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Nutrient losses through prescribed burning of aboveground litter and understorey in dry dipterocarp forests of different fire history

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Abstract

Anthropogenic burning in dry dipterocarp forests has become a common practice throughout Thailand. It is feared, that too frequent fires may result in a loss of soil fertility and thus ecosystem productivity. The aim of this study was to quantify aboveground nutrient pools in fine fuels and nutrient losses during prescribed fires applied to plots of different fire frequency histories in the Huay Kha Khaeng Wildlife Sanctuary, Thailand. Fire frequency was determined from satellite images and ranged from frequent, infrequent, rare and unburned with fire occurrences of 7, 2, 1 and 0 out of the past 10 years, respectively. Element losses were calculated as the difference between nutrient pools in the fuel before burning and the post-burning residues comprising ash, charcoal, and unburned matter, which were recovered quantitatively using aluminium trays. The percent nutrient loss was highest at sites that had undergone frequent burning in the past and was lowest at infrequently burned sites. When viewed over a ten-year period, nutrient losses from a fire regime with one fire per decade had much lower losses than the more frequent fire occurrences. Frequent fires in these forests promoted a grassy understorey, and there appeared to be a positive feedback of fire frequency on nutrient losses, because the fine fuel consumption through fire was higher in the grassy understorey than in previously less frequently burned understoreys. A comparison between estimates of ecosystem nutrient inputs and fire-related losses of N, P, Ca, and K associated with burning regimes representing 7, 3, and 1 fire per decade showed that the frequent recurrence of fire will lead to a long-term depletion of P, Ca, and K, and probably also N. Owing to the relatively low fine fuel accumulation following fire, which reached a maximum of ca. 12 t ha^{-1} after ca. 10 years, prescribed fires can be carried out at longer intervals such as once per decade in a safe manner to conserve nutrients on site.

Keywords: Nutrient losses; Fire frequency; Dry dipterocarp forest; Fuel loads

1. Introduction

Fire is an important factor shaping many forest ecosystems around the world (Chandler et al., 1983; Brown, 2000). With the increase in human population, anthropogenic fire regimes have replaced natural fire regimes in many regions. If the frequency of fire increases, nutrient losses and shorter periods for recovery may lead to reduction in site productivity and degradation of the ecosystem. Conversely, long interval between fires or fire exclusion may result in structural and compositional changes of ecosystems and possibly an increased risk of high-intensity wildfires (Mueller-Dombois and Goldammer, 1990; DeBano et al., 1998). With regard to nutrient dynamics, nutrients can increase or decrease in response to fire, depending on the nature of each element, the burning conditions and weather conditions after burning (Raison et al., 1985a). This raises the question of how ecosystem nutrient pools are maintained and balanced in relation to different fire regimes over long periods of time. These processes are poorly understood and therefore models to predict the effects of fires on ecosystem nutrient cycles do not exist in most cases.

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Fire influences both aboveground and belowground ecosystem nutrient cycles and processes by burning some of the vegetation layer, litter and duff, and thereby losing some nutrients held in these ecosystem compartments (Raison, 1979; DeBano et al., 1998; Neary et al., 1999). The magnitude of nutrient losses during and immediately after burning is dependent upon the interaction of fuel consumption, fire behaviour, microclimate, vegetation composition and structure, fire severity, fuel moisture content and fuel compactness (Raison, 1979; Macadam, 1989; Kauffman et al., 1994; Neary et al., 1999). Owing to the variations in chemical properties of different fuel types, there may be positive or negative feedbacks related to fire-induced vegetation changes; e.g. nutrient losses will increase disproportionally if frequent fire leads to vegetation with higher nutrient concentrations.

During burning, nutrients can be lost to the atmosphere through volatilisation (gaseous form) and particulate transport (solid form). While particulates may be re-deposited on the burned site or in adjacent areas, either as dry fallout or rainfall, non-particulate losses through volatilisation are more likely to represent permanent losses from the site (Raison et al., 1985a). After the fire, nutrients are deposited on the soil surface in ash, which may then be lost by wind or water erosion or leached into the soil. Nutrients in the soil may also be lost through erosion or through leaching beyond the rooting zone of vegetation. Nutrients also remain in the unburned surface debris and in the soil (Raison et al., 1985a,b; Kauffman et al., 1993; Carter and Foster, 2004). Of all nutrient loss pathways associated with fire, the atmospheric losses appear to account for the largest portion (Raison et al., 1985a). Therefore, to estimate ecosystem nutrient losses associated with fire, it is particularly important to account for the losses to the atmosphere.

The effects of fire on nutrient dynamics have been extensively investigated in both natural and plantation forests in boreal and temperate regions, as well as for slash-and-burn agriculture in tropical forest (Hough, 1981a; Feller, 1988; DeBano, 1990; Kauffman et al., 1993; Kauffman et al., 1994; Hughes et al., 2000; Carter and Foster, 2004; Geldenhuys and Van Wilgen, 2004; Morley et al., 2004). Losses of C, N, and S can be relatively large due to their low volatilisation temperatures, whereas high volatilisation temperatures for P and base cations result in their accumulation in ash (Kauffman et al., 1994). For example, Hough (1981b) found that the correlation between fuel consumption and element loss was high for C, N, P, S and Mg, and weaker but still significant for K, Ca and Mn.

Thailand's dry dipterocarp forests (DDF) are fire-dependent ecosystems (Sabhasri et al., 1968; Kutintara, 1975) and frequent, often annual, low-intensity fires of human origin, are common in the DDF throughout Thailand (Akaakara, 2000). Fires are commonly ignited to facilitate land clearing, hunting and gathering of non-timber forest products etc. Burning usually occurs during the dry season (January to April) after the deciduous overstorey has shed its leaves and the grasses and other understorey vegetation have desiccated. Fine fuel loads in DDF range from 5 to 10 Mg ha^{-1} (Goldammer, 1991) and contain substantial amounts of nutrients, in particular in leave litter (Sahunalu et al., 1984). However, some of Thailand's DDFs are in national parks and wildlife sanctuaries, where fire is commonly suppressed or excluded. In addition, public concern over air quality has led to an increase in fire prevention and suppression programs in all forests including DDFs. Natural fire regimes in DDF have thus been highly modified by human activity, possibly leading to both, too frequent and too infrequent fires in different parts of the landscape.

While frequent burning may deplete nutrient pools and reduce productivity, infrequent burning or fire exclusion increases the risk of high-intensity wildfire and promotes the gradual replacement of the DDF ecosystem by a more aggressive, less fire-tolerant, and often less desirable ecosystem. An appropriate burning frequency is necessary to maintain species composition and ecological functions in the DDF. However, to date, no attempt has been made to develop and apply appropriate burning practices or to develop a knowledge base to develop such practices. In addition, aboveground nutrient dynamics in DDF in relation to past burning regimes and hence different fine fuel loads and types have not been investigated in Thailand. In this paper, we quantified aboveground nutrient pools and losses during and after prescribed fires applied to plots that have experienced in the past 10 years different fire frequencies in DDF at Huay Kha Khaeng Wildlife Sanctuary (HKK), Thailand. Specifically, our hypotheses were:

1. Fire intensity and associated nutrient losses during prescribed burning increase with the time since the last fire.
2. Relative nutrient losses from fine fuels are influenced by the type of fine fuel. Therefore there may be interactions between the fire frequency and the percent of nutrients lost from fine fuels, if the past fire frequency influences vegetation composition.
3. The short- to medium-term post-fire accumulation of fine fuel mass and nutrients decreases with time. Therefore, over the same time, frequent fires lead to higher nutrient losses than rare fires, even if the latter are of higher intensity.

