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Effects of fire frequency on prescribed fire behaviour and soil temperatures in dry dipterocarp forests

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Abstract. This study investigated how fire frequencies and fuel loads influence fire behaviour and soil heating in dry dipterocarp forests of the Huai Kha Khaeng Wildlife Sanctuary, Thailand. Fire behaviour and soil temperatures during burning were measured on a series of plots with different past fire frequencies ranging from unburned control, to rarely, infrequently and frequently burned, representing fire occurrences in 0, 1, 2 and 7 out of the past 10 years respectively. The pre-burning loads of fine fuel including grasses, herbs, shrubs, seedlings, saplings and litters increased with the length of the previous fire-free interval. The rate of spread, flame height, fireline intensity and maximum soil temperatures at any soil depths were not significantly different between the past burning regimes, so fires were classed as low-intensity and low-severity surface fire. The longest duration of heating with temperatures >60°C at ground level occurred at the rarely burned site (~14 min), followed by the infrequently burned site (~12 min) and the frequently burned site (~8 min). However, the duration of heating above any given critical temperature threshold at 2- and 5-cm soil depths was less than 1 min across all regimes. From a fuel management perspective, there does not appear to be a need to carry out prescribed burns more frequently than every 6–7 years, because fine fuel loads did not continue to accumulate substantially beyond 7 years after a fire.

Additional keywords: fire effect, fire intensity, fire severity, fuel consumption, fuel loads, Huai Kha Khaeng Wildlife Sanctuary, soil heating.

Introduction

Fire behaviour is a highly variable phenomenon influenced by changes in environmental components such as fuel and weather conditions, ecosystem type and topography (see DeBano *et al.* 1998). For example, high fuel loads with low fuel moisture content are likely to produce fires of high intensity and long duration, thereby having a potentially strong effect on the above- and belowground ecosystem. This should be taken into consideration when intervals for prescribed fires are determined. Most of the fire's heat is lost to the atmosphere, and only ~10–15% of the heat energy released during combustion is absorbed and transmitted directly downward into the soil (DeBano and Neary 2005). The greatest increase in temperature occurs at, or near, the soil surface and decreases with increasing soil depths. If the surface organic layer is thick and moist and acting as a temperature-insulating layer, little soil heating will occur. If the upper soil is moist, the evaporation will delay heating of the underlying soil (Whelan 1995). However, if the layer is dry and consumed by fire, the underlying soil can be heated substantially (Frandsen and Ryan 1986). High soil temperatures and a long residence time from heating can kill soil microbes, plant roots and seeds, destroy soil organic matter, and alter soil nutrient availability and water status (Hungerford *et al.* 1991). Thus the magnitude and duration of soil heating are important features of fire that affect soil properties and biota. Biological disruptions begin in the temperature range of 40–70°C, whereas physicochemical disruptions start to occur in the 200–315°C temperature range (DeBano *et al.* 1998). Despite their importance in ecosystem processes, fire behaviour and effects have not been studied in detail in the dry dipterocarp forests of Thailand, where fires are prevalent.

The dry dipterocarp forest (DDF) is an open and relatively low forest vegetation type dominated by deciduous trees such as *Shorea obtusa*, *S. siamensis*, *Dipterocarpus tuberculatus* and *Pterocarpus macrocarpus*. This forest type covers more area on the South-East Asian mainland than any other type, extending from north-eastern India and Myanmar through Thailand to the Mekong River region of Laos, Cambodia and Vietnam (Rundel and Boonpragob 1995). Dry dipterocarp forests occupy ~16 713 km^2 throughout Thailand (Royal Forest Department 2001). The area of its occurrence is characterised by a 5–7-month dry period and between 1000 and 5000-mm annual rainfall; pan evaporation may exceed precipitation for up to 9 months of the year. The natural range of DDFs in Thailand

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Fig. 1. Appearance of dry dipterocarp forests during the rainy season and the dry season.

extends from the drier slopes of the north and around the central highlands to the Korat Plateau to the east. DDFs occur mostly on mountainous or hilly and dry stes (Rundel and Boonpragob 1995). In Thailand, DDFs have been further subdivided into several different plant communities (see Komkris 1965; Khemnark *et al.* 1971; Kutintara 1975; Bunyavejchewin 1983) Native forests in Thailand are no longer harvested for timber; however, they provide a wide range of non-timber forest products (NTFPs), such as fuel wood, mushrooms, edible plants etc., to local people.

The history of fires and fire management for any forest type in Thailand, including DDFs, is not well documented before 1970. In 1976, the Forest Fire Control Section was established to tackle forest fire problems. Even though many national forest fire prevention campaigns had been launched over the course of three decades, it became obvious that fire exclusion would not meet the challenges of reality. In some forest types, such as DDF, fires are almost omnipresent throughout the dry season owing to regular fire use both inside and outside the forest (Akaakara 2003). Frequent anthropogenic, low-intensity fires are a common phenomenon in DDFs (Akaakara 2000). People have been using fire to maintain a forest structure to produce a specific range of NTFPs that are favoured by fire (Stott *et al.* 1990; Goldammer 1993), even though it is now illegal to start fires in forests for any reason. Consequently, there are conflicts between national fire prevention policies and the need to use fire by local smallholders in maintaining their land-use systems. Burning usually occurs between January and April, when the load of surface fuel (i.e. leaf litter) is highest following leaf shedding by the deciduous vegetation dominating these forests (Fig. 1). The desiccation of grasses also provides additional dry fuels. Nevertheless, some DDFs located in protected areas, such as national parks and wildlife sanctuaries, have remained unburned for long periods because of fire prevention and suppression policies. These fire programs have been implemented throughout forested areas regardless of the role fire plays for ecosystem functioning (Sabhasri *et al.* 1968; Kutintara 1975). Consequently, natural fire regimes in DDFs have been highly modified, resulting in over-frequent burning in some parts of the landscape, and infrequent burning owing to attempted fire suppression in other parts of the landscape.

