FIRE, SEASONALLY DRY EVERGREEN FOREST AND CONSERVATION, HUAI KHA KHAENG WILDLIFE SANCTUARY, THAILAND

by

Laura Anne Johnson

B.S.F., University of British Columbia, 1986
M.E.Des., University of Calgary, 1998

A Dissertation Submitted in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

in the Department of Geography

FIRE, SEASONALLY DRY EVERGREEN FOREST AND CONSERVATION,
HUAI KHA KHAENG WILDLIFE SANCTUARY, THAILAND

by

Laura Anne Johnson

B.S.F., University of British Columbia, 1986
M.E.Des., University of Calgary, 1998

Supervisory Committee

Dr. Philip Dearden, (Department of Geography)

Supervisor

Dr. K. Olaf Niemann, (Department of Geography)

Departmental Member

Dr. Richard J. Hebda, (School of Environmental Studies)

Outside Member

Dr. Barbara J. Hawkins, (Department of Biology)

Outside Member

Dr. Brad C. Hawkes, (Canadian Forest Service)

Additional Member

External Examiner

Dr. Peter C. Moore, (GHD Australia)

Supervisory Committee

Dr. Philip Dearden

Supervisor

Dr. K. Olaf Niemann

Departmental Member

Dr. Richard J. Hebda

Outside Member

Dr. Barbara J. Hawkins

Outside Member

Dr. Brad C. Hawkes

Additional Member

ABSTRACT

In recent years landscape-scale fires have occurred in mainland Southeast Asia, including important protected areas (PAs). There has been increasing concern that landscape-scale fires are degrading the seasonally dry evergreen forest (SEF) element of the forest mosaic to more open deciduous forest and savanna, with serious implications for biodiversity conservation. Present management approaches, including fire suppression and prescribed burning, have not been effective managing for landscape-scale fire.

Research was undertaken to investigate the occurrence, cause, effect, frequency and predictability of fire in SEF. SEF has the greatest species biodiversity in the forest mosaic and is potentially the most affected by fire, yet little research has been done on fire in SEF in mainland Southeast Asia. Huai Kha Khaeng (HKK) Wildlife Sanctuary in Thailand was selected as the study area. The objectives included: 1) investigate the area of SEF burned in HKK from 1988 to 2002; 2) investigate the conditions for fire in SEF; 3) determine whether the area of SEF in HKK declined as a result of fire; 4) determine the frequency of fire season years between 1984 and 2001 with the conditions for fire spread in SEF; and 5) determine whether there is a significant relationship between pre-fire season drought codes (Keetch-Byram Drought Index (KBDI) and Canadian Drought Code (DC)) and identified SEF fire season years for 1981 to 2003.

Methods included: development of a Landsat fire history with associated interviews and reconnaissance field checks; fieldwork lighting test fires and measuring fuel characteristics; remote sensing change detection work using Landsat imagery; generation of a twenty-one year daily relative humidity minimum record for SEF; and logistic regression of the pre-fire season drought code values with identified SEF ‘fire’ and ‘non-fire’ years.

Results showed: 1. Extensive areas of SEF have burned, but that Landsat imagery was not suitable for detecting fire in intact SEF. 2. SEF burned in years when there were fires burning adjacent to SEF in mid March and the moisture content of the SEF leaf litter fuel was less than 15%. 3. Fifteen percent of SEF in HKK has been either degraded or converted to deciduous forest forms in 12 years. 4. Conditions for fire spread in SEF occurred four times in 17 consecutive years. 5. A significant relationship exists between both the Keetch-Byram Drought Code (KBDI) and Canadian Drought Code (DC) and the SEF fire years.

Implications are that large-scale fires have adversely affected intact SEF in HKK, and that the current damaging situation can be expected to continue. Whereas the extent of burning in intact SEF is not known, the need to manage the situation is immediate. Landscape-scale fires in HKK can be managed by using January 31st drought code values to predict potential large-scale fire years, followed by an aggressive fire suppression campaign in those years. In other years, fires can be allowed to burn without serious threat to the forest mosaic, and should to some extent be encouraged to maintain open deciduous forests and savanna. Additional research is required to determine whether a similar approach can be used for protected areas in other parts of the region.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENTS

Interdisciplinary work requires the input of many people; this research, so much more so because it was done in Thailand, half a world away from Canada and on a shoe-string budget. I have many people to thank. First, my Supervisor Philip Dearden and committee members Richard Hebda, Brad Hawkes, Barbara Hawkins, and Olaf Niemann. Thank you for your direction, flexibility, careful review, and patience. Also, thanks to Dr. Joji Iisaka who guided me in remote sensing change detection work, and Dr. Tuller who provided critical input on climatological aspects of the work.

I met so many people in Thailand who supported the research. Many faculty members from Kasetsart University Faculty of Forestry encouraged the research, including Suree Bhumibhamon, Surachet Chettamart, Kankhajane Chuchip, San Kaitpraneet, Utis Kutintara, Somsak Sukwong, Nipon Tangtham. Officers of the Royal Forest Department who approved and assisted included, Siri Akaakara, Sarayudh Bunyavejchewin, Suwit Ongsomwant, Anak Pattanavibool, Sukan Pungkul, Theerapat Prayurasiddhi, Noppawan Tanakanjana, Ronglarp Sukmasuang, Sompon Tanhan, Schwann Tunhikorn, Thanee Viriyarattanaporn, as well as Surachai Ratanasermpong, and Warapan Wicharn of the National Research Council of Thailand.

The help of many was essential to the fieldwork of Huai Kha Khaeng Wildlife Sanctuary. I was tremendously supported by the following, Mr. Wirot (Chief, HKK), Mr. Surapon (Chief, Fire, HKK), Rattanawat Chaiyarat (Ph.D. researcher), Thanawat Thongtan (Fire research technician), Chatuporn Phanthong (interpreter), and Sansanee Chawanakul (interpreter) as well as Khun Prapod, Yah-tek-ho and all the guards who assisted in the research at the Sanctuary.

Other researchers were generous in sharing technical information and perspective: Patrick Baker, Sripen Durongdei, Gordon Frazer, Chandra Giri, Anja Hoffmann, Nicholas Koher, Cesar Carmona-Moreno, Rey Ofren, Veerachai Tanipat and Horst Weyerhaeuser.

I thank my UVIC friends, Thai friends, Calgary friends, and especially Karen Quinn (advisor) – for believing in me, sharing the good times and the not-so-good, and helping me achieve my goal - spirit intact.

Finally, my deepest thanks to my family. My sister, Elizabeth, spent countless hours helping me develop and refine the figures in this document, effectively adding another dimension to the work. My parents, Ron and Shirley, edited and proofed. Other family members supported and encouraged my efforts.

For my mentors, Karl Weber, Grant Ross, Naoto Kobayashi,
and Ronald Johnson,
with deep appreciation

and for my family,
with love

CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT AND OBJECTIVES

Landscape-scale fires have become a serious concern in mainland Southeast Asia. Fire has always played a part in the region's historic forest mosaic of seasonal evergreen forest[1], closed deciduous forest, and open deciduous forest and savanna. In general, people set fires to clear fields and maintain hunting grounds. Fires historically were confined in size, burning through fields, open deciduous forests and savanna, but mostly stopping at the less flammable forest types, seasonal evergreen and closed deciduous forest, which also made up significant portions of the landscape. However, the situation is now different. Large areas of forest in mainland Southeast Asia have been cleared and the former forest mosaic replaced with extensive areas of flammable open deciduous forest and savanna (Blasco et al., 1996). In dry years, fires burn extensively across the landscape, including protected areas (PAs).

The forest mosaic, and particularly seasonally dry evergreen forest or seasonal evergreen forest (SEF) is important for conservation because it supports a significant proportion of the region's biodiversity, including a number of endangered endemic large mammal species (Lekagul, 1988; Ashton, 1989; Wikramanayake et al., 2001). However, relatively little of the forest mosaic remains; and that which does, is largely in PAs. PAs in the

[1] Synonymous with seasonally dry evergreen forest.

region have not been immune to landscape-scale fires with extensive burning reported in many of the areas. There is concern that the extensive scale and frequency of burning in PAs will degrade the remaining seasonal evergreen and closed deciduous forests to more open deciduous forest and savanna forms, with serious repercussions for biodiversity conservation in the region.[2]

The historical approach to managing fire in PAs and in the region in general has been to try to eliminate fire (Pyne, 1982, 2004). The thinking has been that by preventing fires from occurring, it may be possible to reduce the threat of more extensive landscape-scale burns. However, this approach is increasingly considered to be of limited use in PAs where the goal of management is maintaining the ecological integrity of landscapes and forest mosaics. Ecosystems such as open deciduous forest and savanna require fire in order to be maintained. PAs management must allow for, if not encourage regular burning of these vegetation types (cf., Mutch, 1970; Agee, 1993).

