Research article

Fuel characteristics and fire behavior in Melaleuca peat forest, southern Thailand

Sutthiphong Chairak[a], Kobsak Wanthongchai*[,b], San Ketpraneet[b], La-ongdao Thaopimai[c]

[a] *Department of National Parks, Wildlife and Plant Conservation, Bangkok 10900, Thailand*
[b] *Department of Silviculture, Faculty of Forestry, Kasetsart University, Bangkok 10900, Thailand*
[c] *Forestry Research Center, Faculty of Forestry, Kasetsart University, Bangkok 10900, Thailand*

Article Info

Abstract

Importance of the work: Understanding fire behavior in peat forest dominated by *Melaleuca cajuputi* is very important for precision fire management.

Objectives: To examine fuel characteristics and fire behavior using systematic burning experiments in peat forest dominated by *M. cajuputi*.

Materials and Methods: Three vegetation types were investigated (lowland and upland forest stands of pure *M. cajuputi* and a grassland) in Khuan Khreng tropical peat forest, with four replicated plots (each 30 × 30 m) of each vegetation type. The fuel and fire behavior were investigated.

Results: The aboveground fuel consisted of litter, undergrowth, leaves and bark, of which the litter and undergrowth dominated in the Melaleuca stands and grassland, respectively. Total aboveground fuel loads in the upland and lowland forests and the grassland were 23.28 t/ha, 15.84 t/ha and 13.21t/ha, respectively. The heat value of Melaleuca bark was measured at 5,503 cal/g. The average peat depth was 1.4 m, with a bulk density of 0.23 g/cm³, while the deepest recorded peat layer reached 3.10 m. The grassland fires exhibited very active fire behavior, with a rapid spread rate of 4.01 m/min and a flame length of 1.3 m, surpassing the fire behavior in the Melaleuca stands. The grassland fires were classified as medium intensity (639 kW/m), whereas the fires in the lowland and upland *M. cajuputi* areas were of lower intensity (120 kW/m and 152 kW/m, respectively). The laboratory experiments showed that the peat smoldered for several days with a slow spread rate of 3.24 cm/hr, while temperatures typically exceeded 620 ℃.

Main finding: Peat forests contain substantial fuel loads, comprising both aboveground vegetation and belowground peat deposits. Often, the direction of peat combustion is unpredictable and detection is challenging. Consequently, peat fire behavior tends to be intense and can result in severe ecological and environmental impacts.

* Corresponding author.
  E-mail address: fforksw@ku.ac.th (K. Wanthongchai)

Introduction

Tropical peatlands are unique ecosystems, where forests grow on thick layers of peat or organic soil, formed over thousands of years under waterlogged conditions, with these ecosystems playing a crucial role in the global carbon cycle, although they are increasingly declining in extent (Vegas-Viaruba et al., 2010; Page et al., 2011). The carbon sequestration capacity of tropical peatlands is increasingly being threatened by land-use changes and climate change. Notably, covering approximately 440,000 km²—around 10% of the world's peatland area (Page et al., 2011)—tropical peatlands have acted as persistent carbon sinks since the Holocene (approximately 11,600 years ago), greatly influencing the global carbon budget. Tropical peat fires tend to have higher emission factors than boreal and temperate fires due to the higher carbon content in the fuel (Hu et al., 2018). However, human activities, such as drainage, followed by land conversion for agriculture, have led to carbon loss from peat burning (Patel et al., 2025).

Tropical peatlands in southern Thailand can be categorized into two types: undisturbed and disturbed. Primarily, most disturbed peat forests consist of two main vegetation types: pure stands of *Melaleuca cajuputi* and mixed-species grasslands. These ecosystems play vital environmental roles, including carbon storage, hydrological regulation and biodiversity conservation (Suntisuk and Niyomtham, 1985). Additionally, tropical peatlands provide valuable resources for humans, such as fish, timber and non-timber forest products (ASEAN Secretariat, 2006). In the past, many people relied on peat land for their livelihood; however, now this is being threatened by the decrease in peat area as a result of draining water, tree removal and burning the area for conversion to agricultural products such as oil palm and para rubber (Forestry Research Center, 2013). While many tools have been used for clearing the forest in preparation for agriculture, the most popular has been fire because of its low cost and ease of use and widespread effectiveness (ASEAN Secretariat, 2006). In addition, fire is also important for local culture as it has been used to clear the forest floor for easier traveling and for access to fishing areas, hunting and gathering food (Forestry Research Center, 2013). Such persistent, widespread use of fire has affected many peat forest areas when weather conditions have been favorable, such as in the big fires in 2010 and 2012, that occurred in the Khuan Khreng tropical peat forest (KK-TPF), Nakhon Si Thammarat province, Thailand, where people had encroached on KK-TPF by draining water off the peat land followed by burning (Forestry Research Center, 2013). Burning during the droughts in 2010 and 2012 resulted in the loss of 3,055.2 ha and 1,948.64 ha, respectively resulting in changes to the ecosystem's structure and function. For example, in 2012, the species of 89 wild birds, 14 mammals, 15 reptiles and 12 amphibians were affected by fire, with a community loss of income estimated approximately USD 116,500 (Forestry Research Center, 2013). Thus, an understanding of fuel and fire behavior is necessary for successful fire management and planning. Unfortunately, there has been no systematic investigation regarding peat fire information in Thailand, specifically on fuel characteristics, fuel dynamics and fire behavior. Several other forest fire studies in Thailand have considered surface fire behavior only (Patchaiyo, 2012; Wanthongchai et al., 2013); however, there has been no published information on studies regarding ground fires. Therefore, the aims of the current study were to examine the fuel characteristics, surface and ground fire behavior in KK-TPF using systematic burning experiments.