Addressing these hypotheses, we aimed to determine an interval length between fires that would provide a compromise between the aim to maintain low levels of fine fuels that will not support high severity fires and potential nutrient losses associated with burning.

2. Material and methods

2.1. Study area

The study was conducted in the HKK, located approximately 350 km northwest of Bangkok in Thailand. The study site was located in DDF, in the northeast region of the sanctuary (Fig. 1). The region has a tropical monsoonal climate with 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 mean relative air humidity is 89.1%, which varies from 79% in April, to 93% in September (Forest Fire Research Center, 2006). The elevation of the study area

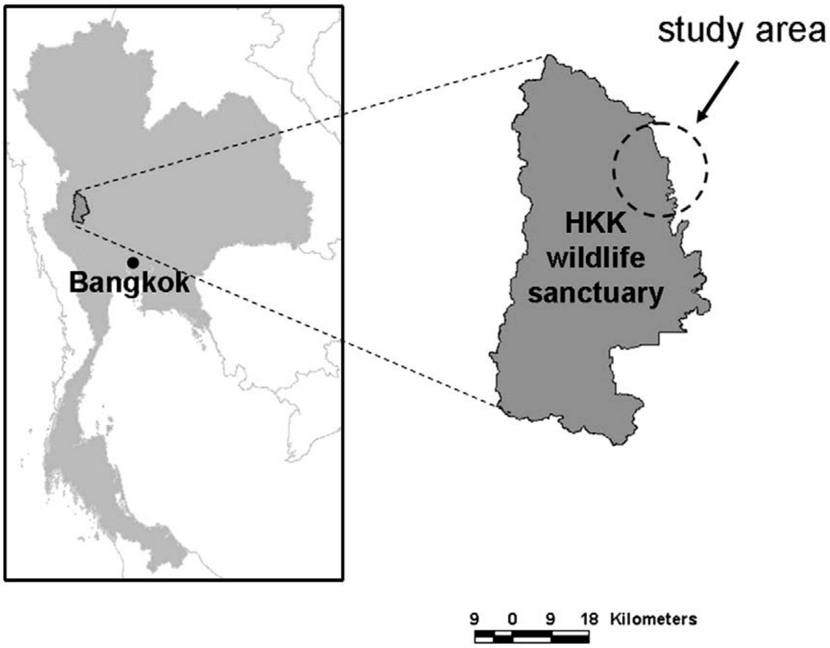

Fig. 1. Location of the Huay Kha Khaeng Wildlife Sanctuary (HKK) in Thailand.

ranges from 300–400 m a.s.l. The DDF is dominated by the deciduous tree species belonging to the Dipterocarpaceae, such as *Shorea obtusa*, *S. siamensis*, *Dipterocarpus tuberculatus*, and to the Leguminosae, such as *Xylia kerrii* and *Sindora siamensis.* The understorey consists mainly of a grass layer dominated by *Heteropogon contortus* and *Imperata cylindrica* as well as other shrubs, herbs, and saplings and seedlings of overstorey tree species (Forest Research Center, 1997).

2.2. Fire history reconstruction

The past burning regime (burning history) was reconstructed for the study area by mapping burned areas using fire reports from 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, 4 different burning histories were identified. These included fire frequencies of 7, 2, 1 and 0 fires over the past 10 years, which are subsequently referred to as frequent (FB), infrequent (IB), rare (RB) and unburned (CB) respectively. The times since last fire in relation to these burning regimes were 1, 3, 7, and 10 years for FB, IB, RB, and CB respectively.

For experimental purposes, three replicate plots were established for each burning regime. It was not possible to replicate patches of the same fire frequency and time since last fire in the landscape, so that treatments were not interspersed in space. Therefore the plots represent pseudoreplications (Hurlbert, 1984) of the same fire event and history. However, within each treatment, plots were approximately 300–500 m apart. Within the mapped areas of different fire frequencies, all plots were selected to represent the same geologic parent material, soil unit, and forest type. They were also located at similar elevation and topography.

2.3. Experimental burning

Prior to burning, 3 experimental plots of 50 × 50 m, containing an inner 30 × 30 m plot for measurements were set up in each treatment. Fuel breaks were set up outside the 50 × 50 m plot and forest fire control equipment was prepared by the Forest Fire Research Center staff to prevent an accidental forest fire. With the exception of the unburned area (CB), experimental burning was carried out in nine plots during the period from 28th December 2004 to 9th January 2005, which was earlier than the normal peak of the dry season. However, the unusually dry conditions during the year 2004 resulted in an earlier beginning of the dry season. The total rainfall in the year 2004 was only 996.4 mm compared to 1332.9 and 1453.7 mm for the years 2003 and 2005 respectively (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 1 and 6 p.m., when air humidity was lowest, using a three-strip (3 strips of ca. 16 m width) burning technique. To assure an even fire front, four people ignited the fire simultaneously in each strip.

Prior to burning, one set of 2 m tall iron stakes with heights marked at 0.5 m intervals were placed at 5 m distance and perpendicular to the fire front to estimate the rate of fire spread and flame height (Fig. 2). The rate of fire spread was estimated as the average time of fire progress between iron stakes as described by Rothermel and Deeming (1980). Flame height was recorded by taking photographs. Fire temperature at 20 and 50 cm height above ground was measured at 5 locations for each strip using a Spot Infrared Thermometer (MINOLTA TA-510). Ambient soil temperature of four different depths (1, 2, 5, and 10 cm below the surface) was recorded for 15 points per plot (5 points per strip) using thermometers (TESTO-926) 5 min