Some researchers (e.g., Stott et al., 1990; Kanjanavanit, 1992; Ofren, 1999) suggest that the way to manage the fire problem in PAs in mainland Southeast Asia is to restore fire in deciduous forest and savanna. The existing fire elimination policy, it is argued, has led to a buildup of fuels in open deciduous forest and savanna, which in turn facilitates the

[2] While the focus of this paper is on biodiversity and conservation-related concerns, there are several other major issues arising from landscape-scale fires in mainland Southeast Asia, including smoke and health related concerns, erosion of soils and loss of agricultural production, and release of C02 gases and global warming.

movement of fire through adjacent closed deciduous and evergreen forests. A regular program of prescribed burning in open deciduous forest and savanna has been recommended.

However, neither the presence of a fire elimination policy nor high fuel loads in open deciduous forest and savanna, explain landscape-scale fire years and the movement of fire through closed deciduous and evergreen forest. Although there has been a fire elimination policy in effect for decades, it has never been effective and fires have continued to burn on a near-annual basis. Further, the movement of fire through closed deciduous and evergreen forest ecosystems depends on the fire environment within these ecosystems, and not on the buildup of flammable fuels in adjacent vegetation types (Pyne et al., 1996). Of concern is the fact that the research focus on fire-prone ecosystems such as open deciduous forest and savanna diverts attention away from other important ecosystems in the mosaic.

The purpose of this dissertation is to investigate the occurrence, cause, effect, frequency, and predictability of fire in seasonal evergreen forests (SEF). The research was conducted in Huai Kha Khaeng Wildlife Sanctuary (HKK), western Thailand, a World Heritage Site and one of the largest areas of remaining forest mosaic in mainland Southeast Asia (Fig. 1.1). The hope is that this research will contribute to the

Figure 1.1 Countries of mainland Southeast Asia. The location of Huai Kha Khaeng Wildlife Sanctuary is shown.

development of a conservation-based fire management strategy for HKK and other PAs in the region.

The objectives of the research are:

- To investigate the extent of SEF burned in HKK from 1988 to 2002;
- To investigate the conditions for fire in SEF, and specifically to identify sources of ignition as well as quantify the primary fuel-related factors that limit the spread of fire;
- To determine whether the area of SEF in HKK declined as a result of fires from 1989 to 2000;
- To determine the frequency of fire season years between 1984 and 2001 with the conditions for fire spread in SEF (i.e., fire in the vicinity of SEF in March and estimated SEF litter moisture contents less than 15% at that time);
- To determine whether there is a significant relationship between January 31st (i.e., pre-fire season) Keetch-Byram Drought Index (KBDI) and Canadian Drought Code (DC) values, and identified SEF fire season years for 1981 to 2003.

1.2 APPROACH

The underlying basis for the study was the need for information on fire in SEF. SEF is by far the richest ecosystem in terms of biodiversity in the forest mosaic (Lekagul, 1988; Ashton, 1989), and potentially the most adversely affected by fire; yet little research has been done on fire in this important forest type.

Four areas of information were required in order to begin to address the problem. First, information was required on the extent of burning in SEF. While there have been reports of fire in SEF in some years, little research has been done to assess the extent to which SEF has burned in Southeast Asia in recent years. Understanding the extent of burning in SEF is important in order to know whether fire in SEF is even a valid concern for PA managers. This preliminary information was obtained by investigating the area of SEF burned in HKK from 1988 to 2002.

The second information requirement was to assess the reasons that SEF have burned. In general, our understanding has been that SEF rarely, if ever, burn because they are too moist, yet little research has been done to determine the conditions for fire in SEF in mainland Southeast Asia. Understanding why SEF burn is important to the development of a fire management approach in the region because it provides a basis for understanding why forests that are not expected to burn have been burning. This information was obtained by investigating the conditions for fire in SEF, and specifically the identification of sources of ignition, as well as quantification of the primary fuel-related factors that limit the spread of fire.

Third, information was sought concerning whether fire in SEF has had a significant negative effect on SEF in recent years. The understanding from other parts of the tropics is that fire has an adverse effect on evergreen forest species, possibly leading to long-term ecosystem change (cf., Slik et al., 2002; Cochrane, 2003). However, little research has been done on this subject in mainland Southeast Asia. Information on the effect of fire on SEF is important to the development of a management approach for fires in PAs in the region since a management intervention in a PA is only justified where there is evidence of significant negative impact to an ecosystem. Information on the effect of fire on SEF was obtained by determining whether the area of SEF in HKK declined as a result of fire from 1989 to 2000.

Finally, information was sought on how frequently the conditions for fire in SEF occur, as well as whether it is possible to predict the years when fire in SEF is likely to occur. The general understanding is that the conditions for fire rarely if ever occur, and that it is not yet possible to predict when SEF are likely to burn. However, some research exists to suggest that the conditions for fire in SEF may be more common than is generally thought (cf., Ofren, 1999), and that it may be possible to predict years that SEF will burn by monitoring soil drought conditions (cf. Nepstad et al., 2004). Information on fire frequency and predictability in SEF is important because it elucidates the practicality of managing the fire problem by targeting fire suppression resources and effort to specific years. Information for this part of the research was obtained by first, determining the frequency of fire season years between 1984 and 2001 with the conditions for fire spread in SEF (i.e., fire in the vicinity of SEF in March and estimated SEF litter moisture contents less than 15% at that time (cf. Chapter 4)); and second, determining whether there is a significant relationship between January 31st (i.e., pre-fire season) drought code vales, and identified SEF fire season years for 1981 to 2003.

1.3 STUDY AREA

The research was based in Thailand because of the significant amount of field research that both Philip Dearden, Ph.D. supervisor, and the researcher had separately in that country. P. Dearden has had an ongoing research programme (Dearden, 1996a) looking at human impacts on the forests of highland Thailand, including work on fragmentation (Pattanavibool & Dearden, 2002), hunting (Tungittiplakorn & Dearden, 2002b), development (Dearden, 1996b) and cash cropping (Tungittiplakorn & Dearden, 2002a). The fire studies were meant to complement these other aspects in order to provide further understanding of human impacts on biodiversity. Also, the researcher had completed her Master's research in Thailand, and spent two years researching watershed instability and possibilities for restoring degraded forests in the northern region (Johnson, 1998).

Huai Kha Khaeng Wildlife Sanctuary (HKK) in western Thailand, which is described in detail in Chapter 2, was selected as the study area for several reasons. First, HKK is a large and important PA in the region. Designated a UNESCO World Heritage Site in 1991, the Sanctuary is approximately 2,800 km^2, and contains significant proportions of deciduous forest, evergreen forest, and savanna (46%, 45%, and 9% respectively).[3] Second, more research on fire has been done in Thailand and particularly in HKK than in other parts of mainland Southeast Asia, providing a critical base of materials from which to build a common understanding of fire in the region (Stott, 1986; Kanjanavanit, 1992; Vibulsresth et al., 1994; Ofren, 1999). Third, resources were available at HKK including a research library, drying ovens, historical weather data, maps, air photos, satellite images, and a basic Geographic Information System (GIS) which might not be found elsewhere, as well as support offered in the form of access to research facilities, vehicles, equipment, support personnel and even helicopter transportation on occasion. Finally, there was an expressed need for fire research in the Sanctuary,[4]

> *Fire is a critical element in shaping the ecology of the area, yet little or no information exists on the fire ecology of the WEFCOM (includes HKK). In support of ecological monitoring efforts, it is essential that a more focused in-depth study of a key factor like fire ecology is undertaken.*
>
> (WEFCOM, 1998, p. 33)

1.4 OUTLINE

The dissertation comprises seven chapters. This chapter introduces the research problem, purpose, objectives, approach and study area. Chapter 2 provides background

---

[3] Estimate is a simplification and regrouping of the RFD 1995 land use classification for HKK.

[4] Huai Kha Khaeng Wildlife Sanctuary is a key element in the Western Ecosystem Forest Complex (WEFCOM), a management unit that contains 17 protected areas (6 Wildlife Sanctuaries, 9 National Parks and 2 proposed National Parks), which adjoin each other.

information on Southeast Asia relating to conservation importance, fire situation, fire management, as well as a similar overview for HKK. Chapter 3 describes an investigation of the extent of burning in SEF in HKK in recent years. Chapter 4 presents fieldwork and experimentation relating to the conditions for fire in SEF in HKK. Chapter 5 presents an assessment of whether fire has had a significant adverse effect on SEF in HKK. Chapter 6 addresses the topic of how commonly the conditions for fire in SEF in HKK can be expected to occur, as well as whether it is possible to predict the occurrence of fire in SEF in HKK using existing drought codes. Finally, Chapter 7 provides a summary of landscape-scale fire in protected areas in mainland Southeast Asia, discusses its implications, and makes recommendations for further research in mainland Southeast Asia, and management activities in HKK.

CHAPTER 2 MAINLAND SOUTHEAST ASIA AND THE STUDY AREA

2.1 INTRODUCTION

Landscape-scale fires or large uncontrolled fires that have been affecting protected areas (PAs) in mainland Southeast Asia are a recent phenomenon in the region. Little is understood about the occurrence, cause or the effects of such widespread burning. Still, management-oriented research solutions are required to try to mitigate potential undesirable long-term effects.