Materials and Methods

Study site

The study area was in the KK-TPF in Nakhon Si Thammarat province, southern Thailand, approximately 824 km from Bangkok (Fig. 1). Covering 26,532 ha, KK-TPF includes the Chaipattana Foundation area, two non-hunting areas and four national forests spanning three provinces—Nakhon Si Thammarat, Songkhla and Phatthalung. The area remains flooded for most of the year and is dominated by pure stands of *M. cajuputi*. Stand densities in the burned and unburned areas were 1,040 and 933 individuals/ha, respectively. In the burned areas, the tree height, diameter at breast height over bark (DBH) and aboveground biomass averaged 7.71 m, 11.30 cm and 30.96 t/ha, while in unburned areas, these values were 7.88 m, 12.14 cm and 27.97 t/ha (Patchaiyo, 2016). The *M. cajuputi* pure stand had existed for nearly 50 yr, following the destruction caused by Typhoon Harriot, which was later exacerbated by land encroachment and burning for oil palm plantations. The region experiences a mean annual temperature of 27 °C and an average annual rainfall of 2,035 mm, with precipitation occurring during 10 month of the year. The area records an average of 152.8 rainy days/yr and has a mean annual relative humidity of 79%, peaking in October and November. The typical fire season extends from April to August.
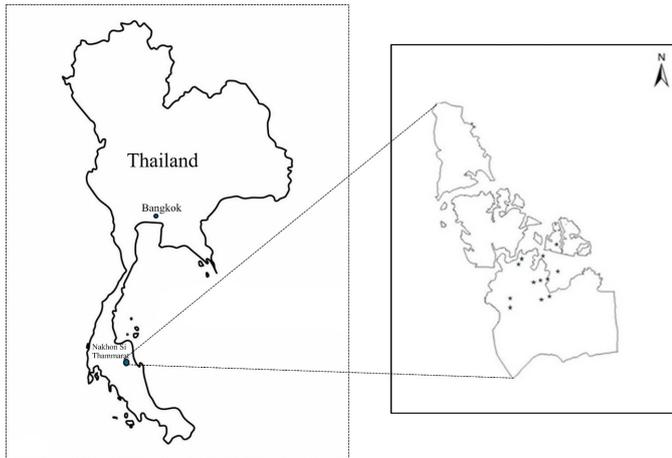
Fig. 1 Location of Khuan Khreng tropical peat forest (cross hatched area) in Nakhon Si Thammarat province, southern Thailand

The study area was classified into three categories: a pure stand of lowland *M. cajuputi*, a pure *M. cajuputi* stand in the upland and a grassland. The lowland and upland stands were identified based on flooding characteristics, with the lowland area having a longer flooding period and a higher flooding level than the upland area. The grassland was dominated by either *Lepironia articulata* or *Cyperus imbricatus*.

Experimental surface fire

Forest fire behavior in KK-TPF was monitored during March–August by establishing 12 main plots (each 30 × 30 m), with 8 main plots in *M. cajuputi* stands (4 lowland and 4 upland) and 4 main plots in the grassland. Prior to burning, in each of the *M. cajuputi* plots for each tree in each plot, the following parameters were measured: DOB and bark thickness at breast height (1.3 m above the ground); total height; and crown base height. Since fire consumes the bark and fresh leaves of *M. cajuputi*, the bark and leaf biomass were defined as a part of the flammable fuel. The biomass of these tree parts was estimated using Equations 1–2 (Forestry Research Center, 2013):

$$Wb = 0.0029 (D \times H)^{1.4567} \tag{1}$$

$$Wl = 0.2226 (D)^{1.0641} \tag{2}$$

where Wb and Wl are the tree bark and leaf biomass (measured in kilograms), respectively, D is the DBH (measured in centimeters) and H is the total tree height (measured in meters).

In each of the 12 main plots, surface fuel data were collected in each plot using 8 randomly located 1 × 1 m subplots. Four sapling subplots (each 4 × 4 m) were located systematically in each of the eight main plots in the *M. cajuputi* stands (Fig. 2) and each sapling (defined as taller than 1.3 m and DBH < 4.5 cm) in the sapling subplots was measured for DBH and total height. Each sapling was defined as a part of the surface flammable fuel, with its biomass estimated using Equations 3–5 (Forestry Research Center, 2013):

$$Ws = 105.04(D)^{1.9916} \tag{3}$$

$$Wb = 20.059(D)^{2.1419} \tag{4}$$
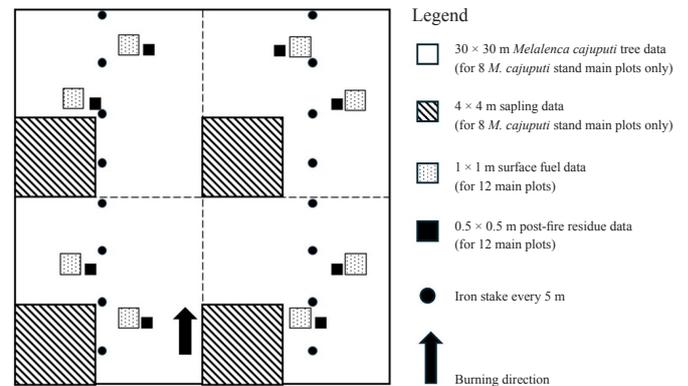
$$Wl = 6.247(D)^{2.9918} \tag{5}$$

Fig. 2 Plot layout for fuel and residue determination, burning pattern and fire behavior investigation in each plot

where Ws, Wb and Wl are the stem, branch and leaf biomass, respectively, (measured in kilograms) and D is the DBH (measured in centimeters).