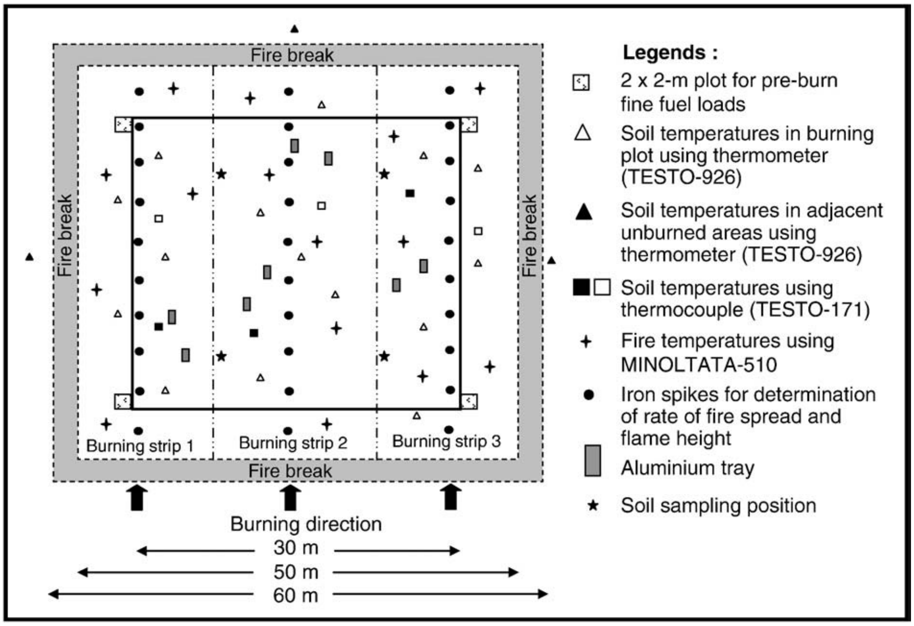

Fig. 2. Plot layout with burning patterns, and locations for fuel and residue determinations and the positions of fire and soil temperature measurements.

after the fire front had passed. In addition, soil temperatures were also measured at similar depths in 3 unburned areas adjacent to each treatment plot. Maximum soil temperature, duration of soil heating, as well as soil temperatures of three different layers (soil surface, 2 and 5 cm beneath the soil) were continuously recorded at 6 points (2 points per strip) using thermocouples (TESTO-171). Relevant meteorological data such as wind speed, relative air humidity and air temperature were recorded during the burning experiment using a portable Kestrel Pocket Weather Tracker (Nielsen-Kellerman, Boothwyn).

For the purpose of this study, “fine fuel” was defined as all understorey vegetation, including shrubs, herbs, grass, saplings and seedlings which their dbh lower than 4.5 cm, as well as leaf litter and small twigs. Approximately 3 h prior to burning, four representative 2 × 2 m quadrates were established systematically at the corner of the plot to determine available fine fuel loads (Fig. 2). These were harvested and weighed separately for each fine fuel type. All live understorey plants were clipped at ground level, whereas leaf litter was carefully removed by hand to avoid contamination with mineral soil. Sub-samples of each fuel type were brought back to the laboratory to determine pre-burning fuel moisture content, fuel loads and nutrient concentrations.

The remaining harvested fine fuel was further grouped into two categories, i.e. leaf litter and understorey. For each litter type, known quantities were placed on four 52 × 38 × 2.5 cm aluminium trays, respectively. The amount of litter or understorey material placed on the trays was equivalent to the average quantities found in the field for an area of 52 × 38 cm. Two hours prior to burning, these trays were then placed carefully on the ground so that the material on the tray formed a continuous layer with the fuel surrounding the tray.

Immediately after the fire had passed, each tray was covered with aluminium lids to prevent ash loss caused by the wind. All post-burning residues in aluminium trays were carefully collected, sorted into fine ash, charred material (partly burned or charcoal), as well as unburned fractions and weighed. Residue samples were sieved (0.5 mm) to separate ash from the other residues. Subsequently charred and unburned material was visually separated. These fractions were brought back to the laboratory to determine mass and element concentration.

Soil nutrient contents were determined for the 0–5 cm layer both prior to and immediately after burning. For the soil samples which were sampled immediately after the fire, ash was removed from the soil surface before collecting the soil (Table 1).

2.4. Laboratory analysis

To determine fuel weights, plant and litter samples were oven-dried at 105 °C for 48 h. For chemical analysis, fine fuel

Table 1
Soil nutrient content in 0–5 cm, before and immediately after burning of different burning regimes: frequently burned (FB), infrequently burned (IB), rarely burned (RB), and unburned (CB)

Burning regime	Total C (t ha^{-1})		Total N (kg ha^{-1})		Available P (kg ha^{-1})	
	Pre	Post	Pre	Post	Pre	Post
FB	6.9^{a}	7.6^{a}	400.1^{a}	429.0^{aA}	3.25^{a}	4.24^{a}
	(0.95)	(0.91)	(25.30)	(26.4)	(0.35)	(0.88)
IB	9.5^{a}	9.7^{a}	464.1^{a}	462.9^{a}	20.59^{b}	25.94^{b}
	(0.67)	(0.66)	(24.48)	(27.0)	(3.61)	(4.37)
RB	9.6^{a}	9.8^{a}	492.2^{a}	486.0^{a}	13.96^{b}	16.28^{b}
	(0.87)	(0.89)	(36.79)	(37.48)	(3.75)	(3.82)
CB	9.1^{a}	n.a.	478.5^{a}	n.a.	3.89^{a}	n.a.
	(0.70)		(30.71)		(0.77)	

Standard errors are given in parentheses.
Burning regimes carrying the same lower-case letters were not significantly different at $P < 0.05$. Burning regimes carrying the same capital letters were not significantly different at $P < 0.05$.

Table 2
Pre-burning fuel loads and fuel consumption at frequently burned (FB), infrequently burned (IB), rarely burned (RB), and unburned (CB) sites

Fuel category	Burning regime			
	FB	IB	RB	CB
Saplings (kg ha^{-1})	92.6^{a}	1312.8^{b}	$2282.5^{b,c}$	2974.7^{c}
	(72.0)	(466.6)	(709.3)	(566.7)
Seedlings (kg ha^{-1})	214.2^{a}	238.2^{a}	154.3^{a}	381.7^{a}
	(49.7)	(96.8)	(69.1)	(87.3)
Shrubs (kg ha^{-1})	21.1^{a}	204.9^{b}	90.9^{b}	289.8^{b}
	(13.6)	(66.4)	(30.7)	(129.8)
Herbs (kg ha^{-1})	173.7^{a}	147.1^{a}	564.3^{a}	71.3^{b}
	(47.4)	(34.7)	(279.3)	(48.9)
Grass (kg ha^{-1})	947.2^{a}	323.3^{b}	236.0^{b}	85.9^{c}
	(135.2)	(54.3)	(61.3)	(11.5)
Litter (kg ha^{-1})	3622.3^{a}	6689.4^{b}	$8237.8^{b,c}$	8442.8^{c}
	(317.0)	(631.4)	(699.5)	(569.7)
Total fuel loading (t ha^{-1})	5.1^{a}	8.9^{b}	11.6^{c}	12.2^{c}
	(0.4)	(1.0)	(0.9)	(0.9)
Fuel consumption (%)	84	65	70	n.a.
Litter	87	78	84	
Understorey	81	51	57	

Standard errors are given in parentheses.
Different letters (a, b, c) indicate significant differences between burning regimes for a given fuel category; ANOVA, $P<0.05$, followed by Duncan's multiple range test.

and post-burning residue samples were oven-dried at 60 °C for 24 h. Samples were finely ground and analysed for total N, P, K, Ca, Mg, S, C and Mn. Total C and N were determined by dry combustion using an automated C/N-analyzer (Truspec CN, LECO). The other elements were determined by Inductively Coupled Plasma spectrometer (ICP) following a wet digestion (pressurized digestion with HNO_3) of the organic material. For digestion 100–200 mg of the sample was mixed with 2 ml of 65% HNO_3 in Teflon vessels, which were subsequently placed into an aluminium chamber. These chambers were then placed in the oven at 190 °C overnight. The digested solution was filtered, and the residue left over on the filter paper was further combusted at 850 °C for 4 h in a furnace to determine silica mass.