These two extremes of frequent fires on the one side and fire exclusion on the other may result in ecosystem impoverishment, or even degradation in DDFs (Sabhasri *et al.* 1968; Kutintara 1975). Frequent burns may reduce the risk of high-intensity surface wildfires in DDFs, but they may also result in decreased soil fertility, altered vegetation composition (i.e. regeneration pattern, vegetation structure), and declines in ecosystem productivity. However, complete fire prevention results in the accumulation of fuels that may foster high-intensity fires with severe consequences for ecosystem structure and functioning of this forest type. Stott (1986) showed that the recovery rates of *Shorea obtusa* seedlings after low-intensity fires are good, whereas high-intensity fires can kill 95% of *S. obtusa* saplings. Williams *et al.* (1999) found that plant survival decreased linearly with increasing fire intensity, and stem death following a severe, single, high-intensity fire was comparable with that of a fire regime of an annual late dry-season burning for 5 years. Therefore, an appropriate burning frequency is crucial for maintaining the ecological structure and functioning of DDFs. Russell-Smith *et al.* (1998) reported that vegetation density, fuel load and soil fertility will increase with increasing time since the last fire.

There are only few studies on fire in Thailand's forest (see Stott 1986; Sunyaarch 1989; Akaakara and Kittisatho 1992; Sompoh 1998; Marod *et al.* 2002; Akaakara *et al.* 2003; Himmapan 2004) and they are limited to aboveground fire behaviour and do not consider heat duration or soil temperature. In addition, the effects of different burning frequencies on fire behaviour in DDFs have not been examined for this fire-resilient ecosystem (Sabhasri *et al.* 1968; Kutintara 1975). Different burning frequencies, through their influence on fuel loads and vegetation conditions, may affect fire intensity, soil temperatures and hence ecosystem processes (DeBano and Neary 2005). Knowledge about the effects of burning frequency on fire behaviour is an important basis for fire management decisions in DDFs.

We implemented several experimental fires at DDF sites with different past fire frequencies. Specifically, our hypotheses

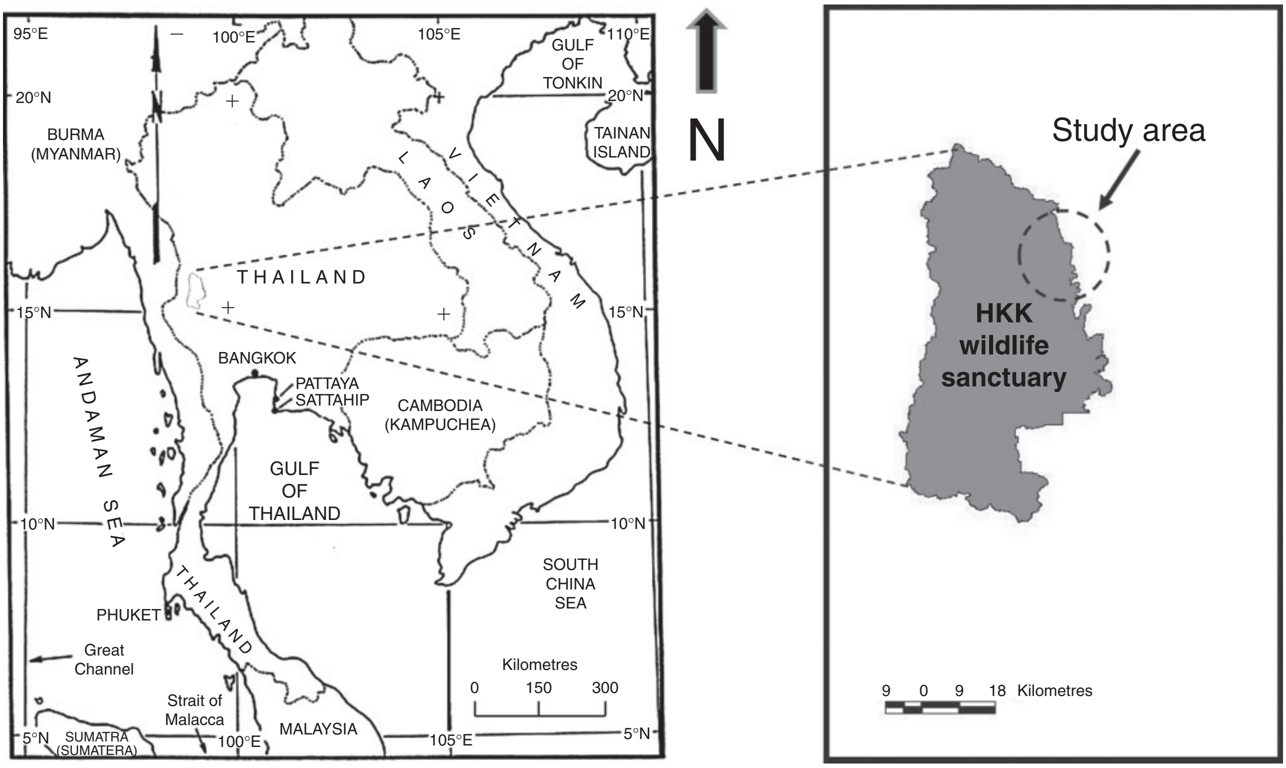

Fig. 2. Location of our experimental study area in a dry dipterocarp forest of the Huai Kha Khaeng (HKK) Wildlife Sanctuary in Thailand.

were that: (1) different fire histories affect both the amount and the proportion of various types of fine fuel; and (2) rate of spread, flame height, fireline intensity, soil temperatures, the duration of heating and fuel consumption during fires increase or become more extreme in relation to the length of the previous fire-free interval.