This chapter first, describes the region, the importance of the forest mosaic, the concern with landscape-scale fire, and PA fire management in mainland Southeast Asia. In the second part, there is a description of Huai Kha Khaeng Wildlife Sanctuary (HKK), the fire history, and the current fire situation and management approach for the Sanctuary.

2.2 MAINLAND SOUTHEAST ASIA

2.2.1 Description of the region

Mainland Southeast Asia is located between the latitudes of 5^0 and 28^0 north, longitudes 92^0 and 109^0 east, and includes the countries of Cambodia, Laos, Myanmar, Thailand and Vietnam (Fig. 1.1). The seasonal climate of continental Southeast Asia is the result of monsoon winds. The Southwest Monsoon brings humid air from the Indian Ocean with heavy rainfall from May to October for most of the region, while the Northeast Monsoon comes from continental China and brings cool dry air from December to April (Macleod, 1971 in FFCD, 2005). Effectively, there are three seasons: a warm rainy season; a cool dry season; and a hot dry season. The warm rainy season is from May to October with temperatures from 24^0C to 31^0C. Of the average annual 1450mm of rainfall received in the region, 86% of the region's rainfall occurs at this time. The cool dry season is from November to January with mean daily temperatures from 18^0C to 29^0C and 6% of the rainfall. The hot dry season is from February to April with mean daily temperatures from 21^0C to 32^0C, and 8% of the rainfall (Mekong Travel, p.99) (Fig. 2.1).

There are three major classes of vegetation in the region including, tropical evergreen forests, tropical deciduous forests, and tropical open deciduous forest and savanna.[5] Tropical evergreen forests are closed-canopy broadleaved evergreen forests that retain an evergreen appearance throughout the dry season. This forest type is usually multi-storied and dense with an upper tree layer of 45m height and above. These forests tend to have a dense understory of tree seedlings with a ground cover of leaf litter (Fig.2.2a). Common tree species are of the genera *Dipterocarpus*, *Shorea*, *Parashorea*, *Hopea* and *Anisoptera*.

[5] The classification presented is a modified version of Stibig and Beuchle (2003). One modification is that only three vegetation classes are presented. The other significant modification is the removing of open DDF from the Stibig and Beuchle (2003) classification and placing it in with the savanna class of vegetation. This was done to reflect the fact that grass is a major structural component of this class of vegetation and the primary fuel type.

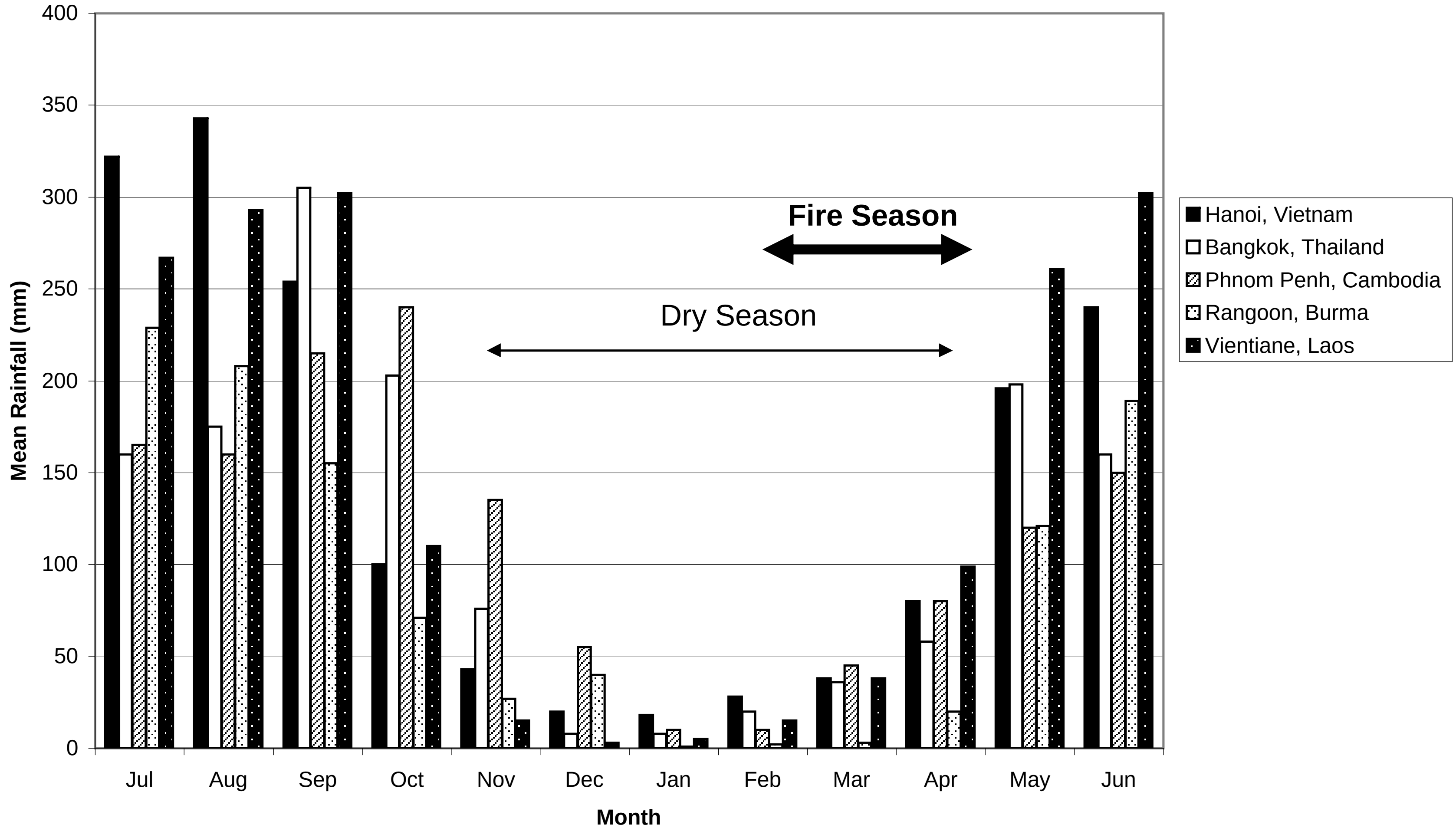


Figure 2.1 Monthly mean rainfall for mainland Southeast Asia. The dry season is from November to April and the fire season is from February to April.

Source for data: Mekong Travel (2004)

Fig. 2.2a Seasonal evergreen forest in HKK in the dry season (2001). The forest floor is shaded and covered with tree seedlings and leaf litter.

Fig.2.2b Closed deciduous forest in HKK in the dry season (2001). The primary fuel is leaf litter.

Fig 2.2c open canopied dry dipterocarp forest in HKK in the dry season (2002). Fires such as this one are common in grass fuels

SEF, which are also known as semi-evergreen and dry evergreen forest (Santisuk, 1988), are tropical evergreen forests that contain a considerable amount of deciduous tree species in the canopy. In mainland Southeast Asia, SEF is the most widespread type of tropical evergreen forest (Stibig & Beuchle, 2003). These forests are usually 25 to 30 meters tall, with closed canopies and lower tree strata of some 5 and 17 meters in height.[6] Frequent species encountered in SEF are *Hopea ferrea*, *Anisoptera costata*, *Dipterocarpus alatus* or *Lagerstroemia spp*. (Rundel & Boonpragob, 1995; Blasco et al., 1996; Stibig & Beuchle, 2003). Previously extensive over large parts of the region, SEF now tend to be restricted, due to the combined effects of deforestaton and fire, to valley and riparian areas where the soils are deep, and to higher (lowland) elevations that receive more rainfall. Another type of forest included in the SEF class is moist mixed deciduous forest. Although these forests have over 50% deciduous trees in the forest canopy, the middle canopy layer is evergreen and as such a fairly complete canopy is maintained through the dry season (Stibig & Beuchle, 2003).

The second major class of vegetation that is present in mainland Southeast Asia is closed deciduous forest. These forests have a closed canopy but are predominately or completely leafless during the dry season with dry leaf litter covering the forest floor (Fig. 2.2b). Two major types of deciduous forests, which belong to the closed deciduous forest class, are mixed deciduous forest (MDF) and dry dipterocarp forest (DDF). MDF

---

[6] SEF of seasonally dry climates are lower in stature than tropical evergreen forests of more humid areas.

have an upper canopy layer that may reach 30 metres or more, with the secondary tree layer ranges between 10 and 20 metres. The proportion of deciduous trees in the forest canopy varies, but is above 50 percent. Trees are typically of the genera *Xylia, Terminalia, Dalbergia, Afzelia, Pterocarpus, Pentacme or Lagerstroemia.* Teak (*Tectona grandis*), a species of commercial importance, may also be present (Rundel & Boonpragob, 1995). The understory of the mixed deciduous forest of successional stands may be dominated by one or more species of bamboo. Closed deciduous forests tend to be found in both hill and valley areas.