Other surface fuels were assessed by clipping all live understory vegetation at ground level within the subplot, while leaf litter was removed carefully by hand to prevent contamination with the underlying mineral soil. The collected samples were weighed in the field and subsamples from each fuel type were taken to the laboratory for oven drying to determine the moisture content and dry mass.

Belowground fuel loads (peat soil) samples were collected in the middle 1 × 1 subplot using a soil core and then oven-dried and weighed to determine the peat bulk density. The peat depth was estimated based on excavation in a soil pit. The peat load was estimated by multiplying the peat bulk density by the peat depth.

Burning experiments took place during late March–early August 2014 around 1200 hours when the air temperature was high and the relative humidity was lowest to ensure burning was effective (Table 1).

The rate of spread (ROS) in each plot was estimated using two rows of iron stakes (2 m high) were placed every 5 m perpendicular to the fire front as it passed through each plot (Fig. 2). Immediately after burning, post-fire residues (ash plus charcoal and unburned material) were fresh weighed in 8 subplots (each 50×50 cm) within each of the 12 main plots. Then, in the laboratory, the heat value content of each unburnt fuel sample was determined (in calories per gram) using a Parr 6300 calorimeter (Parr Instrument Co.; Illinois, USA) for six fuel types consisting of: litter, undergrowth (saplings and other species excluding *L. articulata*), tree bark (*M. cajuputi*), tree leaf (*M. cajuputi*) , a grassland weed (*L. articulata*) and peat soil.

Fire intensity (I_B) was calculated using Equation (6) according to Byram (1959):

$$I_B = 0.007H \times w_a \times r \tag{6}$$

where I_B is the fire intensity (measured in kilowatts per meter), H is the net low heat of combustion (measured in calories per gram), w_a is the fuel consumed in the active flame front (measured in t/ha) and r is head-fire rate of fire spread (measured in meters per minute). Byram (1959) developed an empirical relationship between I_B and flame length (L) for surface fires, which remains widely used in wildland fire science and management (Equation 7):

$$L = 0.08(I_B)^{0.46} \tag{7}$$

where L is the flame length (measured in meters) and I_B is the fireline intensity (measured in kilowatts per meter).

The total aboveground fuel consumption consisted of surface fuel and any *M. cajuputi* bark and leaves lost through burning. The surface fuel was estimated as the pre-burned fuel load (litter plus undergrowth) minus the post-burned fuel load (ash, charcoal and unburned fuel). *M. cajuputi* bark loss (B_{loss}; measured in kilograms), was estimated using Equation (8), whereas *M. cajuputi* leaf loss (L_{loss}, measured in kilograms) was estimated using Equations (8–9), as shown in Fig. 3:

$$B_{loss} = \frac{(B_{D1} - B_{D2})}{B_{D1}} \times 100 \times (S_C / H) \times B_B \tag{8}$$
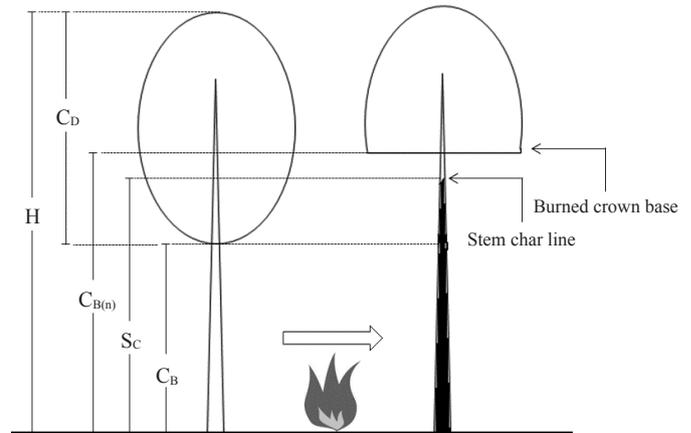

Fig. 3 *Melaleuca cajuputi* dimension factors measured from experimental plots in Khuan Khreng tropical peat forest, where H = total stem height, C_D = crown depth, $C_{B(n)}$ = post-burned crown base S_C = stem char line and C_B = pre-burned crown base, all measured in meters

Table 1 Weather conditions during experimental burning.

Site	Plot no.	Date	Wind speed (m/s)			Temperature (°C)			Relative humidity (%)			Wind direction
			Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	
Lowland	32	28/06/2014	2.0	0.4	1.0	32.9	32.1	32.4	60.5	52.5	56.7	SW
	237	01/08/2014	na	na	na	na	na	na	na	na	na	na
	236	31/07/2014	na	na	na	na	na	na	na	na	na	na
	279	28/06/2014	2.2	0.0	0.7	30.9	29.7	30.3	92.4	86.7	89.9	NW
Upland	188	29/04/2014	1.1	0.0	0.3	34.8	32.9	33.7	49.2	41.2	45.3	NE
	189	29/04/2014	2.3	0.0	0.7	40.2	34.4	37.1	29.4	21.8	27.4	E
	255	28/04/2014	1.1	0.0	0.3	36.3	32.5	34.1	66.3	45.8	54.5	SW
	275	31/07/2014	1.1	0.0	0.2	32.6	30.1	31.0	90.4	72.1	79.9	SW
Grassland	29	30/04/2014	2.4	0.0	1.2	36.2	30.4	33.4	73.6	39.7	53.3	N–SE
	351	28/06/2014	4.2	1.3	2.4	35.2	34.1	34.5	45.3	42.6	44.1	SW
	KJ1	02/08/2014	na	na	na	na	na	na	na	na	na	na
	KJ2	02/08/2014	na	na	na	na	na	na	na	na	na	na

na = not available; Max = maximum; Min = minimum; Avg = average.

where B_{D1} is the pre-burned bark thickness (measured in millimeters), B_{D2} is the post-burned bark thickness (measured in millimeters), S_C is the stem char line (measured in meters) H is total stem height (measured in meters) and B_B is the *M. cajuputi* bark biomass (measured in kilograms).

$$L_{loss} = \frac{C_{B(n)} - C_B}{C_D} \times L_B \qquad (9)$$

where C_B is the pre burned crown base (measured in meters), $C_{B(n)}$ is the post-burned crown base (measured in meters), C_D is crown depth (measured in meters) and L_B is the *M. cajuputi* leaf biomass (measured in kilograms).