Materials and methods

Study site

The study was conducted in the Huai Kha Khaeng Wildlife Sanctuary (HKK), located ~350 km north-west of Bangkok, Thailand. The investigated DDF is located in the north-east region of the sanctuary (Fig. 2). The study site has a tropical monsoonal climate, with a dry season extending from November to April, and a wet season from May to October. The average annual rainfall is 1348 mm year^{-1}. The mean daily temperature varies from 23.2°C in December to 30.9°C in April. The average relative humidity is 89.1% with the lowest monthly average during April (~79%) (Forest Fire Research Center 2006). The elevation of the study area ranges from 300 to 400 m above sea level. This DDF is dominated by deciduous tree species such as *Shorea obtusa*, *S. siamensis*, *Dipterocarpus tuberculatus*, *Xylia kerrii* and *Sindora siamensis.* The understorey consists mainly of a grass layer dominated by *Heteropogon contortus* and *Imperata cylindrica*, as well as other understorey shrubs, herbs, saplings and seedlings (Forest Research Center 1997).

The recent burning history of the study area was reconstructed by mapping burned areas with the use of fire reports kept by the National Park, Wildlife and Plant Conservation Department, and a series of satellite images spanning a 10-year period from 1995 to 2004. As a result, four different burning regimes were identified. These included fire frequencies of 0, 1, 2 and 7 fires over the past 10 years, which are subsequently referred to as unburned control (UB; ~10–12 years since fire), rare (RB; 7 years since fire), infrequent (IB; 3 years since fire) and frequent (FB; 0 years since fire) (Wanthongchai *et al.* 2008). Vegetation structure in terms of density, basal area, canopy area and overstorey species diversity generally increased with the length of fire-free interval.

Experimental burning

Three replicate plots were established for each burning regime. It was physically impossible to establish replicate plots with an identical history of fire frequencies and time since the last fire for spatially separate and independently burned areas within the landscape. As a result, replicate plots of the same fire frequency were located within the same site, influenced by the same previous fire event (Fig. 3). Therefore the plots represent pseudo-replications (Hurlbert 1984). Within each treatment, plots were located ~500 m apart. All plots were selected to represent the same geologic parent material, soil unit, forest type, elevation and topography (slope < 10%). Prior to burning, experimental plots of 50 × 50 m, each containing an inner 30 × 30-m area for measurements, were created. Fuel breaks (~5 m wide) were constructed outside each plot and suppression equipment was used to prevent an accidental fire escape. With the exception of the unburned control areas (UB), experimental burning was implemented on nine plots during the period from

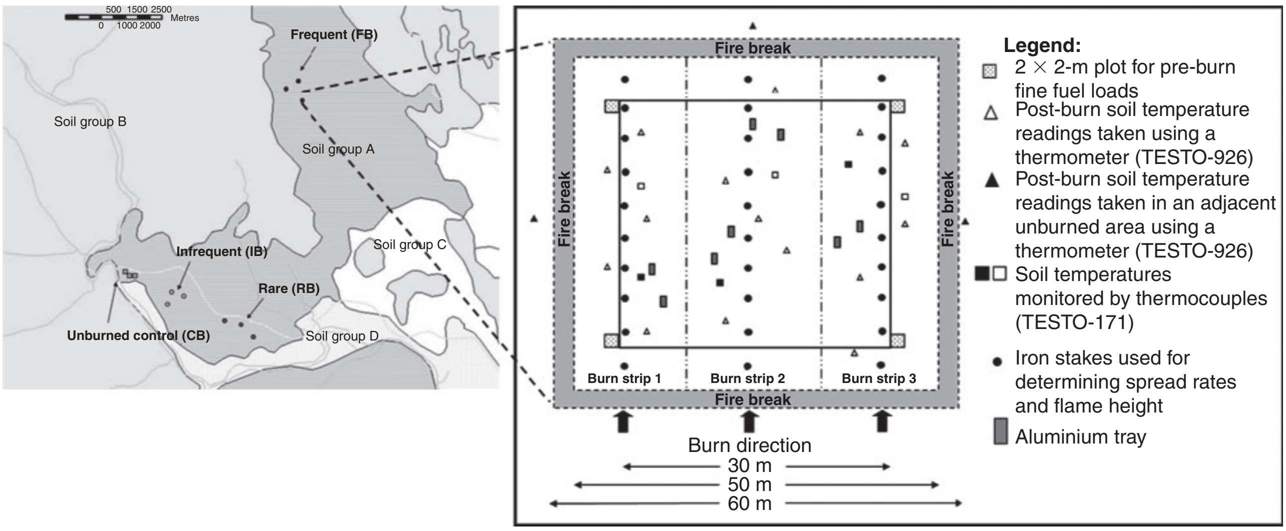

Fig. 3. Distribution of plots with different past fire frequencies across the study area and plot design for fuel and residue determination, burning ignition patterns and the positions of all fire and soil temperature measurements. Fires were ignited at the edge of the plot indicated by thick arrows.

28 December 2004 to 9 January 2005, which was earlier than the long-term average peak for the dry season and the typical occurrence of fire. However, the unusually dry conditions during 2004 resulted in an earlier start of the dry season. The total rainfall in 2004 was only 996 mm compared with 1333 mm in 2003 and 1454 mm in 2005 (Forest Fire Research Center 2006). In addition, the vegetation had shed its leaves and the litter was dry enough to sustain a fire. Burning experiments took place between 1300 and 1800 hours, when relative humidity was lowest. Ignition was facilitated with three-strip head-fires, each with an ignition line covering a third of the plot length started from a location that allowed the fire to spread with the wind. The ignition and burning of an individual strip (~16 m wide) within a plot was completed before the next strip was ignited.