Dry dipterocarp or deciduous dipterocarp forest are forests that are lower in stature than mixed deciduous forests and simpler in species.[7] The average number of species per hectare is 25 (Santisuk, 1988), a relatively low number compared to the other forest types in the region, and tree heights range between 8 and 25 metres. The dominant Dipterocarp species are adapted to fire and include *D. tuberculatus, D. inticatus, D. obtusifolius, Shorea obtuse and S. siamensis*. These forests tend to be located on drier sites (Stibig & Beuchle, 2003). Leaf litter covers the forest floor of both closed deciduous forest types.

The third major class of vegetation in the region includes open deciduous forest and savanna. The primary feature differentiating this class is the presence of grass in the understory as a major structural feature (Fig. 2.2c). Fires, mostly human induced, are

---

[7] DDF can be either open or closed canopied forests

frequent events and often result in transition from dense forest to savanna-like formations (Rundel & Boonpragob, 1995; Blasco et al., 1996). For the purpose of this paper, fallow fields are also included in this vegetation class because grass is also a major component of this vegetation type.

DDF_{open} are as described earlier except that the forest canopy is open. The savannas of these areas are dominanted by grasses, with some trees encountered so that sometimes the canopy may be only 10% complete. Trees species associated with the savanna type include *Careya arborea*, *Acacia siamensis*, *Acacia catechu*, *Pterocarpus macrocarpus* and *Ochna integerrima*, all of which are highly fire resistant species. The primary grasses include *Imperata cylindrica*, *Vetiveria zizanioides*, *Panicum repens*, and *Sorghum halepense* (Ongsomwang, 2000). Open deciduous forests and savanna are found at lower elevations on dry shallow soils, or in areas that burn frequently.

One other vegetation class is present in the region, tropical montane evergreen forest. This forest class is found above 1000-1200 meters in mountain areas. Montane forests represent a relatively small area and are not discussed further. A modified version of Stibig et al. (2003) shows the major vegetation classes for the region (Fig. 2.3).

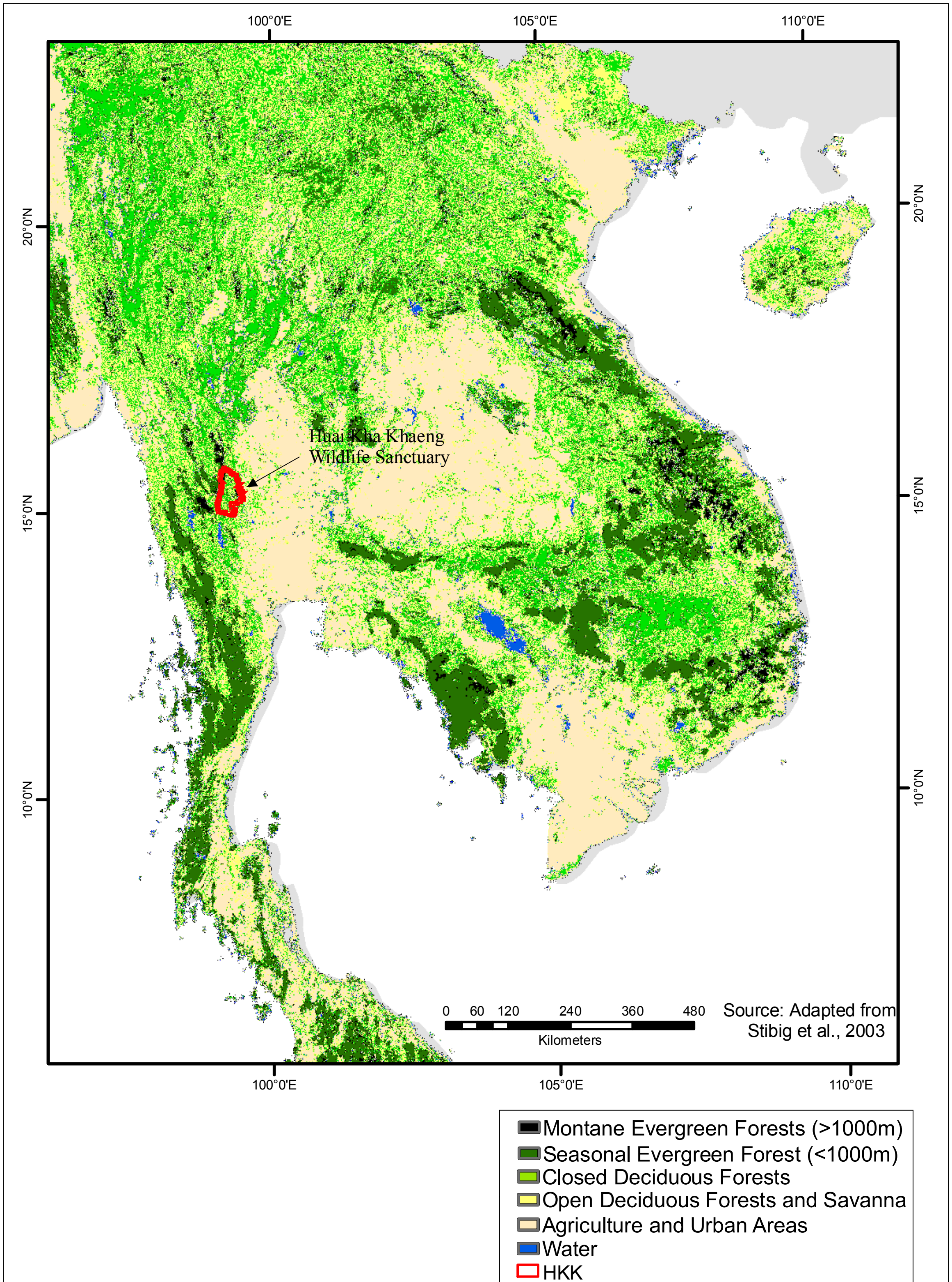


Figure 2.3 Vegetation class distribution of mainland Southeast Asia. Three classes form a mosaic in lowland mountain environments.

2.2.2 Biodiversity, the forest mosaic and seasonal evergreen forest

Within a global context, mainland Southeast Asia is considered to be a hotspot[8] for biodiversity (Briggs, 1996; Myers et al., 2000; Sodhi et al., 2004). There are estimated to be 12,000 vascular plant species in Thailand, more than 8000 vascular plant species in Vietnam, and 12,000-15,000 in Cambodia, Laos PDR and Vietnam combined. As many as 10% of these species may be endemic to each country, as is the case in Vietnam (Davis, 1995). Further, the region is known to support a number of large endangered mammals including the tiger (*Panthera tigris*), Asian elephant (*Elephas maximus*), Eld's deer (*Cervus eldi*), banteng (*Bos javanicus*) and gaur (*Bos gaurus*), some of which are not found anywhere else (Dinerstein et al., 1995; Wikramanayake et al., 2001).

The richest sites of biodiversity are in lowland mountain environments where the three lowland vegetation classes occur near to each other. Here, tropical evergreen forests, deciduous forests and savanna form what is often referred to as a forest or landscape mosaic (Baker, 2001; Bunyavejchewin et al., In Press). The forest mosaic is rich because each class of vegetation has its own species' assemblages, and also because the landscape arrangement facilitates the needs of migratory species.

---

[8] A biodiversity hotspot is a biogeographic region that is both a significant reservoir of biodiversity and is threatened with destruction (Wikipedia, 2006).

Within the context of the forest mosaic, the presence of SEF is particularly important for two reasons. First, SEF is by far the richest in species including endemics of the three main forest types (Ashton, 1989). Second, SEF is the only vegetation class that provides shelter through the long dry season. These forests maintain closed canopy and the associated cool moist interior conditions when other vegetation classes are leafless and exposed during the long hot, dry season (Bunyavejchewin & Baker, 1995). Many migratory species or species with large home ranges are dependent on this ecosystem type for survival. Rabinowitz (1990, p. 99) explains:

> *All carnivores showed a disproportionately low use of DDF compared to other habitat types, and all took refuge in evergreen forest during the driest times of year. Some carnivore species were restricted to evergreen forest alone. The evergreen forest was a crucial component of carnivore home ranges.*

Lekagul (1988, p. XXIII) details:

> *Dry evergreen forest typically occurs mixed with bamboo, mixed deciduous forest, and scattered fire-climax grasslands, so it is difficult to confine species of wildlife to this forest type. However, it is clear that dry evergreen forest has much greater diversity of mammals than does deciduous forest, with fruit bats, monkeys, gibbons, squirrels, flying squirrels, forest rats, and civets being prominent groups in the trees; tapis, Sumatran rhino, gaur, banteng, elephant, sambar, wild pig and other terrestrial forms typically feed in forest clearing or along streams.*

2.2.3 Fire and the conservation concern

Fire has always been present in mainland Southeast Asia (Kealhofer, 2002; Maxwell, 2004). Though lightning occurs, most fires are started by people (Stott, 1990; Kanjanavanit, 1992). People historically burned to clear forests, maintain fields and hunting grounds, as well as for a host of other reasons (Richards, 1952; Wharton, 1966; Kunstadter et al., 1978; Rowell & Moore, 2000; Maxwell, 2004). Fires were lit in fields or clearings during the dry season when they were likely to burn. Most fires were surface fires that burned in grass fuels. Fires were generally limited in extent, in that they stopped on entering ‘dense’, closed deciduous and evergreen forest in the adjacent areas (Wharton, 1966; Ogino, 1976). In this way successional elements of the forest mosaic, open deciduous forests, savanna and fields, were maintained in a larger landscape matrix of closed forest.