The data were processed and analysed using the SPSS® for Windows software (version 13.0; SPSS Inc.; Chicago,, Il, USA). Analysis of variance was used to test for differences between plots (upland, lowland, grassland) followed by Duncan's multiple range test, with significance tested at $p < 0.05$.

Experimental peat burning

The peat bulk density at the study site was 0.26 g.cm^{-3} (Kuawong et al., 2015). In total 53 kg of peat were dug from the site, put in plastic bags to maintain the same moisture content and brought to the laboratory. The peat was used to fill a $1 \times 1 \times 0.3$ m^3 glass box to achieve the same peat bulk density. Combustion was initiated in the center of the box using igniter (charcoal and litter). The time was recorded from when the fire was lit until the peat was burning steadily into the peat layer. Thermal images were recorded for checking the fire using a thermal imager camera (Fluke Ti32; Fluke Corporation; Washington USA). The burning distance for each time period (non-fixed rotation time to take a thermal image in this study) was approximately 72 hr. The thermal images were analyzed using the image overlapping method and the burning distance in each period was measured to determine the horizontal fire spread in the peat layer.

Results and Discussion

Pre-burned fuel load

The fuel moisture content (in the litter and undergrowth) varied significantly among sites, with the highest levels observed in the lowland plots (Table 2). Based on the results for the prior burned fuel characteristics (Table 3), the mean *M. cajuputi* leaf biomass was highest in the lowland plots (4.25 t/ha), while the mean *M. cajuputi* bark biomass was highest in the upland plots (4.19 t/ha). However, there was considerable variation in the leaf biomass among the lowland plots, as it was calculated using the tree DBH and tree density, with the leaf load determined based on an equation. This variation was influenced by differences in the tree density and DBH within the plots, resulting in a large SD. The mean litter fuel load was highest in the upland plots (9.91 t/ha), the undergrowth fuel load was highest in the grassland plots (7.97 t/ha), while the mean total pre burned fuel loads in the upland, lowland and grassland plots were 23.28 t/ha, 15.84 t/ha and 13.16 t/ha, respectively. However, there was significant variation in the undergrowth (grass) fuel load due to its non-homogeneous distribution.

Table 2 Pre-burned fuel (litter and undergrowth) moisture content in experimental plots in Khuan Khreng tropical peat forest

Plot	Pre-burned fuel moisture content (%)	
	Litter	Undergrowth
Lowland	271.32±296.59[a]	254.69±82.81[a]
Upland	86.98±42.00[a]	158.23±23.71[b]
Grassland	110.15±72.14[a]	124.80±38.12[b]

Undergrowth comprises grass, herbs, climbers, *M. cajuputi* saplings and seedlings.
Values (mean ± SD) with different lowercase superscripts are significantly different (analysis of variance F test, $p < 0.05$) in pre-burn fuel moisture between sites.

Table 3 Pre-burned fuel load at experimental plots in Khuan Khreng tropical peat forest

Plot	Pre-burned fuel load (t/ha)				
	Leaves	Bark	Litter	UG	Total
Lowland	4.25[a]±3.06	2.59[a]±1.85	4.00[a]±3.53	4.99[a]±2.73	15.84[a]±5.93
Upland	3.58[a]±1.03	4.19[a]±2.29	9.91[b]±3.96	5.60[a]±3.94	23.28[a]±9.23
Grassland	-	-	5.63[ab]±2.44	7.97[a]±6.05	13.61[a]±4.25

UG = undergrowth comprising grass, herbs, climbers, *M. cajuputi* saplings and seedlings.
Values (mean ± SD) with different lowercase superscripts are significantly different (analysis of variance F test, $p < 0.05$) in pre-burn fuel load between sites.

The aboveground fuel load ratios among three forest types were different. In the *M. cajuputi* pure stand forest plots, the fuel ratio of the undergrowth-to-litter was higher than in the lowland plots, while in the upland plots, the ratio of litter-to-undergrowth was higher. There were no significant differences in the values for the *M. cajuputi* leaf-to-bark ratio in each plot. However, in the grassland plot, the ratio of undergrowth-to-litter was higher (Fig. 4).
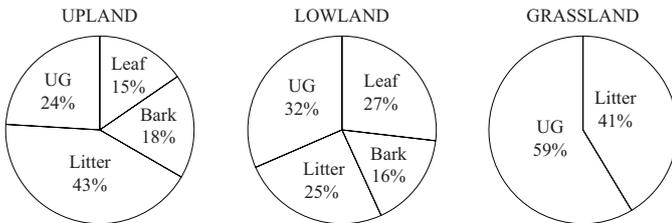

Fig. 4 Aboveground fuel ratio in Khuan Khreng tropical peat forest, where UG = undergrowth (grass, herbs, climbers, *Melaleuca cajuputi* saplings and seedlings)

The calculation of peat loads in the plots was based on the peat bulk density and peat depth. Clearly, the peat bulk density (0.21–0.25 g/cm^3.cm^{-3}) was generally lower than the soil bulk density. The peat depth was in the range 0.92–1.20 m. Therefore, peat loads were in the range 1,953–3,000 t/ha, with the peat loads in the pure *M. cajuputi* stands being higher than for the grassland (Table 4).