Prior to burning, one set of 2 m-tall iron stakes with heights marked at 0.5-m intervals was placed every 5 m perpendicular to the front of the fire to estimate the rate of fire spread and flame height (Fig. 3). The rate of fire spread was estimated as the average time for fire to progress between individual stakes. Flame height was recorded by taking photographs as the fire passed each stake. Relevant meteorological data (i.e. air temperature, relative air humidity and wind speed) were also recorded during the experiment using a portable Kestrel Pocket Weather Tracker (Nielsen Kellerman, Boothwyn, PA).

Soil measurements were carried out in two different ways. Approximately 5 min after the fire had passed the stakes, ambient soil temperatures were measured at four different depths (1, 2, 5 and 10 cm beneath the soil surface) by digging a small soil pit and inserting the probe (TESTO-926, Type T thermometer, Testo Co., Lenzkirch, Germany) into the side of the pit at the appropriate depth. Soil was dug at the 5-min mark after the fire. This was completed for five points along each of the three strips of iron stakes for a total of 15 soil temperature pits (Fig. 3). In addition, soil temperatures were also measured in a similar manner at three control points (i.e. unburned areas) adjacent to each treatment plot. Soil temperature measurement using this thermometer probe method will inevitably miss soil temperature peaks and the true duration of soil heating at certain temperatures occurring during the passage of the fire front. To deal with this limitation, we used temperature probes (Type K) connected to TESTO-171 thermocouple data loggers (Testo Co.) buried ~20 cm beneath the mineral soil surface before the ignition of plots. Maximum soil temperatures and the duration of soil heating were continuously recorded (every 2 s) at the mineral soil surface and at 2- and 5-cm depth during burning at two locations adjacent to each of the three strips. The duration of soil heating was determined for three different temperature thresholds of >60°C for plant tissue, >80°C for soil biological processes, and >100°C for soil chemical processes (DeBano *et al.* 1998; Neary *et al.* 1999).

For the purpose of this study, 'fine fuel' is defined as all understorey vegetation, leaf litter and small woody fuel and dead twigs (<1 cm in diameter), shrubs, herbs, grasses, saplings and seedlings (<4.5 cm DBH (diameter at breast height)) (Smitinand 2001). Coarse woody fuels including bark and branches were not included, as these were present only in very small amounts at the study sites. The fuel bed within our study site could be stratified into three horizontal strata, including a litter–lichen–moss stratum (i.e. leaf litter, small down and dead twigs), a non-woody vegetation stratum (i.e. herbs and grass), and a shrub stratum (i.e. shrubs, saplings and seedlings) (Ottmar *et al.* 2007). The tree canopy layer was not assessed because surface fires in DDFs do not burn standing mature trees. Approximately 3 h before burning, four representative 2 × 2-m areas were established systematically at the corner of the inner 30 × 30-m area of each plot to determine available fine-fuel loads (Fig. 3). All biomass within the quadrates was harvested and weighed separately for each fine-fuel type. All live understorey vegetation was clipped at ground level, whereas the leaf litter was carefully removed by hand to avoid contamination with the underlying mineral soil. Samples were weighed in the field, with subsamples from each fuel type brought back to the laboratory for moisture content and dry mass determination.

The harvested fine fuels were grouped into two categories: (1) leaf litter (leaves that had fallen down from tree canopy); and (2) undergrowth (i.e. grass, herb, shrub and young tree species). For each litter type, known quantities were placed on four $52 \times 38 \times 2.5$-cm aluminium trays. The amount of litter or vegetation placed on the trays was equivalent to the average quantities found in the field in a similar surface area. Two hours before burning, the trays were carefully placed on the ground inside the plots, so that the material on the tray formed a continuous layer and fuel surrounded the tray. Although the trays held a quantity of fuel that was equivalent to that of the surrounding area, the depth and compactness of the fuel layer was different. The differences in the physical fuel layer characteristics were minimal for the litter, but the clipped vegetation was certainly less high and more compact on the trays than in the undisturbed surroundings.

Data analysis

The selected fire behaviour parameters refer to surface fire behaviour (i.e. rate of spread, flame length and height and fireline intensity), whereas fire severity parameters refer to soil temperature and the duration of heating above critical temperature (Khanna and Raison 2006). Fireline intensity was calculated using Byram's (1959) formula: $I_B = H \times w \times r$, where I_B is fireline intensity (kW m^{-1}), H is low heat of combustion at 18 649.05 kJ kg^{-1} (Sompoh 1998), w is fuel consumed (kg m^{-2}), and r is the rate of fire spread (m min^{-1}). Flame length was determined using Byram's formula: $L = 0.08(I_B)^{0.46}$, where L is flame length (m).

The data were processed and analysed using *SPSS® 13.0* for Windows (SPSS Inc. 2005). All variables were first tested for homogeneity of variance (Levene's test) and for normal distribution (Kolmogorov–Smirnov test) to meet the prerequisites of the ANOVA. In the event that these assumptions were not met, the data were transformed using either common logarithm or square-root forms. Statistically significant differences between the burning regimes ($P < 0.05$) were further analysed using Duncan's multiple range test. If, after transformation, the data still did not conform to the prerequisites for performing an ANOVA, an analogous, non-parametric test (Kruskal–Wallis test) was applied, followed by a Mann–Whitney U test. Paired-sample t-tests were used to ascertain the effect of burning on soil temperatures within each burning regime. Correlations between fuel loads, fire and soil temperature, and fire behaviour descriptors were analysed using the Pearson correlation coefficient (Townen 2002).