The fire situation began to change in the 1980s as a result of deforestation. Thailand was one of the first countries to experience rapid deforestation in the region (Arbhabhirama, 1988; Collins et al., 1991; Potter, 1993). Agricultural consolidation in the lowlands and dam-building in the hills pushed subsistence farmers into even more remote hill country. Industrial logging cleared forest lands, which were soon settled by new migrants. The migrant farmers brought with them traditional lowland farming techniques, which involved annual burning of lands (Thawatchai, 1988; Johnson, 1998). Ultimately, extensive areas of closed deciduous and evergreen forest were converted to more flammable open deciduous forests, savanna and fields, with the deforestation process eventually spreading throughout the region (Stott, 1990; Stott et al., 1990; Ruangpanit, 1995; Blasco et al., 1996).

The migration of peoples to remote forest areas, coupled with the conversion of closed forests to more open deciduous forests, savanna and fields changed the fire regime in mainland Southeast Asia. In a brief period, there were now more people lighting fires over a greater area on an annual basis, as well as larger areas of flammable vegetation to burn (Johnson, 1998). Although the extent of burning in the region has not been established, recent research using satellite sensors and remote sensing provides some insight.[9] Jones (1997) compiled a thirty-day composite of one kilometer resolution AVHRR satellite scenes for the 1992/3 dry season which provides an indication of the number and location of fire ignitions in a single fire season (Fig. 2.4).[10] Further, Carmona-Moreno et al. (2003) documented the global extent and frequency of fires using AVHRR satellite data with a coarse pixel resolution of eight kilometers for 1982 to 1993 (Fig. 2.5). The Carmona-Moreno et al. (2003) work, of which only a part is shown, indicates both the high frequency of burning in some years and the extensive areas of continental Southeast Asia affected by fire.

Landscape-scale fire years occur in dry years when grass fires extend into adjacent closed deciduous and evergreen forests. The largest fire year is considered to be 1998[11] when "unprecedented" levels of burning occurred (Siegert et al., 2001).[12],[13] Landscape-scale

---

[9] Research is ongoing to try to validate various satellite systems and improve estimates of forest cover and of burning (GOFC, 2005).
[10] The 1992-93 dry season was not a landscape-scale fire year for the region.
[11] Warmest year on record until 2005 (R. Hebda, pers com., March 2006).
[12] A burn area estimate for the region could not be obtained.
[13] Rowell and Moore (2000) comment, "Although 1997 (1997/8) was a bad year, some experts believe that it was not unprecedented. In 1982/83, at the end of what was at the time the worst El Nino event in the century, some 2.7 million hectares of tropical forest burned in East Kalimantan."

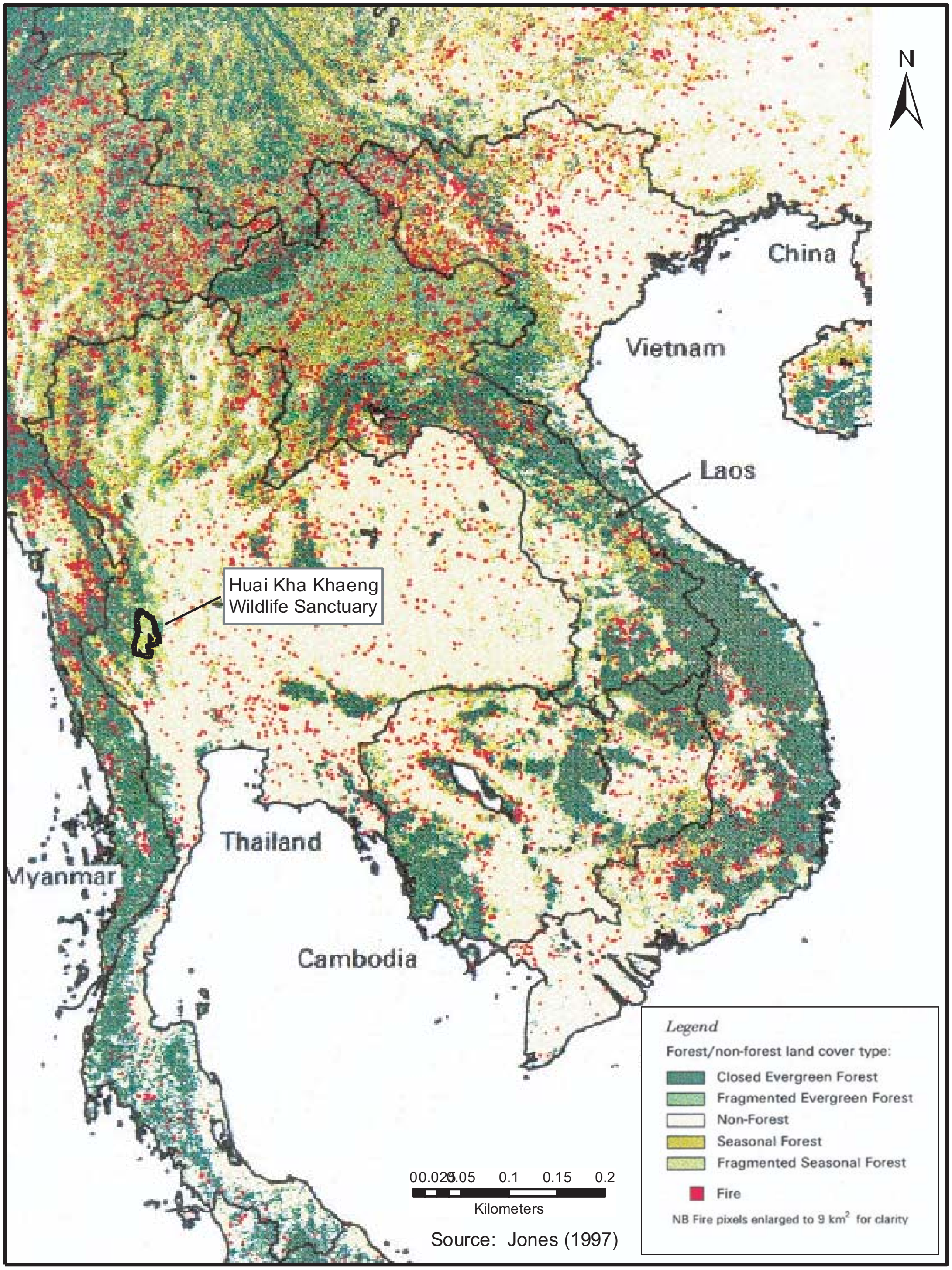


Figure 2.4 Distribution of fire locations in mainland Southeast Asia for the 1992-93 dry season. Numerous independent fires are shown.