2.5. Calculations and statistics

The transfer of elements to the atmosphere during burning was calculated as the difference between the quantities of elements initially contained in the litter and undergrowth (pre-burned) and the quantities recovered in the post-burned residues. Analysis of variance (ANOVA) followed by Duncan's multiple range test were used to test for significant differences in nutrient concentrations and pools among different burning regimes. In addition, paired-sample *T*-tests were used to ascertain the effect of burning on nutrient losses within each burning regime. Relationships between nutrient concentrations, pools and losses with selected fire behaviour parameters, and soil temperature were investigated using Pearson's correlation coefficient. All statistical computations were carried out using SPSS® 13.0 for Windows (SPSS Inc., 2005).

3. Results

3.1. Pre-burning fine fuel loads and post-burning residues

Total fuel loads differed significantly between the sites characterised by four different fire regimes. The total fuel loads were similarly high in the rarely burned (RB) (11.6 t ha^{-1}) and control (CB) (12.2 t ha^{-1}) sites, whereas they were substantially lower at the infrequently (IB) and frequently burned (FB) sites, reaching 8.9 and 5.1 t ha^{-1} respectively (Table 2). The sites with different burning histories differed also in the composition of fine fuels. At frequently burned sites, grass contributed 947 kg ha^{-1} to the fine fuel load, while it amounted to only 236 and

Table 3
Element concentrations in each fine fuel type in pre-burning samples

Fuel type	Element concentration							
	C (mg g^{-1})	N (mg g^{-1})	Ca (mg g^{-1})	K (mg g^{-1})	Mg (mg g^{-1})	Mn (mg g^{-1})	P (mg g^{-1})	S (mg g^{-1})
Grass	46.6^{a}	0.4^{a}	2.5^{a}	13.2^{c}	1.3^{a}	0.1^{a}	1.0^{a}	0.4^{a}
	(0.2)	(0.0)	(0.2)	(0.7)	(0.0)	(0.0)	(0.1)	(0.0)
Herbs	46.8^{a}	0.8^{cd}	8.0^{b}	11.5^{c}	2.6^{b}	0.1^{a}	1.3^{a}	0.7^{b}
	(0.2)	(0.1)	(0.6)	(1.0)	(0.1)	(0.0)	(0.2)	(0.1)
Litter	48.3^{bc}	0.6^{bc}	13.1^{d}	4.8^{a}	2.7^{b}	0.3^{b}	0.9^{a}	0.6^{b}
	(0.6)	(0.0)	(1.0)	(0.5)	(0.2)	(0.0)	(0.2)	(0.0)
Saplings	47.0^{ab}	0.6^{ab}	10.7^{c}	7.7^{b}	2.3^{b}	0.1^{a}	1.0^{a}	0.6^{b}
	(0.4)	(0.0)	(0.8)	(0.8)	(0.3)	(0.0)	(0.2)	(0.1)
Seedlings	47.9^{abc}	0.7^{bc}	10.1^{c}	6.1^{ab}	2.4^{b}	0.1^{a}	1.2^{a}	0.7^{b}
	(0.5)	(0.1)	(0.9)	(0.9)	(0.2)	(0.0)	(0.2)	(0.0)
Shrubs	49.0^{c}	0.9^{d}	7.3^{b}	6.8^{ab}	1.6^{a}	0.1^{a}	0.8^{a}	0.6^{ab}
	(0.4)	(0.1)	(0.5)	(1.3)	(0.2)	(0.0)	(0.1)	(0.1)
df	5	5	5	5	5	5	5	5
F	5.198	9.744	26.838	13.028	10.502	10.346	1.079	2.686
P-value	0.001	0.000	0.000	0.000	0.000	0.000	0.384	0.032

Standard errors are given in parentheses.
Different letters (a, b, c) within columns indicate significant differences between fuel types for a given element; ANOVA, $P<0.05$, followed by Duncan's multiple range test.

Table 4
Pre-burning nutrient pools in fine fuels and losses of each element in sites of different burning regimes: frequently burned (FB), infrequently burned (IB), and rarely burned (RB)

Element	Burning regimes						Average losses (%)
	FB		IB		RB		
	Pools (kg ha^{-1})	Losses (%)	Pools (kg ha^{-1})	Losses (%)	Pools (kg ha^{-1})	Losses (%)	
C	2388.7^{A}	90^{b}	4271.5^{B}	70^{a}	5298.9^{C}	78^{a}	79.3
N	29.1^{A}	88^{b}	52.4^{B}	63^{a}	70.0^{C}	75^{a}	75.3
S	3.0^{A}	63^{b}	6.2^{B}	48^{a}	6.7^{B}	54^{a}	55.0
K	40.6^{A}	47^{c}	53.3^{B}	36^{b}	57.8^{B}	20^{a}	34.3
P	2.5^{A}	36^{b}	13.0^{B}	24^{a}	12.6^{B}	28^{ab}	29.3
Mg	11.7^{A}	39^{b}	26.5^{B}	21^{a}	30.6^{B}	22^{a}	27.3
Mn	0.8^{A}	24^{ab}	2.8^{B}	19^{a}	3.9^{C}	33^{b}	25.3
Ca	49.6^{A}	28^{a}	135.6^{B}	18^{a}	121.0^{B}	16^{a}	20.7

Different capital letters within rows denote significant differences in nutrient pools between burning regimes. Different lower-case letters within rows denote significant differences in percent element loss between burning regimes (ANOVA, $P < 0.05$, followed by Duncan's multiple range test).

86 kg ha^{-1} in RB and CB plots, respectively. The contribution of understorey vegetation to the total fine fuel load was significantly lower in the frequently burned sites than in all other treatments (IB, RB and CB). In quantitative terms, leaf litter was the most important fine fuel in these dry dipterocarp forests, comprising more than 70% of the total mass. In the prescribed fire, approximately 75–80% of leaf litter was combusted, while only 30% of understorey vegetation was consumed. The relative fuel consumption was significantly higher at FB (84%), than at RB (70%) and IB (65%) sites (Table 2).

3.2. Pre-burning nutrient pools in fine fuel

Element concentrations in fine fuel varied with fuel type (Table 3), but within each fuel type there were no differences attributable to past burning regimes (data not shown). The nutrient pools in fine fuel increased for most elements as the fire-free interval increased, however, in many cases the increase occurred only between FB and IB and not from IB to RB. The total aboveground N pool increased significantly from 29 kg ha^{-1} at the FB site to 52 and 70 kg ha^{-1} in IB and RB sites, respectively. The C pool increased similarly from 2.4 t ha^{-1} in FB to 4.3 and 5.3 t ha^{-1} in the IB and RB sites, respectively. The pools of K increased in the same way, although the increase with decreasing fire frequency was less pronounced (Table 4).

