wildfires in Sumatra, Indonesia. The smouldering peat fires during this experiment survived up to 10 days against three rainfalls. Horizontal spread rate was measured by using infrared camera and subsurface thermocouple. There is no significant difference between horizontal spread rate observed on the surface by infrared and measured at the subsurface by thermocouples. The spread rate reported here is 0.3±0.1 to 0.8±0.2 cm/h and agree with the laboratory results in the literature, fit within soil conditions with high moisture (MC) and inorganic (IC) contents, i.e. MC between 23 to 141% and IC between 49 to 72%. The persistent nature of the smouldering observed here also proves that degraded peatlands with high inorganic content are still required to be consistently monitored and mapped for prevention and conservation measures. GAMBUT presents a unique understanding of peatland wildfires at field conditions and aims to contribute to the better monitoring and mitigation acts.

5. Reference

Amin HMF, Hu Y, Rein G (2020) Spatially resolved horizontal spread in smouldering peat combining infrared and visual diagnostics. Combustion and Flame 220, 328–336. doi:https://doi.org/10.1016/j.combustflame.2020.06.039.

Badan Pusat Statistik Kabupaten Rokan Hilir (2015) Rata-Rata Curah Hujan di Kabupaten Rokan Hilir (mm) 2013-2015. https://rohilkab.bps.go.id/subject/151/iklim.html#subjekViewTab3.

Christensen EG, Fernandez-Anez N, Rein G (2020) Influence of soil conditions on the multidimensional spread of smouldering combustion in shallow layers. Combustion and Flame 214, 361–370. doi:10.1016/J.COMBUSTFLAME.2019.11.001.

Hu Y, Christensen EG, Amin HMF, Smith TEL, Rein G (2019) Experimental study of moisture content effects on the transient gas and particle emissions from peat fires. Combustion and Flame 209, 408–417. doi:https://doi.org/10.1016/j.combustflame.2019.07.046.

Huang X, Rein G (2017) Downward spread of smouldering peat fire: the role of moisture, density and oxygen supply. International Journal of Wildland Fire 26, 907–918. https://doi.org/10.1071/WF16198.

Huang X, Restuccia F, Gramola M, Rein G (2016) Experimental study of the formation and collapse of an overhang in the lateral spread of smouldering peat fires. Combustion and Flame 168, 393–402. doi:10.1016/J.COMBUSTFLAME.2016.01.017.

Page SE, Siegert F, Rieley JO, Boehm H-D V, Jaya A, Limin S (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature 420, 61–65. doi:10.1038/nature01131.

Pastor E, Oliveras I, Urquiaga-Flores E, Quintano-Loayza JA, Manta MI, Planas E (2017) A new method for performing smouldering combustion field experiments in peatlands and rich-organic soils. International Journal of Wildland Fire 26, 1040–1052. https://doi.org/10.1071/WF17033.

Prat-Guitart N, Rein G, Hadden RM, Belcher CM, Yearsley JM (2016) Propagation probability and spread rates of self-sustained smouldering fires under controlled moisture content and bulk density conditions. International Journal of Wildland Fire 25, 456–465. https://doi.org/10.1071/WF15103.

Rein G (2016) Smoldering Combustion. ‘SFPE Handb. Fire Prot. Eng.’ (Eds MJ Hurley, D Gottuk, JR Hall, K Harada, E Kuligowski, M Puchovsky, J Torero, JM Watts, C Wieczorek) pp. 581–603. (Springer New York: New York, NY) doi:10.1007/978-1-4939-2565-0_19.

Santoso MA (2021) Experimental study of smouldering wildfire mitigation: spread, suppression and transition to flaming. Imperial College London. doi:https://doi.org/10.25560/91115.

See SW, Balasubramanian R, Rianawati E, Karthikeyan S, Streets DG (2007) Characterization and Source Apportionment of Particulate Matter ≤ 2.5 μm in Sumatra, Indonesia, during a Recent Peat Fire Episode. Environmental Science & Technology 41, 3488–3494. doi:10.1021/es061943k.

Simpson J, Wooster M, Smith T, Trivedi M, Vernimmen R, Dedi R, Shakti M, Dinata Y (2016) Tropical Peatland Burn Depth and Combustion Heterogeneity Assessed Using UAV Photogrammetry and Airborne LiDAR. Remote Sensing 8, 1000. doi:10.3390/rs8121000.

Smith TEL, Evers S, Yule CM, Gan JY (2018) In Situ Tropical Peatland Fire Emission Factors and Their Variability, as Determined by Field Measurements in Peninsula Malaysia. Global Biogeochemical Cycles 32, 18–31. doi:https://doi.org/10.1002/2017GB005709.

Usup A, Hashimoto Y, Takahashi H, Hayasaka H (2004) Combustion and thermal characteristic of peat fire in tropical peatland in Central Kalimantan, Indonesia. Tropics 14, 1–19. doi:10.3759/tropics.14.1.

Young AM, Higuera PE, Duffy PA, Hu FS (2016) Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. Ecography 1–12. doi:10.1111/ecog.02205.

Yu ZC (2012) Northern peatland carbon stocks and dynamics: a review. Biogeosciences 9, 4071–4085. doi:10.5194/bg-9-4071-2012.