Table 4 Peat bulk density, peat depth and loads in Khuan Khreng tropical peat forest

Plot	Peat bulk density (g/cm^3)	Peat depth (m)	Peat load (t/ha)
Upland	0.22[a]±0.03	0.92[a]±1.08	2024[a]±2387
Lowland	0.25[a]±0.05	1.20[a]±0.35	3000[a]±865
Grassland	0.21[a]±0.04	0.93[a]±1.02	1953[a]±782

Values (mean ± SD) with different lowercase superscripts are significantly different (analysis of variance F test, $p < 0.05$) in peat bulk density, peat depth and peat load between sites.

Aboveground post-burned fuel and fuel consumption

The main fuel type consumed by fires was surface fuel (litter plus undergrowth), with more than 63% of the surface fuel being consumed in grassland burning, while 45–51% of the surface fuel was consumed in the *Melaleuca* stands. Only low percentages of the bark and leaf components of the Melaleuca stands were burnt compared to those of surface fuel (litter plus undergrowth). Based on the results from the total aboveground fuel consumption from the experimental burnings, grassland burning consumed greater amounts of fuel than was burnt in the Melaleuca stands (Fig. 5). There was high variation in the fuel consumption from the experimental burning among the sites, as shown by high SD values (Table 5).

Heat value content

Five types of aboveground fuel and peat were classified. The heat value content of all the fuels was in the range 3,281–5,503 cal/g (Table 6). The highest heat value was in *the M. cajuputi*'s bark (5,503 cal/g) and the lowest was in the peat (3,675 cal/g), with this latter value being the lowest likely due to the presence of clay particles, which is a natural characteristic of peat in the study area.
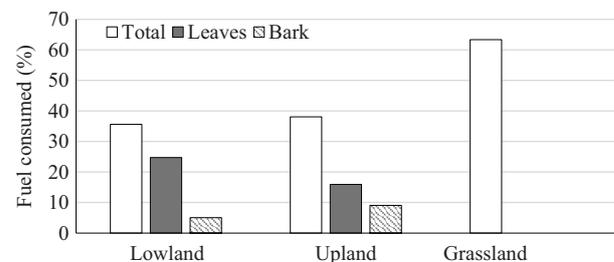

Fig. 5 Total fuel, *Melaleuca cajuputi* leaves and bark consumed at each site in Khuan Khreng tropical peat forest

Table 5 Aboveground post-burned fuel loads and fuel consumption in Khuan Khreng tropical peat forest

Plot	Post-burned fuel loads (t/ha)					Fuel consumed (t/ha)			
	Leaves	Bark	Ash	Unburned	Total	Surface fuel	Leaves	Bark	Total
Lowland	3.20[a]±1.73	2.02[a]±1.63	0.59[a]±0.43	4.38[a]±3.42	10.2[a]±3.79	4.02[a]±3.28	1.05[a]±1.55	0.13[a]±0.36	5.64[a]±4.98
Upland	3.01[a]±0.91	3.81[a]±2.41	1.52[a]±1.25	6.08[a]±4.26	14.42[a]±5.92	7.91[a]±7.63	0.57[a]±0.28	0.38[a]±0.2	8.86[a]±8.01
Grassland	-	-	1.29[a]±1.02	3.7[a]±2.46	4.99[a]±3.39	8.62[a]±7.14	-	-	8.62[a]±7.14

Values (mean ± SD) with different lowercase superscripts are significantly different (analysis of variance F test, $p < 0.05$) for each parameter between sites.

Table 6 Aboveground fuel heat value content of different fuel types in Khuan Khreng tropical peat forest.

Fuel types	Heat value (cal/g)					
	litter	undergrowth	Melaleuca leaf	Melaleuca bark	peat	L. articulata
Heat values	4,289.2[b] ± 106.6	4,075.1[a] ± 15.8	5,181.5[b] ± 24.5	5,502.9[b] ± 24.9	3,280.7[a] ± 222.1	3,675.5[a] ± 43.9

Values (mean ± SD) with different lowercase superscripts are significantly different (analysis of variance F test, $p < 0.05$) in heat value between fuel typ. The heat value of litter and undergrowth is influenced by the mixture of various plant species in the area, while the heat value of leaves and bark comes specifically from *Melaleuca cajuputi*.

Surface fire behavior

There was a clear relationship between the fire temperature and flame height, with the fire temperature decreasing with the distance from the ground surface. The highest fire temperature was 773 °C at 20 cm aboveground in the lowland plot. The recorded aboveground values for average ROS, fire intensity and flame length were highest in the grassland plot (2.09 m/min and 639 kW/m, 1.3 m respectively), as shown in Table 7, because the main flammable fuel characteristics, size and arrangement of the grass species allowed the fire to spread continuously. In addition, the weather conditions, especially the wind velocity and turbulence in open areas, such as grassland, produced high values for the fire parameters.