Results

Pre-burn fuel loads

Total pre-burn fuel loads differed significantly among the three burning regimes (RB, IB and FB). Fuel loads were high at the unburned control (UB) (1.22 kg m^{-2}) and the RB (1.16 kg m^{-2}) sites, and substantially lower at the sites that had undergone intermediate (IB) (0.89 kg m^{-2}) and frequent fires (FB) (0.51 kg m^{-2}) in the past (Fig. 4 and Table 1). In addition, the varying burning regimes also affected the fine-fuel composition. At the FB sites, grass contributed 0.095 kg m^{-2} (18.7%) to the fine fuel load, whereas at the RB and UB sites, grass amounted to only 0.024 kg m^{-2} (2.6%) and 0.009 kg m^{-2} (0.7%) respectively. In terms of quantities, leaf litter was the most important fine fuel in these DDFs, making up more than 70% of the total fine-fuel load. The amount of litter increased significantly with decreasing fire frequency. The amount of leaf litter ranged from 0.362 kg m^{-2} at FB sites to 0.844 kg m^{-2} at UB sites. Further, the contribution to the sites' fuel load by undergrowth (all fine fuel except grass and litter) was significantly lower in the FB than in any of the other treatments.

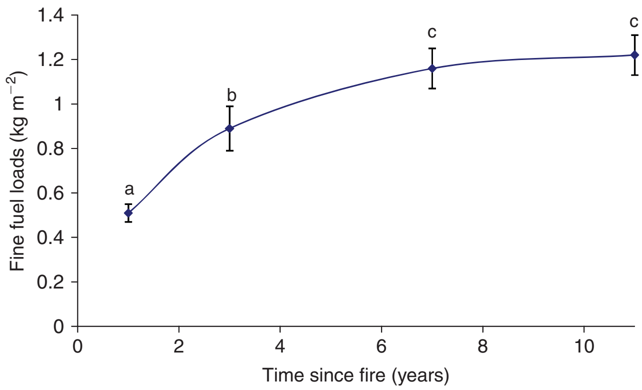

Fig. 4. Amounts of pre-burn fine fuel (mean ± s.e.) in a dry dipterocarp forest as a function of time since the last fire in the Huai Kha Khaeng Wildlife Sanctuary.

Fuel moisture content and weather conditions

At 3 h before burning, the average fuel moisture content of each fine-fuel type increased in the following order: leaf litter (~15%), grass (~22%), shrubs (~45%), herbs (~51%), saplings (~85%) and seedlings (~93%). Moisture content of all fuel types, except for shrubs, was not significantly different between treatments (Fig. 5). Moisture contents of grass and litter were generally less than 25%, sufficiently low to sustain fire.

Weather conditions, particularly wind speed, fluctuated during the burning period. The wind speeds at the time of burning varied between 0 and 8.1, 0 and 24.8 and 0 and 7.9 km h^{-1} for the FB, IB and RB sites respectively. The air temperatures varied from 24.5 to 37.8, 28.6 to 38.1 and 29.3 to 38.1°C at the FB, IB and RB sites respectively, whereas the relative humidity was between 17.2 and 38.8, 16.7 and 37.5 and 13.8 and 36.2% respectively (Table 2). Statistical analyses revealed that wind speed was highest ($P < 0.05$) at the IB site (3.1 km h^{-1}), compared with 2.4 km h^{-1} at the FB and 2.2 km h^{-1} at the RB site.

Fuel consumption and fire behaviour characteristics

The quantities of fuel consumed in the fires increased with pre-burn fuel loads. However, the percentage fuel consumption was highest at the FB site (84%), as compared with the IB (65%) and RB (70%) sites (Table 1).

The rate of spread was highly variable between the different burning strips within the plot and among plots. The average rate of spread was highest at the FB site (2.7 m min^{-1}) and lowest at the RB site (1.3 m min^{-1}) (Table 3).

The differences in observed flame heights among the past burning regimes were not significant. The height of the highest

Table 1. Pre-burn fuel loads and fuel consumption during prescribed fire in relation to different past fire frequencies
Standard errors are given in parentheses. Different letters (a, b, c) indicate significant differences (ANOVA, $P < 0.05$, followed by Duncan's multiple range test) in the fuel category values between the fire frequency plots. Vegetation forms were classified according to Smitinand (2001). Abbreviations are: FB, frequently burned; IB, infrequently burned; RB, rarely burned; and UB, unburned control

Fuel category	Study sites			
	UB	RB	IB	FB
Saplings (kg m^{-2})	0.297^{c} (0.057)	0.228^{b,c} (0.071)	0.131^{b} (0.047)	0.009^{a} (0.007)
Seedlings (kg m^{-2})	0.038^{a} (0.009)	0.015^{a} (0.007)	0.024^{a} (0.010)	0.021^{a} (0.005)
Shrubs (kg m^{-2})	0.029^{b} (0.013)	0.009^{b} (0.003)	0.020^{b} (0.007)	0.002^{a} (0.001)
Herbs (kg m^{-2})	0.007^{b} (0.005)	0.056^{a} (0.028)	0.015^{a} (0.003)	0.017^{a} (0.005)
Grasses (kg m^{-2})	0.008^{c} (0.001)	0.024^{b} (0.006)	0.032^{b} (0.005)	0.095^{a} (0.013)
Leaf litter and small fuel (kg m^{-2})	0.844^{c} (0.057)	0.824^{b,c} (0.070)	0.669^{b} (0.063)	0.362^{a} (0.032)
Total fuel load (kg m^{-2})	1.22^{c} (0.09)	1.16^{c} (0.09)	0.89^{b} (0.10)	0.51^{a} (0.04)
Fuel consumption (kg m^{-2})	n.a.	0.81^{c} (0.02)	0.58^{b} (0.02)	0.43^{a} (0.01)
Fuel consumption (%)	n.a.	70^{a} (0.50)	65^{a} (2.01)	84^{b} (1.77)