Owing to the high amount of leaf litter in relation to other types of fine fuel, the majority of nutrients in fine fuel were stored in litter (~60–86%) followed by saplings, except at the frequently burned site (Fig. 3). At the frequently burned site, a substantial proportion of nutrients was contained in the grass, which was here more dominant. The higher degree of combustion of understorey vegetation including the grass at this site indicates that the shift in vegetation also influences the susceptibility of nutrient loss through fire. Seedlings, shrubs, and herbs, were only of minor importance as nutrient stores.

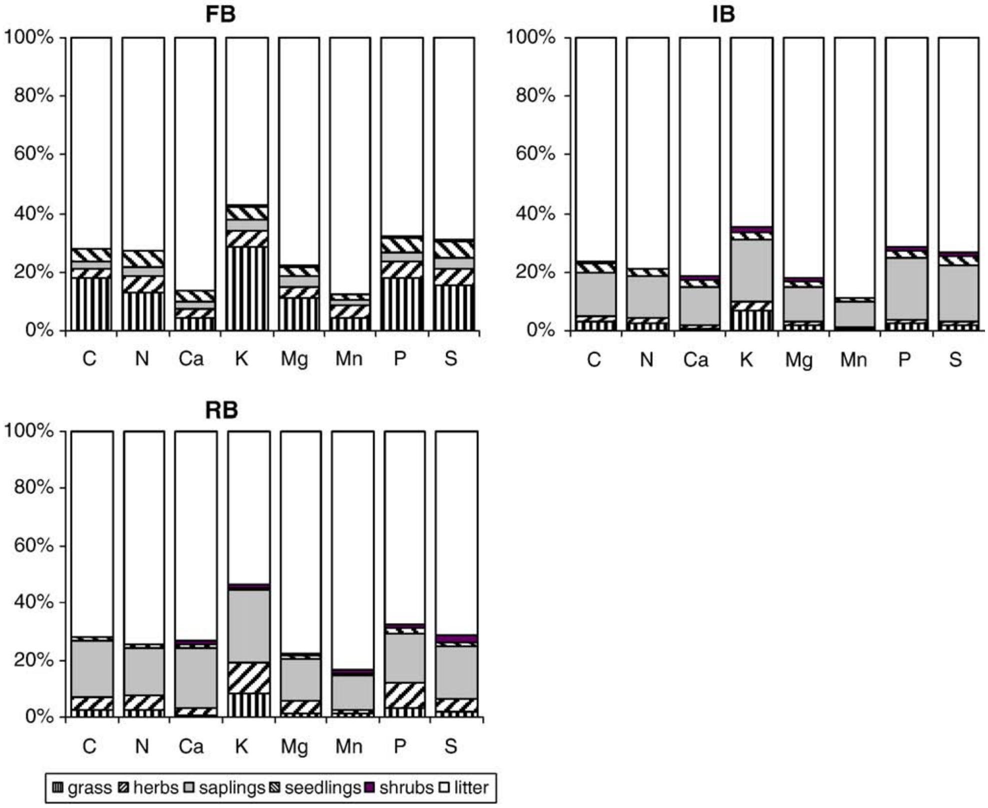

Fig. 3. The distribution of nutrient pools across different types of fine fuel in the three burning regimes: frequently burned (FB), infrequently burned (IB), and rarely burned (RB).

3.3. Fire intensity, fire and soil temperature during prescribed burning

Fuel moisture content of each fine fuel type at 3 h before burning was lowest for leaf litter (~15%), followed by grass (~22%), shrubs (~45%), herbs (~51%), saplings (~85%), and it was highest for seedlings (~93%). Fire temperatures increased significantly ($P<0.01$) with the length of the fire-free interval of the site (Table 5). Fire behaviour descriptors such as the rate of spread, flame height, and fireline intensity were not significantly different between past burning regimes, although they tended to be highest at IB plots. Also maximum soil temperatures at ground level, and at 2 and 5 cm soil depths were not significantly different between past burning regimes and never exceeded 400 °C. The duration of heating >60 °C at ground level was obviously the longest ($P<0.05$) for the RB site (~14 min), followed by the IB site (~12 min), and the FB site (~8 min) (Table 6). However, the duration of heating above any given critical temperature threshold at 2 and 5 cm soil depths were generally less than 1 min.

3.4. Nutrients retained in post-burning fine fuel residues

To characterise the residues following burning, the initial classification of fine fuel types needed to be expanded. Residues were further classified into ash, charred material and unburned material. The element concentrations in residues differed between sites of different burning regimes. Concentrations of most nutrients in the ash and charred material, in particular of N, Mn, and P, were significantly lower at FB than at less frequently burned sites (IB and RB). In contrast, K concentrations in charred material were significantly lower at less frequently than at frequently burned sites.

Regardless of the origin of fuel type and burning regime, C and N contents in ash were significantly lower than in the other residue types (Table 7). The concentrations of Ca, K, Mg, Mn, P and S dramatically increased in the ash, where they were 2–12 times higher than in charred and unburned material (data not shown). As a result, the highest content of these elements in the residues was found in ash. Owing to the increase in element concentrations in ash and charred material, nutrients losses were disproportionately low when compared to the percent fuel consumption.

Table 5
Quantitative fire behaviour characteristics, and fire and soil temperatures recorded from experimental fires applied to different burning regimes: frequently burned (FB), infrequently burned (IB), and rarely burned (RB)

Fire behaviour descriptors and maximum fire and soil temperature	Burning regime		
	FB	IB	RB
Rate of spread (m min^{-1})	2.7^{a} (1.0)	2.6^{a} (0.3)	1.3^{b} (0.2)
Flame height (m)	1.2^{a} (0.1)	1.5^{a} (0.7)	1.2^{a} (0.1)
Fireline intensity (kW m^{-1})	361.1^{a} (149.9)	466.8^{a} (61.5)	291.2^{a} (43.1)
Fire temperature at 20-cm aboveground (°C)	423^{a} (20.9)	593^{b} (12.2)	671^{c} (10.6)
Soil temperature at ground level (°C)	329.5^{a} (26.8)	261.2^{a} (30.5)	279.9^{a} (31.0)
Soil temperature at 2-cm belowground (°C)	50.1^{a} (3.9)	52.8^{a} (6.6)	47.2^{a} (1.6)
Soil temperature at 5-cm belowground (°C)	38.7^{a} (1.2)	38.9^{a} (1.3)	38.3^{a} (1.0)

Standard errors are given in parentheses.
Burning regimes carrying the same lower-case letters were not significantly different at $P<0.05$.