Peat fire behavior

The results of the peat fire rate of spread are provided in Fig. 6 and Table 8. The average horizontal rate of ground fire spread for peat burning was estimated for each burned patch. The burning pattern for peat fire was not uniform, as can be seen from the patchy nature in Fig. 6. Both spatial and temporal variation in the patched burning were observed, resulting in variable ROS values (0.91–9.95 cm/hr.) with an average of 3.24 cm/hr. Thus, the combustion process for peat fire could be classified as smoldering fire. Notably, the perimeter of the burned area could reignite when the weather conditions were appropriate (a strong wind and a high air temperature). Without any appropriate fire detection and control, the peat fire could spread up to 77.80 cm/d.
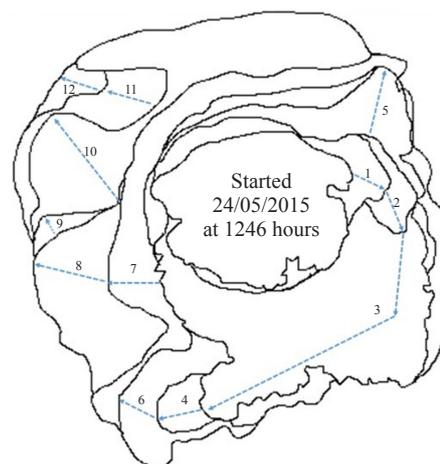

Fig. 6 Horizontal ground fire spread direction (dashed blue arrowed lines) in $1 \times 1 \times 0.30$ m³ experimental box

Table 7 Aboveground fire characteristics in Khuan Khreng tropical peat forest.

Plot	Fire Temp. (°C)			ROS	Heat value	FI	FL
	20 cm	50 cm	100 cm	(m/min)	(cal/g)	(kW/m)	(m)
Lowland	511.1ª ± 18.5	375.5ª ± 45.1	238.8ª ± 46.9	0.96ª ± 0.49	3982.4ª ± 354.3	120.3ª ± 66.5	0.7ª ± 0.2
Upland	478.8ª ± 43.9	300.2ª ± 98.2	248.4ª ± 125.9	0.66ª ± 0.55	4135.8ª ± 306.8	151.7ª ± 158.4	0.7ª ± 0.4
Grassland	520.9ª ± 46.5	410.9ª ± 81.8	266.0ª ± 32.8	2.09ª ± 1.30	3775.4ª ± 199.8	639.3ª ± 820.1	1.3ª ± 0.9

Values (mean ± SD) with different lowercase superscripts are significantly different (analysis of variance F test, $p < 0.05$) for each parameter between sites
ROS, FI, and FL stand for rate of fire spread, fire intensity, and flame length, respectively.

Table 8 Burning time and distance in experimental peat burning

Date and time		Line No.	Burning distance (cm)	Burning time (hrs.)	Average distance (cm/hr)
date	time				
24th May	12.46 pm	Start	-	-	-
	7.08 pm	1	5.78	6.37	0.91
	9.24 pm	2	6.67	3.27	2.04
25th May	6.00 am	3	44.44	8.60	5.17
	8.06 am	4	7.11	2.10	3.39
	10.23 am	5	11.11	1.12	9.95
	11.43 am	6	6.67	1.33	5.00
	2.21 pm	7	8.00	1.63	4.90
	6.02 pm	8	11.56	3.68	3.14
	8.08 pm	9	3.56	2.07	1.72
26th May	12.09 pm	10	15.56	16.02	0.97
	6.41 pm	11	8.89	6.53	1.36
27th May	1.15 pm	12	6.67	18.13	0.36
	Horizontal rate of fire spread (cm/hr)				3.24
	Horizontal rate of fire spread (cm/d)				77.80

These data is the results of ground fire in experimental peat burning

Khuan Khreng tropical peat forest fuel characteristics and surface fire behavior

Unlike other fuel types in tropical forest ecosystems, the fuel types in KK-TPF were not limited to only undergrowth and litter as aboveground fuel in addition to bark and fresh leaves, but also included the peat soil belowground as a apart of the fuel load. Therefore, the total fuel load for KK-TPF was very high, compared to the fuel loads of other forest ecosystems in Thailand (Table 9). For example, the aboveground fuel loads in dry dipterocarp forest and pine forest were only 3–11.9 t/ha (Wanthongchai et al. 2011) and 12.9 t/ha (Wanthongchai et al. 2013), respectively, compared to 13–23 t/ha in the current study. However, the fuel loads in Table 9 do not include belowground fuel loads, making the total fuel loads in KK-TPF seem even larger.

Surface fire behavior and spotting fire potential of aboveground fuel

Fire behavior in KK-TPF was classified as low-to-moderate fire intensity, according to Andrew (1980). Undergrowth fuel loads may have played an important role in the fire behavior of the grassland plot. Flame length was affected by wind and fuel height, with the flame length for the grassland site being the highest because of the openness of the site (and hence the increased wind velocity) and optimum fuel compactness. In addition, the better fuel arrangement and fuel continuity in grassland leads to a faster fire spread, compared to the Melaleuca sites, where patches of burning sometimes occurred. Furthermore, the higher tree density on the Melaleuca sites limited the influence of wind on fire behavior. Although the fuel properties for the upland site were drier, the main fuel type and tree density were similar to those of the lowland sites, resulting in the same pattern of fire behavior.

Although the fuel loads in KK-TPF were relatively high, the surface fire behavior descriptors were not exceptionally high. Generally, fuel characteristics, topography and weather all influence fire behavior. Weather conditions, especially velocity and turbulence had a significant impact on the ROS and hence on fire intensity. Despite the somewhat similar fuel loads between plots, there was great variation in fire intensity in the current study. For example, the fire intensity in plot no. KJ1(grassland) was more than 1,800 kW/m, while the fire intensity in a plot containing a pure stand of *M. cajuputi* (plot no. 32) was less than 50 kW/m. This variation reflected the influence of the weather factors that control fire behavior. In addition, the burning experiments were conducted over different time periods, which may have resulted in varying fire behavior between sites. Furthermore, the differences in fire behavior may have been due to the different fuel components, with grassland fuel composed mainly of grass, while the pure stand of *M. cajuputi* contained litter.