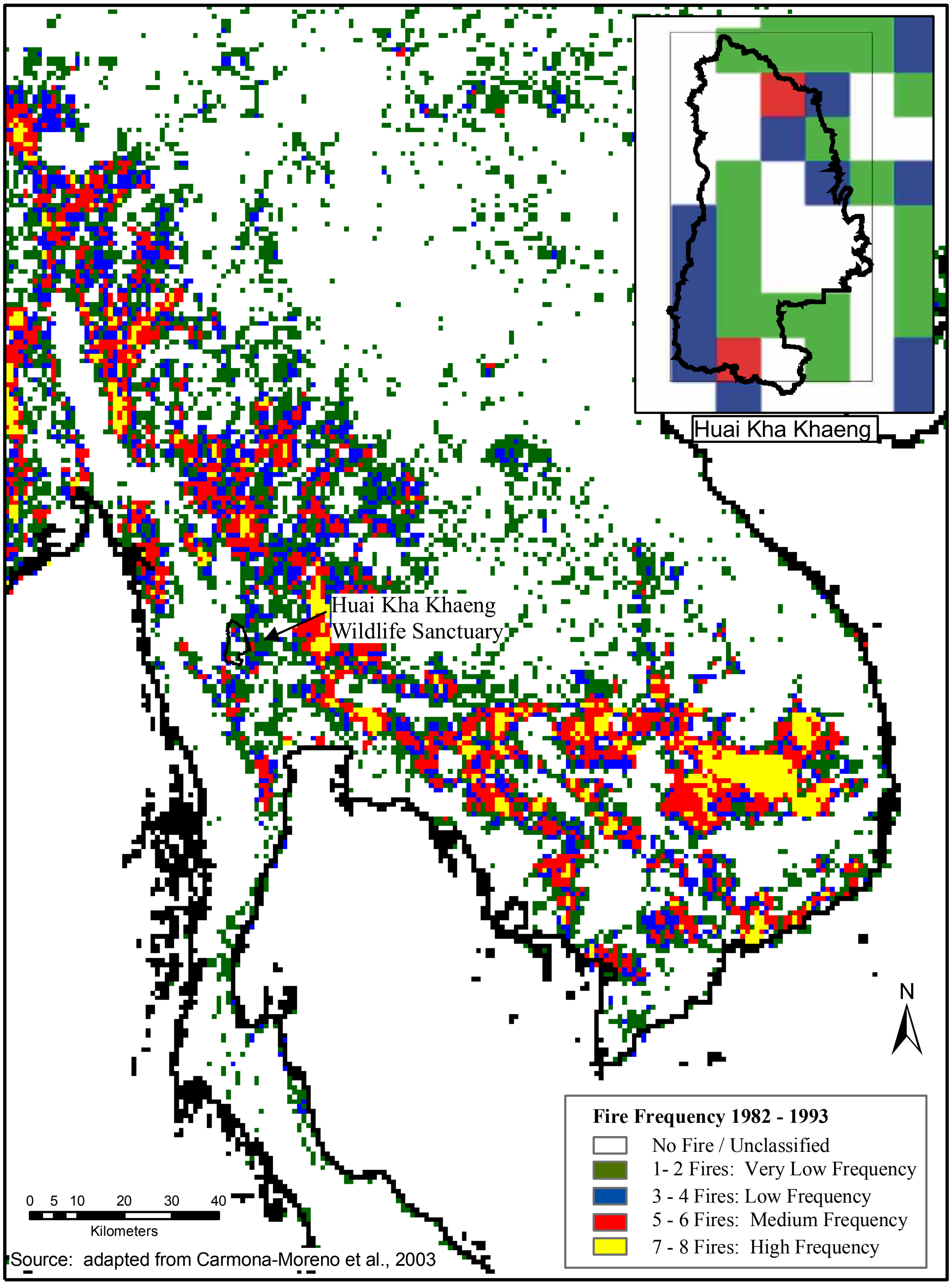


Figure 2.5 Fire frequency in mainland Southeast Asia from 1982 to 1993. Extensive areas of the landscape burn on a regular basis.

fires of mainland Southeast Asia are not the stand-replacing, high intensity crown fires experienced in North America. Landscape-scale fires in mainland Southeast Asia are surface fires that burn extensively. These fires burn in grass fuels associated with fields, open deciduous forests, and savanna, and then continue as understory fires, burning in leaf litter fuels associated with closed forests. Although the intensity of fires in grass with heavy fuel loads can be quite high, surface fires in litter fuels are generally low intensity, patchy burns. Generally these understory fires have been thought to be confined to closed deciduous forests; however recently there have also been reports of fire in SEF, previously thought to be too moist to burn (cf., Wharton, 1966; Ogino, 1976; Elliott et al., 1989; Pattanavibool, 1999; RFD, 2002).

Although surface fires in closed deciduous forests and SEF do not destroy the entire forest on contact, there is still considerable conservation concern. As discussed earlier, SEF is by far the richest in biodiversity. Further, this forest type is considered to have evolved in the absence of fire (e.g., Cochrane & Schulze, 1999; Cochrane, 2003). Evidence from other parts of the tropics indicates that fire kills the more sensitive evergreen trees,[14] potentially converting these forests to more open deciduous forest and savanna. Comparatively little of the historic area of SEF with the forest mosaic is left in mainland Southeast Asia. Most of the remaining areas are now in PAs (Dinerstein et al.,

[14] Trees die two or three years after the fire event.

1995; Kohler, 2005).[15] Still, PAs have not been immune from the problem of large-scale burning (e.g., Nakhasathien & Stewart-Cox, 1990; Rabinowitz, 1990; Pattanavibool, 1999; S. Akaakara, pers. com., 2001; UNEP, unpub). Conversion of SEF to more open deciduous forest would have serious repercussions for species dependent on access to this forest type.

2.2.4 Protected areas and fire management

The historical approach to dealing with the problem of landscape-scale fires in PAs has been to try to eliminate all fire (Pyne, 1982, 2004). The thinking has been that if fires can be prevented from starting, or suppressed when they are small, it may be possible to prevent large-scale fires of potentially greater consequence. This approach was adopted in the early 1900s in North America, and has been fairly strictly adhered to since the 1950s. People living near parks were educated not to burn and fire suppression programs were developed. However in the 1970s the thinking about fire began to change. Parks managers began to notice problems with the fire management approach. For instance, some forest types were not regenerating properly, important grass and meadow wildlife habitat areas were not being maintained, and forest health problems associated with increasing areas of old forest stands were starting to emerge (Agee, 1993; Noss & Cooperrider, 1994; Woodley, 2002). Over the following 30 years recognition of the importance of maintaining fire in the landscape continued to grow. Conservation goals

---

[15] Over 14% of the total land surface of Indochina has been secured in protected areas in the region, varying from around 9% in Vietnam to 20% in Cambodia (Kohler, 2005)

were adjusted to that of maintaining 'ecological integrity' of PAs, and in some cases prescribed burning programs were adopted as a means of safely and effectively restoring fire to PA ecosystems (e.g., Parr & Brockett, 1999).

The thinking in terms of PAs and fire management in mainland Southeast Asia has followed a similar trend. Thailand first adopted a fire elimination policy in the early 1970s. At the time there was growing concern that fire was adversely affecting economic forests in the country. J. C. Macleod, a Canadian forester, was commissioned to provide advice to the Thai government on forest fire management. Macleod spent seven months in Thailand in 1971 assessing the forest fire situation, and found the forested area burned in that year was about 18,772,000 ha with most fires occurring in the north and northeast of the country. Though the "burned-over area bore no visible evidence of harmful effects, the fire would often result in a serious loss of increment" (Macleod, 1971 in Kanjanavanit, 1992). He recommended the establishment of a Forest Fires Act with protection policy, and emphasized that: "Even if no funds are budgeted for fire control, there need be no slackening of effort to provide protection against fire" (Macleod, 1971 in FFCD, 2005). The policy, which was adopted and remains in place today, is largely representative of the fire management policies in the larger Southeast Asia region, including for PAs.

However as early as the mid 1980s, concerns over a fire elimination policy for Thailand were being raised. Philip Stott, a British geographer, contended a need for fires in the country in order to maintain ecological integrity (Stott, 1986, 1990; Stott et al., 1990). He indicated that the primary vegetation for Thailand was open deciduous forest and savanna, and that fire is a regular disturbance feature of this vegetation class. If fire was excluded from the landscape, one could expect fuels to build up, with the end result being high intensity fires that were difficult to suppress and which sometimes progressed into evergreen forests. Instead Stott urged that the protection policy be dropped and a wide-scale prescribed burn program be adopted in its place, the thinking being that restoring the natural burn frequency to open deciduous forests and savanna would limit the potential for larger landscape-scale fires occurring. Along these lines three pieces of research were conducted. First, Stott undertook to determine the fuel conditions in DDF and savanna that lead to destructive wildfires (Stott, 1986). Second, Stott's Ph.D. student, Saranarat Kanjanavanit undertook research to determine when prescribed burning could be conducted safely in DDF and savanna (Kanjanavanit, 1992). Finally, another Ph.D. student from Australia, Rey Ofren focused on developing a system to identify high hazard areas in Huai Kha Khaeng Wildlife Sanctuary (*i.e.*, vegetation types that are the most likely to burn and hold the highest fuel load) to prioritize fire management activities (Ofren, 1999).

However, the situation in PAs in mainland Southeast Asia is not the same as in PAs in western countries. For one thing, open deciduous forests and savanna have never really been deprived of fire in the region. Although a fire elimination policy has been in effect for some sanctuaries in the region for over thirty years, the policy has never been effective (Stott, 1988). Fires have largely continued to burn on a near annual basis (pers. obs.). Furthermore, prescribed burning on the scale suggested even for a PA would be simply impractical. There are numerous isolated areas of open deciduous forest and savanna, which generate large fuel loads on an annual, even biannual basis.[16] All these areas would have to be identified, assessed for burning, burned on a near annual basis. Further, the buildup of high fuel loads in open deciduous forest and savanna does not actually explain observations of fire in closed deciduous and seasonal evergreen forests. Closed forests will only continue to burn where the fire environment within these ecosystems, not adjacent ecosystems, is conducive to fire. As such there is no assurance that prescribed burning in open deciduous forests and savanna would prevent large-scale fires that affected closed forests. Unfortunately, a significant consequence of handling the landscape-scale fire problem by focusing on open deciduous forest and savanna has been to take the focus away from the chief conservation concern – the fact that SEF may be being adversely affected by fire. Little research has been done on managing the fire concern for SEF.

---

[16] Ofren (1999) provides a figure showing high hazard areas in HKK, presumably that would require prescribed burning.

2.3 HUAI KHA KHAENG

2.3.1 Description

The Huai Kha Khaeng Wildlife Sanctuary (HKK) covers over 2,800 km^2 and is located about 300 km northwest of Bangkok between 15^0 00' to 15^0 50' N and from 99^0 00' to 99^0 28' E in west-central Thailand (Fig. 1.1). Geographically, the Sanctuary contains most of the catchment of the Huai Kha Khaeng River, which runs south through the center of the Sanctuary (Fig. 2.6). The hills and mountains build out from this central drainage feature. The elevation in the Sanctuary generally ranges between 300 and 1000 meters, though the land rises more steeply to nearly 1700 meters in the west. Geologically, this area is composed of various limestone formations interspersed with massive intrusions of granite and smaller outcrops of quartzite and schist. Soils are primarily acidic red-yellow podzols derived from granite and tend to erode easily (Nakhasathien & Stewart-Cox, 1990; Kanjanavanit, 1992).