Table 6
Average resident time (min) of different heat levels from thermocouple data at different soil locations in each burning regime; frequently burned (FB), infrequently burned (IB), and rarely burned (RB)

Heat levels	Measurement location	Burning regime		
		FB (min)	IB (min)	RB (min)
>60 °C	Ground level	8^{a}	$12^{a,b}$	14^{b}
	2-cm belowground	1^{a}	1^{a}	$<1^{a}$
>80 °C	Ground level	4^{a}	7^{b}	7^{b}
	2-cm belowground	$<1^{a}$	$<1^{a}$	0^{a}
>100 °C	Ground level	3^{a}	5^{b}	5^{b}
	2-cm belowground	0^{a}	$<1^{a}$	0^{a}

Standard errors are given in parentheses.
Burning regimes carrying the same lower-case letters were not significantly different at $P<0.05$.

3.5. Nutrient losses

Burning resulted in a significant reduction in the pools of all nutrients, however, the degree of loss varied between past burning regimes, largely owing to the differences in fuel types that had developed under different past fire frequencies. The most substantial reductions in element pools occurred for C and N, which were on average 79 and 75%, respectively (Table 4). After burning, most of the Ca, K, Mg, Mn, P and S in residues were contained in ash, while most C and N was found in charred and unburned material (Table 7).

The total amounts of nutrients lost through burning increased with the length of the fire-free interval before burning, except for Ca and K. However, with the exception of Mn, the relative loss of elements was always highest at the sites that had undergone frequent burning in the past (Table 4). The magnitude of relative nutrients losses was related to the relative fuel consumption, which increased in the following order: FB>RB>IB. Owing to the dominance of litter in the fine fuel, losses of most nutrients were largely caused by combustion of litter rather than understorey vegetation. Regardless of fuel type and burning regime, the magnitude of element losses in this study followed the order: C>N>S>K>P>Mg>Mn>Ca.

Positive linear correlations between relative fuel consumption and relative element losses were particularly close for C ($r=0.946$, $P<0.01$), N ($r=0.913$, $P<0.01$) and S ($r=0.736$, $P<0.01$) (Table 8). This suggests that percent loss of C, N, and S can be estimated from the percent fuel combustion. Further, we detected positive correlations between fire temperature and element losses, in particularly for C ($r=0.762$, $P<0.01$), N ($r=0.697$, $P<0.01$), S ($r=0.612$, $P<0.01$) and P ($r=0.556$, $P<0.01$). In contrast, fire behaviour descriptors such

Table 7
Percent distribution and quantities (kg ha^{-1}) of elements in post-burning pools in the residue types; ash, charred material, and unburned material for each burning regime: frequently burned (FB), infrequently burned (IB), and rarely burned (RB)

Element	Residue types								
	Ash			Charred material			Unburned material		
	FB	IB	RB	FB	IB	RB	FB	IB	RB
C (%) (kg ha^{-1})	19^{b}(4.3)	5^{a}(7.7)	10^{a}(12.9)	30^{a}(13.2)	28^{a}(8.07)	27^{a}(56.7)	51^{a}(28.3)	67^{a}(233.5)	63^{a}(131.6)
N (%)(kg ha^{-1})	26^{b}(0.1)	9^{a}(0.2)	5^{a}(0.3)	35^{a}(0.3)	40^{a}(1.7)	39^{a}(1.5)	39^{a}(0.3)	52^{a}(2.8)	46^{a}(1.2)
Ca (%) (kg ha^{-1})	76^{b}(3.1)	44^{a}(6.9)	56^{a}(9.7)	14^{a}(0.7)	24^{b}(6.9)	10^{a}(2.8)	10^{a}(0.8)	32^{a}(10.0)	34^{a}(2.0)
K (%)(kg ha^{-1})	75^{c}(1.4)	40^{a}(1.7)	60^{b}(4.1)	17^{ab}(0.6)	22^{b}(1.5)	12^{a}(1.2)	8^{a}(0.4)	38^{b}(3.2)	29^{b}(1.2)
Mg (%)(kg ha^{-1})	77^{b}(0.7)	43^{a}(1.3)	64^{b}(1.8)	15^{a}(0.2)	30^{b}(1.4)	16^{a}(0.9)	8^{a}(0.1)	27^{b}(1.4)	20^{ab}(0.5)
Mn (%)(kg ha^{-1})	81^{b}(0.1)	44^{a}(0.1)	73^{b}(0.2)	15^{a}(0.01)	33^{b}(0.2)	21^{a}(0.1)	4^{a}(0.01)	23^{b}(0.1)	6^{a}(0.02)
P (%)(kg ha^{-1})	73^{b}(0.1)	40^{a}(0.5)	65^{b}(0.9)	15^{a}(0.03)	25^{b}(0.6)	18^{ab}(0.2)	12^{a}(0.04)	35^{b}(0.8)	16^{a}(0.2)
S (%)(kg ha^{-1})	70^{b}(0.1)	38^{a}(0.2)	60^{b}(0.1)	14^{a}(0.02)	24^{b}(0.2)	16^{ab}(0.1)	16^{a}(0.03)	38^{b}(0.3)	24^{ab}(0.1)

Different lower-case letters within rows indicate significant differences in the element proportion between burning regimes (ANOVA followed by Duncan's multiple range test).

as rate of spread, flame height and fireline intensity could not explain the variation in nutrient losses (data not shown).

4. Discussion

4.1. Changes in nutrient pools across burning regimes

Total nutrient pools in fine fuels were influenced by the past burning regime, largely owing to the amount and type of vegetation that had developed since the last fire. This study found an increase of fuel loads with the length of fire-free interval, which is consistent with studies of Fule and Covington (1994), Peterson and Reich (2001), Màrcia et al. (2006), and Govender et al. (2006). In support of the third hypothesis, the accumulation rate of fine fuels declined rapidly so that a steady state was obtained after 10–12 years.

The low saplings and seedlings mass at the frequently burned site is attributable to the fact that frequent fires inhibited successful establishment of tree regeneration. Sukwong (1982) reported that *S. obtusa* seedlings required up to a 7 year fire-free period to escape lethal fire damage. Based on average annual height growth of seedlings in DDF of ca. 40 cm year^{-1} (Himmapan, 2004), and flame heights of 1.2–1.5 m as observed in this study, seedlings may require at least 5–6 years to lift their sensitive bud tissues above the fire and develop into saplings.

The rarely burned sites carried twice the dry mass in fine fuels when compared to the frequently burned sites, and thus contained twice the amount of most elements in fine fuels. While the element concentrations in different fine fuel types were not significantly different between past burning regimes, the proportion of grassy understorey, with relatively low concentrations of most nutrients except K, had increased with the increase in the frequency of past fires. Similarly, Kauffman et al. (1994), who studied the nutrient dynamics along a vegetation gradient in the Brazilian Cerrado, found that K and Ca concentrations in vegetation declined from frequently burning grasslands to infrequently burning "cerrado" forest. Changes in understorey vegetation composition, in particular increase in fire-tolerant species, in relation to different burning frequencies has also been reported by Neumann and Dickmann (2001) and Peterson and Reich (2001).