The bark and leaves of *M. cajuputi* formed a part of the flammable fuel in KK-TPF. These fuels have a light weight and so have a very high potential to cause spot fires, compared to other fuel types in different ecosystems such as dry dipterocarp forest and mixed deciduous forest. In addition, *M. cajuputi*'s bark and leaves have a high heat content (<5,000 cal/g) and an ember from leaves or bark can be carried by the wind for many hundreds of meters from the original fire source. Therefore, fire suppression in such circumstances needs to pay greater attention to the spotting potential.

A fire can spread over a water surface by burning the tips of grass (such as *L. articulata*) that rise above the water surface from submerged stems, when the relative air humidity and air temperature are appropriate. This surface water fire can spread to the bark and stems when the flame front passes *M. cajuputi* trees surrounded by grass.

Table 9 Fuel loads and fire behaviors in some selected forest ecosystems in Thailand

Fuel source	Fuel loads (t/ha)	Rate of spread (m/min)	Fire intensity (kW/m)	Flame length (m)	References
Hill evergreen forest	1.9	0.3–1	35.59	0.3–0.5	Suthichart (1996)
Pine forest	12.9	4.5	627	1.4	Wanthongchai et al. (2013)
Pine-dipterocarp forest	5.3–6.4	2.44–4.44	291.5–542.8	1.0–1.3	Patchaiyo (2012)
Dry dipterocarp forest	3.1–11.9	0.3–4.46	57.77–466.8	0.2–5.5	Wanthongchai et al. (2011)
Mixed deciduous forest	3.3–9.1	0.60–3.41	62.1–227.2	0.3–1	Suthicha (1996); Klayprasit (1998)
Dry evergreen forest	4.6–9.9	0.3–1	32.57–35.59	0.3–0.5	Suthichart (1996)
Grassland	11.7	2.24–8.29	2,166–3,966	2.4–5.7	Akkaakara (1991); Phupet (2007)
Rehabilitated forest	5.5	0.92	108.35	0.78	Daungyotha (2006)
Eucalyptus plantation	16.1–23.6	0.28–2.6	87.4–1,341.3	1.5–9.9	Kumyaem (2005); Baulapha (2006)
Acacia plantation	15.6	0.68	189.49	1.3	Baulapha (2006)
Teak plantation	7.1–8.6	0.86–6.91	150–1022	0.8–1.9	Wanthongchai (2011)
2nd Peat forest	13.6–23.3	0.7–2.1	120.3–639.3	0.7–1.3	This study

Peat burning behavior in Khuan Khreng tropical peat forest

The results from this experiment peat burning study agreed with Usup (2004), who reported 3.83 cm/hr (about 92 cm/d), while Graham et al. (2022) reported 2.7 cm/hr for peat fire horizontal spread in Indonesia. Similarly, peat fire spread in Russia was in the range 0.5–10 cm/hr (Chistjakov et al. 1983). Furthermore, Wein (1983) reported the rate of fire spread in peat layers in Australia and Canada were 4.2 cm/hr and 3-12 cm/hr, respectively. Ground fire risk for tropical peat forest is not high under normal weather conditions. However, landuse changes in nearby forest area, especially converting forest land to oil palm plantations, has led to water drainage out of the peatland, resulting in drying of the whole peatland. This situation has led to the high risk of ground fire in the dry season (May–August) and it can be difficult to detect the extent of the underground burning. In addition, sensitivity analysis by Widyastuti et al. (2020) indicated that the peat fire size was most affected by the water table depth, the peat-dry index and the number of dry days before ignition, stressing the importance of peat rewetting. Recently, predictive modeling has been applied to anticipate fire outbreaks, based on water table depth, temperature and ENSO phases (Mezbahuddin et al., 2023). This result revealed that advanced technologies for ground fire detection and controls are crucial for peat fire management. Unfortunately, it was not possible to evaluate the spread of fire within the peat layer deep underground during the current burning experiment. However, Graham, et al. (2022) reported the vertical fire spread within the peat layer of a peat fire in Kalimantan was 0.8 cm/hr. The rate of burning through the peat profile is very important where high peat accumulations exist.

Conclusion

This study revealed that although fuel load in the upland Melaleuca forest site was relatively high, the associated surface fire behavior was not necessarily severe. In addition, fire behavior varied significantly both within and among sites, highlighting the combined effects of fuel characteristics and weather conditions during the burn. In particular, fire behavior in the open grassland areas was the highest among all sites. Therefore, forest fire managers must pay more attention to preventing and controlling fires in grasslands. The laboratory-based experiments of peat burning demonstrated that the peat smoldered for many days and that the rate of spread was very slow; furthermore, it was difficult to detect the underground burning line. This result suggested that advanced technologies for ground fire detection and controls are crucial for peat fire management. In addition, land use changes, particularly the conversion of forests to oil palm plantations, have caused peatland drainage and widespread underground dryness, heightening the risk of undetectable ground fires during the dry season and complicating fire management efforts. This situation is very concerning, especially given the growing interest in carbon credit initiatives linked to peat forest conservation, where it is crucial to maintain peat integrity and prevent carbon loss through fires. Rewetting practices should be prioritized as a key strategy for forest landscape management.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

References

Akkaakara, S. 1991. Fire behavior in Grassland. Royal Forest Department. Bangkok, Thailand.

Andrew, P.L. 1980. Testing the Fire Behavior Model. In: Proceeding Sixth Conference on Fire and Forest Meteorology. Society of American Foresters. Seattle, W.A. Washington D.C., pp. 70−77.

Baulapha, F. 2006. Fire behaviors and its control at Lad Krating plantation, Chachoengsao province. M.Sc. thesis, Kasetsart University. Bangkok, Thailand.

Byram, G.M. 1959. Combustion of forest fuels. In: Davis, K.P. (Ed) Forest Fire; Control and Use. McGraw-Hill, New York, USA, pp. 61−89.