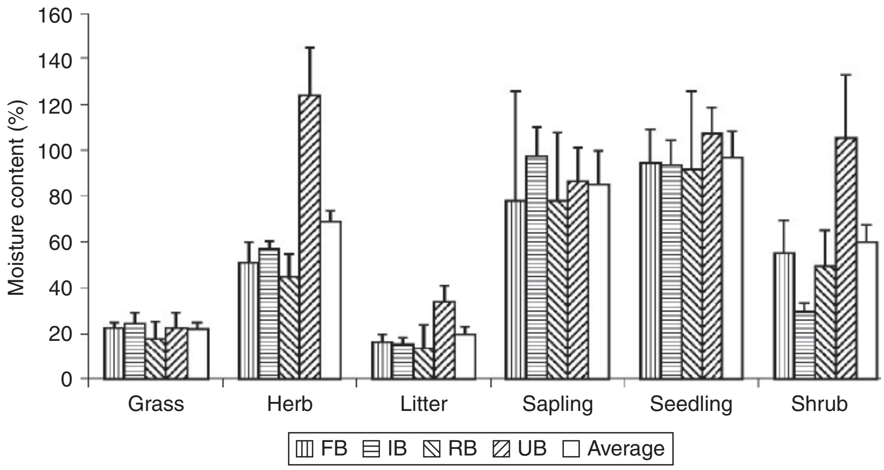

Fig. 5. Fuel moisture content of pre-burn fine fuels associated with the different past fire frequencies: rarely burned (RB); infrequently burned (IB); frequently burned (FB); and unburned control (UB).

Table 2. Weather conditions during burning experiments
Minimum and maximum values for wind speed, temperature and relative humidity are given in brackets. Different letters (a, b) indicate significant differences (ANOVA, $P < 0.05$, followed by Duncan's multiple range test) in weather conditions between fire frequency plots. Data were recorded for every 2 s using a portable Kestrel Pocket Weather Tracker. Abbreviations are: FB, frequently burned; IB, infrequently burned; and RB, rarely burned

Burned plots	Burning date	Burning period	Mean value with range in brackets		
			Wind speed (km h^{-1})	Temperature (°C)	Relative humidity (%)
FB plot 1	28 December 2004	1523–1800 hours	1.7 (0.0–5.1)	30.7 (24.5–37.8)	24.7 (17.2–38.8)
FB plot 2	29 December 2004	1338–1504 hours	2.8 (0.0–7.6)	31.5 (28.6–33.9)	22.6 (19.4–31.0)
FB plot 3	30 December 2004	1310–1447 hours	3.2 (0.0–8.1)	32.3 (29.9–34.1)	18.1 (14.9–23.9)
Average FB			2.4^{b}	31.2^{a}	22.1^{a}
IB plot 1	4 January 2005	1320–1505 hours	2.9 (0.0–24.8)	31.4 (29.4–33.7)	20.6 (16.7–24.7)
IB plot 2	5 January 2005	1253–1445 hours	3.6 (0.0–8.8)	31.2 (28.7–38.1)	24.4 (17.0–31.5)
IB plot 3	6 January 2005	1315–1530 hours	2.2 (0.0–6.0)	31.9 (28.6–36.4)	24.8 (20.0–29.1)
Average IB			3.1^{a}	31.6^{a}	22.8^{a}
RB plot 1	7 January 2005	1312–1502 hours	2.4 (0.0–7.9)	31.2 (29.4–34.3)	24.4 (19.7–28.2)
RB plot 2	8 January 2005	1304–1612 hours	2.2 (0.0–7.8)	32.5 (29.5–38.1)	24.9 (13.8–28.7)
RB plot 3	9 January 2005	1343–1643 hours	2.0 (0.0–5.9)	32.4 (29.3–36.3)	23.1 (16.5–36.2)
Average RB			2.2^{b}	32.2^{a}	23.9^{a}

individual flame observed was ~3 m. Flame lengths, calculated from Byram's (1959) formula, were also not different among the past burning regimes. The fireline intensity at all burned plots was low and it was not significantly different ($P = 0.303$) among past burning regimes (Fig. 6).

Soil temperatures during experimental burning

The average ambient temperatures of unburned soil varied both within and between past burning regimes but they were not significantly different between sites and soil depths. The temperature changes induced by fire (measured 5 min after the fire) were small, yet they were highest, even in deeper layers, at the sites with longer fire-free intervals (e.g. the RB site) (Table 4). The temperature increases due to fire were highest near the surface and barely noticeable at 5-cm depth and beyond.

The maximum surface soil temperature during fire never exceeded 500°C in any of the burned plots. There were no

Table 3. Quantitative fire behaviour characteristics observed at experimental fires at sites with different past fire frequencies

Standard errors are given in parentheses. Different letters (a, b) indicate significant differences (ANOVA, $P < 0.05$, followed by Duncan's multiple range test) in fire characteristics between fire frequency plots. Flame length and fireline intensity were calculated using Byram's formula (Byram 1959)

Fire characteristics	Past fire frequencies		
	Rarely burned	Infrequently burned	Frequently burned
Rate of spread (m min^{-1})	1.3^b (0.2)	2.6^a (0.3)	2.7^a (1.0)
Flame height (m)	1.2^a (0.1)	1.5^a (0.7)	1.2^a (0.1)
Flame length (m)	1.27^a (0.11)	1.53^a (0.09)	1.51^a (0.22)
Fireline intensity (kW m^{-1})	291^a (43)	467^a (62)	361^a (150)

Fig. 6. Prescribed fires in a dry dipterocarp forest in the Huai Kha Khaeng Wildlife Sanctuary of Thailand. Left: Fire backing into the wind. Right: headfire burning with the wind.