The low concentrations of nutrients in grass may indicate either reduced nutrient availability or inherent adaptations of grassy vegetation to such conditions. However, the nutrient concentrations measured for grass may not be representative for the entire year, since nutrients may be retranslocated to belowground structures during the dry season (Sahunalu et al., 1984).

4.2. Nutrient losses during prescribed burning

Fire may affect nutrients in many ways: they can be lost through volatilisation and particulate transport, be transformed from organic to inorganic form and deposited as ash, change in

Table 8
Matrix of correlation coefficients between percent total fuel losses and percent total element losses

Correlation	Total fuel	C	N	Ca	K	Mg	Mn	P	S
Total fuel	1								
C	0.946 **	1							
N	0.913 **	0.966 **	1						
Ca	0.435 *	0.440*	0.494 **	1					
K	0.449 *	0.302	0.275	0.573 **	1				
Mg	0.548 **	0.549 **	0.571 **	0.705 **	0.761 **	1			
Mn	0.302	0.437 *	0.498 **	0.709 **	0.318	0.790 **	1		
P	0.445 *	0.427 *	0.441 *	0.557 **	0.740 **	0.812 **	0.626 **	1	
S	0.736 **	0.776 **	0.825 **	0.835 **	0.482 **	0.822 **	0.828 **	0.587 **	1

* Correlation is significant at $P<0.05$.

** Correlation is significant at $P<0.01$.

availability owing to qualitative changes in organic matter, be lost from the site by wind or water erosion, or remain on site in the form of residues, and uncombusted debris (Raison et al., 1985a). The fate of elemental pools during burning in the current study appeared to be influenced by a number of factors: (1) the degree of fuel combustion, which varied among fuel components; (2) the relative distribution of elements within fuel categories; and (3) the volatilisation temperatures of the respective elements and particulate losses during fire, which was similar to the study conducted by Hughes et al. (2000). For example, the low volatilisation temperature of N, the high degree of fuel combustion, and the high concentration of N in readily combusted fuel such as leaf litter resulted in an average loss of 88% of pre-fire N at frequently burned sites, while only 63% of N was lost at infrequently burned sites, where the degree of combustion was lower.

A recent study by Toda et al. (2007) found that aboveground C and N losses owing to burning in DDF in the Nakornrachasima Province, Thailand, in January 2002, were 96% and 94% respectively, which were higher than in our study. These higher relative nutrient losses might have resulted from higher fire intensity and severity, and differences in fuel composition. Unfortunately, no burning environment data (fire intensity, fire and soil temperature) were reported to verify this assumption. Compared to other ecosystems, the percent losses of all elements except N was lower in our study than in the cases reported by Raison et al. (1985b), Kauffman et al. (1993) and Hughes et al. (2000). We attributed this to the burning conditions and vegetation characteristics prior to burning. In the current study, burning took place during the dry season, when most plants have retranslocated a substantial proportion of elements from aboveground parts (leaves and stem) to underground parts (roots and rhizomes) (Rundel and Boonpragob, 1995), resulting in lower nutrient pools to be lost with burning from the understorey vegetation stratum. In addition, fire intensity in their studies was generally higher than in this current study. For example, flame length reported by Kauffman et al. (1993) and Hughes et al. (2000) was 8 to 10 m and 3 to 22 m, respectively, compared to only 1.2 to 1.5 m in the current study.

For most nutrients, the total losses associated with the prescribed burning event, were highest at the sites with the greatest fuel load (RB). However, relative nutrient losses were highest at the frequently burned site, where the relative fuel consumption was also highest. Moreover, the higher amount of grass in FB, which was generally burned more completely compared to other understorey vegetation (pers. observ.), may have contributed to the higher relative losses of nutrients. These results have to be viewed in relation to the frequency of such losses occurring over a given time. For comparative purposes, we assumed three different fire frequency scenarios, with fires occurring almost every year (7 times), every third year (3 times) or only once (after 7 years) over a ten-year period. For these scenarios we assumed further that (a) the amounts of fine fuel before fire equaled those determined in this study or different fuel accumulation periods (Fig. 4), (b) that they contained the same percent of nutrients as determined in this study for frequently, infrequently and rarely burnt sites, and (c) that the percent loss of nutrients was also the same as for fires occurring at these sites. No assumptions have been made about differences in the replacement rate of nutrients through atmospheric deposition, mineral weathering or N fixation for the different burning regimes.

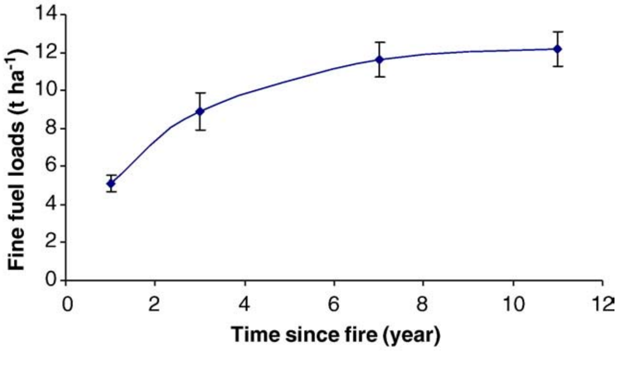

Fig. 4. Fine fuel accumulation with time since last fire in dry dipterocarp forest, Huay Kha Khaeng wildlife sanctuary.

Table 9
Fire-related gross losses of selected elements in a 10 year period of different burning frequencies: frequently burned (FB) — 7 out of 10 years, infrequently burned (IB) — 3 out of 10 years, and rarely burned (RB) — once in 10 years

Burning regime	Gross losses (kg ha^{-1})			
	N	P	K	Ca
FB (7 out of 10)	−179.2	−6.3	−97.3	−132.3
IB (3 out of 10)	−99.3	−9.6	−57.3	−71.7
RB (1 out of 10)	−52.7	−3.5	−11.3	−19.5

Under these assumptions, the gross nutrient loss from frequently burned sites would be several times the loss of rarely burned sites (Table 9). The differences in the magnitude of nutrient losses were most pronounced for Ca, and least for P, possibly pointing to some P conservation mechanisms in plants. While nutrient losses associated with infrequent burning are intermediate between frequent and rare burning for N, K, and Ca, they were highest for P over a 10 year period, which is likely to be related to the higher soil P content at these sites. Rare fires could lead to higher nutrient losses in the longer term than frequent fires, if their intensity was much higher and if the fuels burned in these fires would have a substantially higher nutrient content. This was not the case here. To the contrary, the K and Ca contents in fine fuel were higher at the frequently burned sites than at the rarely burned sites, whereas the differences were negligible for N and P. The K and Ca contents in fine fuels of frequently, infrequently and rarely burned sites were 3.8, 1.5, and 0.9 and 2.8, 3.0, and 1.5 kg t^{-1}, respectively. Despite fuel loads increase with the length of fire-free interval, the fuel accumulation was not proportional fire-free interval (see Fig. 4). Therefore, these simple calculations demonstrate that frequent burning can lead to very high nutrient losses in the medium to long-term, while rare burning does not lead to substantial nutrient losses.