Climatically, the Sanctuary is classified as being in the seasonal tropics.[17] There are three seasons: a cool dry season, a hot dry season, and a warm wet season. The average minimum and maximum daily temperature varies between 15^{0}C and 27^{0}C in the cool dry season (November to January), 18^{0}C and 34^{0}C during the hot dry season (February to

[17] The region is classified as Aw, tropical wet and dry, under the Koppen System (cf. Köppen, 1931).

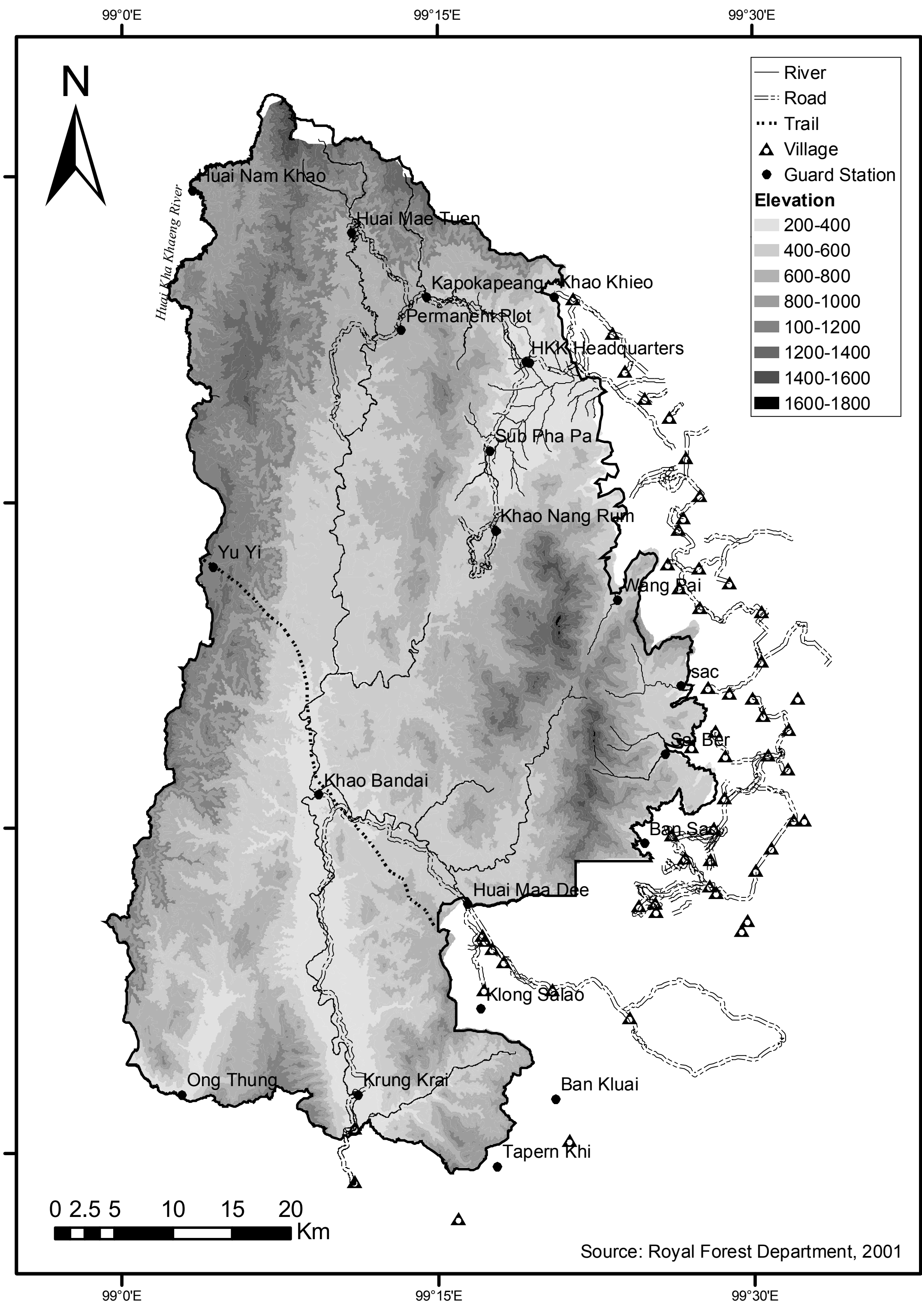


Figure 2.6 Major geographic and cultural features of Huai Kha Khaeng Wildlife Sanctuary

April) and 22^{0}C and 31^{0}C in the warm wet season (May to October) (Fig. 2.7a).[18] The mean annual precipitation near the center of the Sanctuary at Khao Nang Rum Wildlife Station is 1500mm. Rainfall varies with elevation, with lower elevations receiving less rainfall and the higher mountain areas more. Most of the rainfall occurs in the wet season, from May to October, with peaks in May-June and September-October (Fig. 2.7b). The mean monthly rainfall for the dry season, the six months from November to April, is less than 100 mm though the severity of the dry season varies from year to year. Some years there is sporadic rainfall during the dry season with other years having little or no rain.[19] Minimum daily relative humidity in the open ($Rh_{min,field}$) varies from 40% and 50% except during February and March when it is frequently less than 20% (Fig. 2.7c).[20] Mean wind speed near the center of the Sanctuary is less than two kilometers per hour for most of the year (Fig. 2.7d).[21],[22]

The Sanctuary hosts five main vegetation types: tropical mixed deciduous (MDF); dry dipterocarp forest (DDF); seasonal evergreen forest (SEF); hill evergreen forest (HEF), and savanna (Fig. 2.8). Hill evergreen forests, a lower montane tropical evergreen forest type, are grouped in with SEF for simplicity in the figure. A general description of forest types by Smitinand (1992) is included as Appendix 2-1. More detailed studies are

---

[18] Temperature data from Khao Nang Rum Wildlife Station, 1983-1998
[19] Rainfall data from Khao Nang Rum Wildlife Station, 1983 – 1998.
[20] Relative Humidity data from Khao Nang Rum Station, 1994-2003.
[21] Wind data from Kapokapeang Station, 1992-99.
[22] The indication that wind speed is low in the forest places an emphasis on relative humidity as a key influence affecting fuel moisture content.