Chistjakov, V.I., Kuprijanov, A.I., Gorhkov, V.V., Artsybashev, E.S. 1983. Measures for fire prevention on peat deposits. In: Wein, R.W., MacLean, D.A. (Eds). The rule of Fire in Northern Circumpolar Ecosystem. John Wiley and Sons, New York, USA, pp. 259−27.

Daungyotha, P. 2006. Fire behaviors in rehabilitation forest area, Tak province. Department of National Parks, Wildlife and Plant Conservation. Bangkok, Thailand.

Forestry Research Center. 2013. Evaluation of fire damages from the 2012 peat fires at Khuan Khreng peat forest. Faculty of Forestry, Kasetsart University. Bangkok, Thailand.

Graham, L.L.B., Applegate, G.B., Thomas, A., Ryan, K.C., Saharjo, B.H, Cochrane, M.A. 2022. A field study of tropical peat fire behaviour and associated carbon emissions. Fire 3: 62. doi.org/10.3390/fire5030062

Hu, Y., Fernandez-Anez N., Smith T.E.L., Rein G. 2018. Review of emissions from smouldering peat fires and their contribution to regional haze episodes. Int. J. Wildland Fire 27: 293–312. doi.org/10.1071/WF17084

Klayprasit, K. 1998. Rate of fire spread pattern in mixed deciduous forest. Royal Forest Department. Bangkok, Thailand.

Kuewong, M., Wantongchai, K., Diloksumpun, S. 2015. Effects of fire on aboveground carbon storage and emission at Kuan Kreng peat forest, Nakorn Sri Thammarat province. In: Proceedings of Thailand Forest Ecological Research Network (T-FERN): Ecological Knowledge for Sustainable Management. Kasetsart University, Bangkok, Thailand, pp. 243−250.

Kumyaem. C. 2005. Fuel characteristics, fire behaviors and fire effects on growth of *Eucalyptus camaldulensis* plantation. M.Sc. thesis, Kasetsart University. Bangkok, Thailand.

Mezbahuddin, S., Nikonovas, T., Spessa, A., Grant, R.F., Imron, A.I., Doerr, S.H., Clay, G.D. 2023. Accuracy of tropical peat and non-peat fire forecasts enhanced by simulating hydrology. Sci. Rep. 13: 619. doi.org/10.1038/s41598-022-27075-0

Page, S.E., Rieley J.O. and Banks, C.J. 2011. Global and regional importance of the tropical peatland carbon pool. Glob. Change Biol. 17: 798–818. doi.org/10.1111/j.1365-2486.2010.02279.x

Patchaiyo, T. 2012. Fire behavior at Pine-Dipterocarp forest, Watchan, Chiangmai. Silviculture Project. Kasetsart University. Bangkok, Thailand.

Patchaiyo, T. 2016. Effects of fire on growth and natural regeneration of *Melaleuca cajuputi* Powell at Khuan Khreng peat forest Nakhon Si Thammarat Province. M.Sc. thesis, Kasetsart University. Bangkok, Thailand

Patel, N., Ieviņa, B., Kažmēre, D., Feofilovs, M., Kamenders, A., Romagnoli, F. 2025. Towards resilient peatlands: Integrating ecosystem-based strategies, policy frameworks, and management approaches for sustainable transformation. Sustainability. 17: 3419. doi.org/10.3390/su17083419

Phupet, S. 2007. Fire behaviors in tropical grassland, Tung Sa Laeng Laung National Park. Department of National Park, Wildlife and Plant. Bangkok, Thailand.

Sutthichart, K. 1996. Impact of Fire on Soil and Plant at Phu Kradung National Park. M.Sc. thesis, Kasetsart University. Bangkok, Thailand.

Vegas-Velarrubia, T., Baritto, F., Lopez, P., Melean, G., Elena, P.M., Mora, L., Gomez, O. 2010. Tropical Histosols of the lower Orinoco Delta, features and preliminary quantification of their carbon storage. Geoderma. 155: 280–288. doi.org/10.1016/j.geoderma.2009.12.011

Wanthongchai, K. 2011. Effects of early burning in teak plantation on surface fuel carbon release to the atmosphere, Mae Moh District, Lampang Province. Faculty of Forestry, Kasetsart University. Bangkok, Thailand.

Wanthongchai, K., Goldammer, J.G., Bauhus, J. 2011. Effects of fire frequency on prescribed fire behaviour and soil temperatures in dry dipterocarp forests. Int. J. Wildland Fire 20: 35–45. doi.org/10.1071/WF08098

Wanthongchai, K., Tarusadamrongdet, V., Chinnawong, K., Sooksawat, K. 2013. Fuel properties and fire behaviour characteristics of prescribed fire in pine-dominated forests at Nam Nao National Park, Thailand. Int. J. Wildland Fire 22: 615–624. doi.org/10.1071/WF11183

Widyastuti, K., Imron M.A., Pradopo S.T., Suryatmojo H., Sopha B. M., Spessa A., Berger U. 2020. PeatFire: an agent-based model to simulate fire ignition and spreading in a tropical peatland ecosystem. Int. J. Wildland Fire 30: 71–89. doi.org/10.1071/WF19213

Wein, R.W. 1983. Fire behavior and ecological effects in organic terrain. In: Wein, R.W., MacLean, D.A. (Eds). The Role of Fire in Northern Circumpolar Ecosystem. John Wiley and Sons, New York, USA, pp. 81–95.

Usup, A., Hashimoto, Y., Hayasaka, H., Takahashi, H. 2004. Combustion and thermal characteristics of peat fire in tropical peatland in Central Kalimantan, Indonesia. TROPICS. 14: 1−19. doi.org/10.3759/tropics.14.1