The calculations of gross losses (Table 9) did not consider replacement of nutrients between fires. Nitrogen can be replaced naturally by input of N through atmospheric deposition and from biological N fixation (Raison et al., 1985a). Tokuchi et al. (2003) estimated that atmospheric deposition through rainfall was ca. 10 kg N ha^{-1} $year^{-1}$ in DDF, which is in the range provided for other tropical forests reported by Bruijnzeel (1991). Unfortunately, there is no estimate of dry atmospheric deposition. Further, biological N fixation from trees, such as *Pterocarpus macrocarpus* and *X. kerrii*, and from many understorey species such as *Phyllodium insigne* and *Indigofera* sp. may account for a considerable input of N. Cleveland et al. (1999) estimated N fixation rates (both symbiotic and asymbiotic) between 9.4–34.0 kg ha^{-1} $year^{-1}$ for dry forest woodlands, and ca. 14–36 kg ha^{-1} $year^{-1}$ for tropical evergreen forest. Using a conservative estimate of 20 kg N ha^{-1} $year^{-1}$ (10 from atmospheric deposition, and another 10 from N fixation) (Bruijnzeel, 1991), it would require between approximately 1 to 2.5 years to replace N losses from single fire event, or twice as long if total N inputs were only have as much. However, this estimate assumes that the same level of N fixation occurs regardless of past burning regimes. This may not be the case, if burning frequency influences vegetation composition. Our observations indicate that less N-fixing species occurs at frequently burned sites with a grassy understorey, which would result in a negative feedback.

Losses of P through burning may be more serious since natural replacements of P from rainfall or mineral weathering is very low in tropical forest ecosystems. Inputs through bulk precipitation are commonly in the order of 1 kg ha^{-1} $year^{-1}$ or less (Bruijnzeel, 1991). Therefore, even small absolute losses of P would require a long fire-free period to be replenished. The P losses calculated for the burning regimes investigated in this study (Table 9) may be replaced only in the rarely burned treatments if we assume P inputs of 1 kg ha^{-1} $year^{-1}$. Frequent repeated losses of P may have serious consequences for soils that are already low in P such as the ultisols in this study.

The losses in K and Ca associated with frequent and infrequent burning over a ten-year period are also very likely to exceed replacement rates through atmospheric deposition. The inputs of these elements through mineral weathering in the ultisols at the study sites can be considered negligible (Bruijnzeel, 1991). The geographically closest estimate for Ca and K inputs with bulk precipitation are from Doi Pui near Chiang Mai, Thailand (Naprakob et al., 1976, as cited by Bruijnzeel, 1991). The reported 16 kg Ca ha^{-1} $year^{-1}$ and 12.3 kg K ha^{-1} $year^{-1}$ are probably very high estimates for the HKK sanctuary, which is more remote and receives less rainfall. However, even with these high estimates, it is obvious that frequent (7 out of 10 years) and infrequent burning (3 out of 10 years) would lead to a long-term decline in the ecosystem pools of these elements.

The comparison of aboveground element losses in relation to pre-burning pools of elements in fine fuels and the 15 cm soil layer revealed that C and N losses owing to burning were relatively low. However, these losses may be significant for DDF, where burning occurs frequently. In addition, there were no substantial short term changes of soil nutrient contents owing to burning. In accordance with the findings of Certini (2005), we attribute this to the low-intensity, and low-severity of fires which promoted relatively low soil temperatures. In addition, the high variability within burned sites precludes detection of differences from the pre-burned sites.

This study found that amounts of leaf litter on the ground were high at the end of the dry season when the sites were burned. This is confirmed by a recent study of fine fuel dynamics in DDF conducted by Akaakara et al. (2004), which indicated that fine fuel loads were highest in February (~5.7 t ha^{-1}), when the amount of surface litter was highest. Therefore, burning at the end of the dry season will maximise nutrient losses from leaf litter. Earlier burning, when fuels are less dry and there is less leaf litter on the ground, would be cooler and result in lower nutrient losses. However, timing of prescribed fires should be so that the subsequent accumulation of litter in the same dry season is insufficient to support a second fire.

4.3. Determinants of nutrient losses

The relative element losses, especially C, N, and S increased with increasing percent fuel consumption. This finding is consistent with studies of Feller (1988), Raison et al. (1985a), and Little and Ohmann (1988). In addition, the percent element loss (see Table 4) followed element-specific volatilisation temperatures (Raison et al., 1985a). It followed the order; C>N>S>K>P>Mg>Mn>Ca. However, the temperature required for volatilisation of elements bound in organic compounds may be significantly lower than for the simple inorganic forms (Raison et al., 1985a).

Our results indicate that the loss of C, N, and S from the site can be largely accounted for by non-particulate (volatilisation) losses. Organic matter distillation normally starts in the temperature range of 200–315 °C and volatilisation of N commences at 200 °C (Hungerford et al., 1991; DeBano et al., 1998) and volatilisation of some forms of organic P may occur at only 300 °C (Raison et al., 1985a). In contrast, volatilisation of elements such as Ca, Mg, and Mn, was probably negligible in the current study, because fire temperatures did not reach the required levels of more than 1000 °C. Hence the loss of latter elements and P maybe largely attributed to particulate loss of light, nutrient-rich ash material. To minimise the loss of these elements, prescribed burning should be carried out in late afternoons or early evenings when fuel moisture is low but relative air humidity increases rapidly and the reduction in wind currents may help to reduce convective losses in particulate form.

4.4. Implication for prescribed burning

The accumulation of fine fuel mass following fire was initially very fast (Fig. 4). It increased from ~5 t ha^{-1} 1 year after the fire event to ~9 t ha^{-1} within 3 years, and continued to accumulate for about 6–8 years until reaching a steady state (~11–12 t ha^{-1}) at the period of ca. 10 years after fire. The differences in fuel load between the 1st year after fire and the steady state is only ~6 t ha^{-1}. This is in stark contrast to other forest ecosystems such as a *Eucalyptus diversicolor* forest (McCaw et al., 2002), where forest floor litter and elevated dead fuel continued to accumulate at high rates for long periods. The small differences between maximum fuel loads and those in the year after fire in this study suggest that the potential for fuel reduction and therefore the lowering of fire risk through prescribed burning is limited. At the same time, the maximum amounts of fine fuel are still so low, that they are unlikely to support a high severity fire. The risk of such an event is further reduced through the leaf-less stage of trees in all layers during the dry period, so that crown fires cannot develop. Fire behaviour in the rarely burned plots suggests that fuel loads close to the maximum for this forest type can be safely managed using prescribed fire. However, further investigations should determine whether differences in fuel loads found in this forest have a significant influence on the risk for high-intensity fires under severe weather conditions. If that were not the case, long intervals (>7 years) should be selected for prescribed burning to conserve nutrients.

Fire exclusion beyond the period investigated here, however, may change the composition of the forest in favour of more fire intolerant species (Neumann and Dickmann, 2001; Peterson and Reich, 2001), which may not be desirable for DDF (Sabhasri et al., 1968; Kutintara, 1975).

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