Table 4. Comparison of average ambient soil temperatures between burned sites and adjacent unburned sites for the different past fire frequencies

Standard errors are given in parentheses. Different letters (a, b) indicate significant differences (paired *t*-test) between soil temperatures at burned and unburned plots at a specific soil depth for each set of fire frequency plots, using a 95% confidence interval. Values were recorded 5 min after the fire by digging a small soil pit and inserting a TESTO-926 (Type T) thermometer probe into the side of the pit at the appropriate depth

Soil depth	Rarely burned		Infrequently burned		Frequently burned	
	Burned (°C)	Unburned (°C)	Burned (°C)	Unburned (°C)	Burned (°C)	Unburned (°C)
1 cm	45.1^a (1.0)	30.6^b (0.8)	47.4^a (1.2)	33.3^b (0.9)	44.0^a (0.9)	36.3^b (0.4)
2 cm	38.9^a (0.8)	29.7^b (0.8)	41.7^a (0.7)	32.4^b (0.8)	39.6^a (0.7)	34.2^b (0.4)
5 cm	31.7^a (0.4)	28.1^b (0.7)	33.9^a (0.4)	31.0^b (0.8)	30.5^a (0.3)	30.4^a (0.4)
10 cm	28.3^a (0.3)	26.5^b (0.6)	29.7^a (0.3)	28.7^a (0.6)	26.7^a (0.2)	26.9^a (0.8)

Table 5. Average duration of heating (min) at different soil depths for different past fire frequencies

Different letters (a, b) indicate significant differences (ANOVA, $P < 0.05$, followed by Duncan's multiple range test) in the duration of heating at each soil depth between fire frequency plots. Values were automatically recorded for every 2 s using thermocouple probes (Type K), connected to TESTO-171 thermocouple data loggers, which were buried ~20 cm beneath the mineral soil surface. Abbreviations are: FB, frequently burned; IB, infrequently burned; and RB, rarely burned

Temperature threshold (°C)	Soil depth	Duration of heating		
		RB	IB	FB
>60°C	0 cm	14^{b}	$12^{a,b}$	8^{a}
	2 cm	$<1^{a}$	1^{a}	1^{a}
>80°C	0 cm	7^{b}	7^{b}	4^{a}
	2 cm	$<1^{a}$	$<1^{a}$	$<1^{a}$
>100°C	0 cm	5^{b}	5^{b}	3^{a}
	2 cm	$<1^{a}$	$<1^{a}$	$<1^{a}$
>80% of maximum temperature	0 cm	2^{ab}	3^{b}	1^{a}

significant differences in the maximum soil temperatures at the various soil depths among the different burning regimes.

At ground level, the duration of heating >60°C was clearly longest ($P < 0.05$) for the RB site (~14 min), followed by the IB site (~12 min), and then the FB site (~8 min) (Table 5). The same was true for the duration of heating above 80 and 100°C. However, the duration of heating above any of the given critical temperature thresholds was generally <1 min at 2- and 5-cm soil depth.

Discussion

The effects of past burning regimes on fine-fuel type and quantity

The quantity and the composition of fine fuel changed with time since the last fire. An analysis of the fine-fuel layer (undergrowth and leaf litter) alone, rather than all of the biomass fuel found in dry dipterocarp forests, is reasonable as it represents the fuel typically consumed by a low-intensity, prescribed fire (Goldammer 1991). Long intervals between fires usually facilitate fuel accumulation, whereas short fire intervals can drastically reduce the standing fuel biomass (Rothermel 1972; Fulé and Covington 1994; Peterson and Reich 2001; Govender *et al.* 2006; Màrcia *et al.* 2006).

Although there was a 2.5-fold difference in litter loads between the various burning regimes, the litter layer represented a similar proportion (~70%) of the total fine-fuel load across burning regimes. The results of this study show that grass biomass decreased with time since the last fire (ranging between 0.095, 0.032, 0.024 and 0.008 kg m^{-2} for FB, IB, RB and UB respectively), whereas the quantity of litter and undergrowth vegetation increased (ranging between 0.362, 0.669, 0.824 and 0.844 kg m^{-2} for FB, IB, RB and UB respectively) (see Table 1). Frequent fires favour grasses, most of which are well adapted to recurrent fires (Stott *et al.* 1990; Goldammer 1991). As the canopy density increases during recovery after fire (canopy cover was 41, 55, 59 and 71%, at FB, IB, RB and UB sites respectively), the abundance of grasses in the present study most likely declined with reduced light transmission, consistently with the findings of Stott *et al.* (1990) and Giessow and Zedler (1996). Akaakara *et al.* (2004) reported that fine-fuel loads in DDFs were very low (~0.4 kg m^{-2}) and thus comparable with the frequently burned sites (FB) (~0.5 kg m^{-2}). In their study, grasses also contributed to ~17% of the total fine-fuel load. It is unknown whether there is a positive feedback mechanism such that grasses have a higher probability to burn than a non-grassy understorey. A proliferation of grasses may cause changes in fire regimes through a positive feedback cycle, or a so-called grass–fire cycle (D'Antonio and Vitousek 1992). As result, tree and shrub cover declines, facilitating further spread of grasses, which in turn increases the likelihood of future fires, and thus the proliferation self-perpetuates (Rossiter *et al.* 2003). The positive feedback of the grass–fire cycle has been documented for several regions including Hawaii, western North America, Central and South America (D'Antonio and Vitousek 1992; D'Antonio *et al.* 2000; Rossiter *et al.* 2003).

Effects of past burning regimes on fuel consumption and fire behaviour

Total fuel consumption also increased with the site's fire-free interval. However, relative fuel consumption was highest at FB sites, presumably because of the abundance and homogeneity of grassy fuel, which allowed for a more complete burn. In this study, consumption of undergrowth fuel was substantially less (70, 51 and 57% for FB, IB and RB respectively) than fuel consumption of litter (88, 79, 84% for FB, IB and RB respectively). This disparity is likely attributable to the lower moisture content and greater surface-to-mass ratio of litter when compared with undergrowth. The higher percentage in fuel consumption at the regularly burned compared with the infrequently burned site might have been due to the slower rate of spread at the RB site, resulting in a more complete combustion there.

At all plots, fireline intensities were generally low (<500 kW m^{-1}), consistent with the findings of other fire behaviour studies in DDF (Sunyaarch 1989; Sompoh 1998; Himmapan 2004). At a prescribed fire in a DDF with a fuel load of ~0.54 kg m^{-2}, Akaakara *et al.* (2003) measured an average rate of spread of 2.7 m min^{-1} with an average flame length of 1.6 m and a fireline intensity of 543.5 kW m^{-1}. These values are somewhat higher than our results, probably because of differences in weather conditions and burning technique. The average air temperature in their study was 40.0°C compared with 31.7°C in the current study. The strip burning technique used here usually results in lower fire intensities than other prescribed burning techniques (Sparks *et al.* 2002) or natural wildfire (Akaakara *et al.* 2003).

The higher rate of fire spread at the FB sites was probably caused by the abundance of grass with its lower moisture content (~22% compared with >45% for other undergrowth vegetation) and a more loosely compacted arrangement (higher surface-to-volume ratio). Weather conditions at the RB site, the wind speed in particular, which was significantly lower than at the other sites, appear to have influenced fire behaviour characteristics. We assume that the low wind speed at the RB sites was due to the variation of wind speed between the days of burning rather than the influence from understorey density. Wind speed had a positive effect on the rate of spread ($r = 0.54$,

$P < 0.01$) and, consequently, affected fireline intensity, as could be discerned from a high positive correlation between wind speed and rate of spread ($r = 0.93$, $P < 0.001$). Therefore, the higher rate of spread at the IB site may have resulted from a higher wind speed.

Even burning of the DDF sites characterised by longer fire-free intervals and higher fuel loads did not necessarily result in consistently higher fireline intensities or greater fuel consumption. This suggests that it may be acceptable to let fuels accumulate over several years (6–7 years), as long as they are burned under safe conditions. However, even low fuel loads can result in high-intensity fires under suitable fuel and weather conditions.

Soil temperatures and heating duration

The maximum surface temperatures recorded during burning in our study (330, 261 and 280°C for FB, IB and RB sites respectively) were somewhat lower than those recorded by Raison *et al.* (1986), who measured temperatures at several soil depths after a low-intensity prescribed burn in a subalpine *Eucalyptus pauciflora* forest. They measured steep soil temperature gradients, which were attributed to a high organic matter content, low bulk density and low moisture content of the surface soil during the fire. As a result, they found maximum soil surface temperature was 450°C, which was recorded while measuring temperatures >60°C for a duration of ~50 min. In our study, the fire intensity was obviously too low to create surface soil temperatures of sufficient duration to heat the lower soil layers.

In our study, heat penetration into the soil layer must have been primarily influenced by the fuel loads, which varied between the past fire frequencies, whereas other potentially relevant soil factors were comparable. As the total heat increased in relation to fine-fuel loads, so did the depth to which it penetrated into the underlying soil and the peak temperature at any given soil depth, which confirms findings by DeBano *et al.* (1998). Moreover, soil heating is also determined by the residence time of fire, here expressed by the rate of spread. The duration of heating, therefore, was longest at rarely burned sites, which were carrying the highest fuel loads.

Management implications

The design of this study permitted only the use of pseudo-replications for the main experimental factor ‘time since last fire’. The results and implications of this study need to be viewed in light of these design limitations.

According to the fireline intensity classification of Cheney (1994), all of the prescribed burns in our study can be considered low-intensity surface fires, irrespective of the previous burning regimes. Surface fire temperatures under prescribed fires in this study did not exceed 700°C and the duration of heating was generally less than 10 min at the soil surface, with no heat penetrating deeper than 5 cm into the soil. The partial consumption or charring of the aboveground vegetation is a further indication of low-severity fires according to the classifications employed by DeBano and Neary (2005) and Khanna and Raison (2006). This means that, from a fire control perspective, the fires experienced in the current study can be attacked at either the head or flanks by firefighters using only hand tools.

The chronosequence of sites employed in this study demonstrated that fine fuels during the first 5 years accumulated fast; however, did not increase further in later years and reached comparatively low levels of 1.22 kg m^{-2} (see Fig. 4). As these maximum amounts of fine fuels can be burned at low intensity, there is little need for the application of frequent prescribed burning to keep fuel loads at a safe level in these forests. The short duration of soil heating above critical temperatures indicated that there will be very little damage to established vegetation. Thus, infrequent prescribed fires may be safely carried out every 6–7 years or 1–2 fires per decade. However, prescribed fires in this study were carried out early in the dry season, when soil temperatures and fire intensity are known to be lower than in the late dry season. Therefore unplanned wildfires late in the dry season that occur just before the next planned prescribed fire (e.g. 4 to 5 years after the last fire) may cause greater damage owing to their presumably higher intensity. In the absence of information about possibly higher intensities of late-season fires, it may be prudent to carry out low-intensity fuel reduction burns at less than 6–7-year intervals in high wildfire risk areas.

In addition, our recommendation is based on the fact that coarse wood fuels did not play a significant role in the DDF ecology studied here. The loading, size distribution and decay state of large woody fuels may have a significant influence on fire residence time, difficulty of control and burnout time, which affect soil heating (Brown *et al.* 2003).

If coarse woody fuels loads increase as a result of fire exclusion or other disturbances, their influence on fire behaviour must be included in the assessment of risks. Thus, a prescribed fire regime must consider both the role of fuel loads and the time of burn within the dry season, i.e. high fuel loads may require an early burn in order to avoid excessive soil heating, whereas sparse fuel may require a late-season burn to obtain the desired fuel reduction.

Some variation of the burning interval, fire intensity and the burned area may result in both a spatially and a temporally heterogeneous mosaic of burned patches across the landscape, resulting in greater vegetation complexity at the landscape level.

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