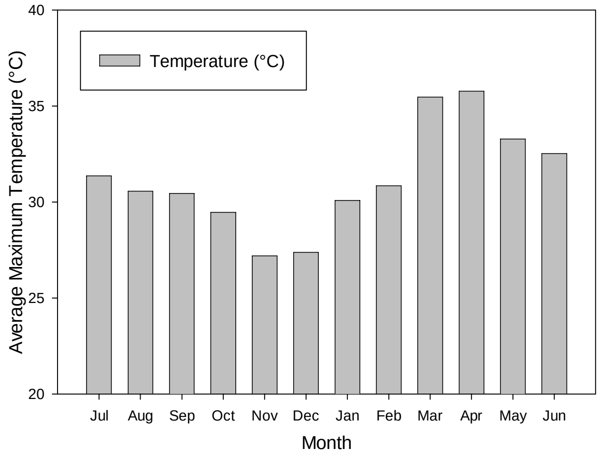


Fig. 2.7a Monthly Temperature Averages

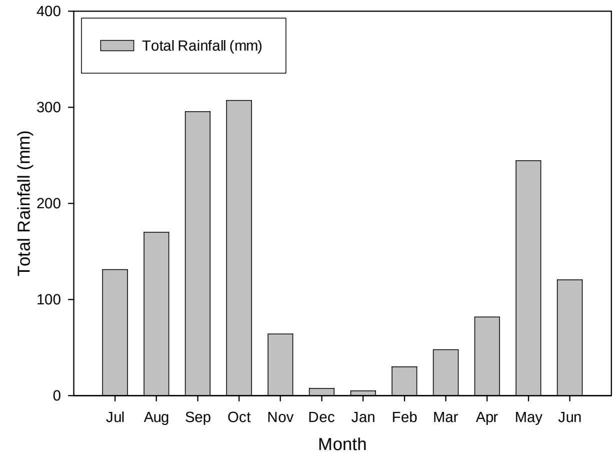


Fig. 2.7b Monthly Precipitation Accumulation

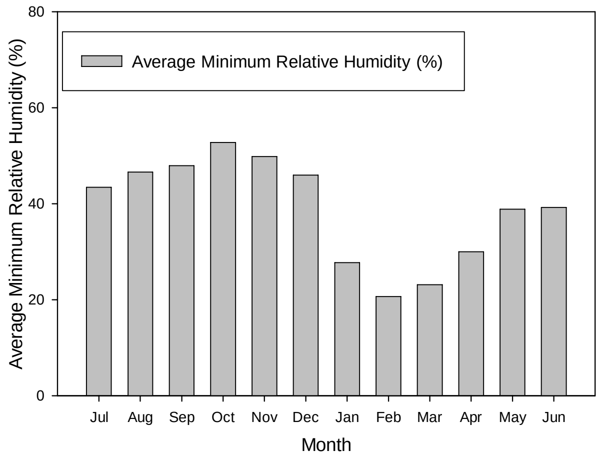


Fig. 2.7c Monthly Relative Humidity Averages

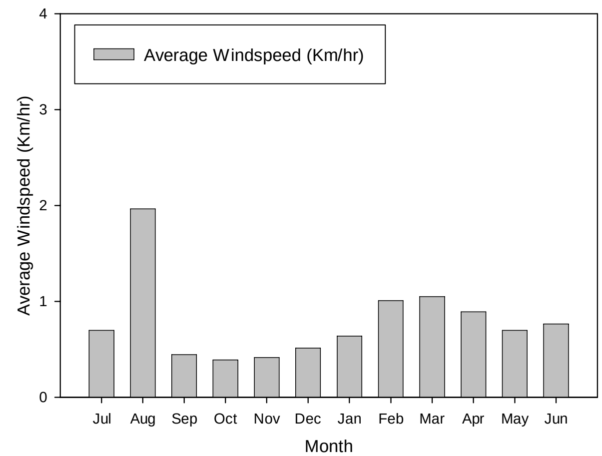


Fig. 2.7d Monthly Windspeed Averages

Figure 2.7 Climate of Huai Kha Khaeng Wildlife Sanctuary

Source: Royal Forest Department as follows: Temperature - Khao Nang Rum Station (1983-1998); Precipitation - Khao Nang Rum Station (1983-1998); Relative Humidity - Khao Nang Rum Station (1997-2003); Wind speed - Kapokapeang Station (1992-1999).

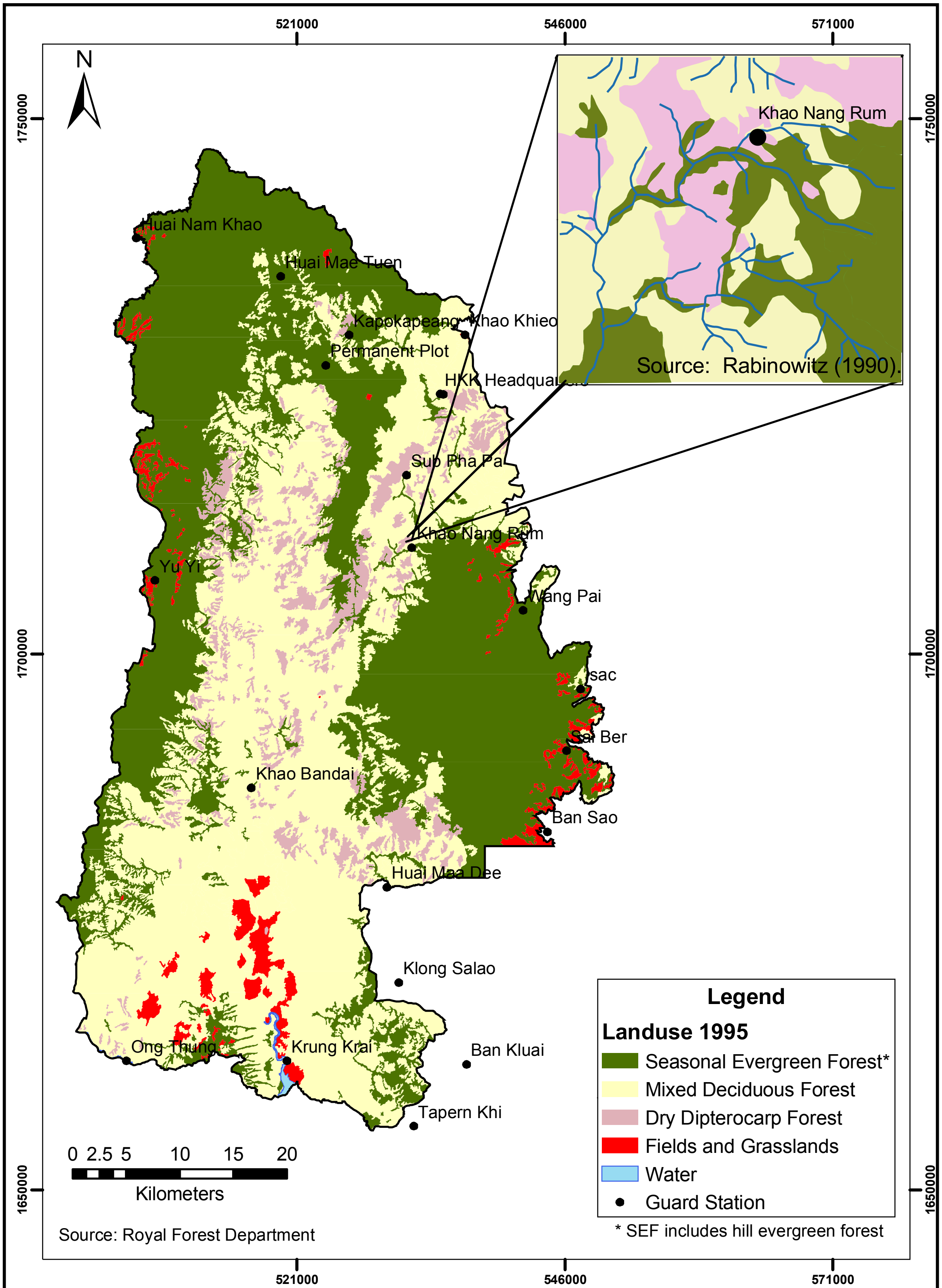


Figure 2.8 Forest Classification (1995) for Huai Kha Khaeng Wildlife Sanctuary. Insert shows the forest mosaic near Khao Nang Rum Station.

provided in Smitinand (1989), Nakhasathien & Stewart-Cox (1990), Fehr (1998), Weyerhauser (1998) and Marod et al. (1999). Further, in-depth analysis of SEF in the 50 ha permanent plot[23] near Kapokapeang (Fig. 2.8) are included in Baker (2001), Baker et al. (2005; In prep), Bunyavejchewin (1999), Bunyavejchewin and Baker (1995), Bunyavejchewin et al. (2001; 2002; 2003; 2004a; 2004b).

The distribution of major forest types in the Sanctuary is most easily discerned from helicopter in February and March. At that time deciduous forests in the lower hills are dry and leafless, while evergreen forest areas in the upper hills and along stream courses remain green and moist (App. 2-2a). While the various vegetation types have generalized landscape locations as noted previously in Section 2.2.1, one also finds that between 600 and 1000m the forests present an integrated mosaic of forest types and ecotones (pers. obs., 2000, 2001). Khao Nang Rum Wildlife Research Station near the center of the Sanctuary is an example of an area of the Sanctuary surrounded by a mosaic of forest types (Fig. 2.8 inset).

---

[23] The permanent plot is a 50 ha plot that was set up by the Smithsonian Tropical Research Institute Center for Tropical Forest Science in a seasonal dry evergreen forest at Huai Kha Khaeng Wildlife Sanctuary (HKK) in western Thailand as one of several large-scale forest dynamics plots (FDP). Established between 1992 and 1995 the primary objective for the plot is to monitor long-term changes in forest composition and structure.

2.3.2 Fire History

Little is known about the historical fire regime in the Sanctuary, however it is reasonable to assume that the extent of burning was limited. Although historically occupied,[24] the Sanctuary was still considered to be remote in 1972 when it was established (Nakhasathien & Stewart-Cox, 1990). At the time there were only four Karen hill tribe villages in the area and these were relocated outside the Sanctuary boundary in 1976 (Nakhasathien & Stewart-Cox, 1990). The little anecdotal evidence available for the area is that the Sanctuary, including lands far outside the eastern boundary, held dense stands of deciduous and evergreen forests which would suggest only limited large-scale fire activity (Wharton, 1966; Ogino, 1976). Rabinowitz (2002) describes the observations of a knowledgeable Sanctuary guard and long term resident of the area:

> *Lung Galong (Uncle Galong) had said that in the past the forest had been so thick that the canopy nearly blotted out the light from the sky. Now there were many open areas.*

The situation began to change in the 1980s when increasing land-use pressure was put on the Sanctuary. Rapid development near HKK and indeed in Thailand in general, raised several threats to the Sanctuary. Road building and logging opened forest reserve lands to the east of the Sanctuary. Population displacement issues in other parts of Thailand caused thousands of settlers mostly from eastern Thailand to move into the area (cf., TDRI, 1986; Santisuk, 1988; Nakhasathien & Stewart-Cox, 1990). A number of Thai

[24] The Sanctuary contains archaeological evidence of occupation back thousands of years, with specific evidence of hill tribe activity back 700 years.

villages were established near the eastern boundary (Fig. 2.6). Further, a number of hill tribe villages, primarily Hmong, illegally moved directly into remote areas in the central and western parts of the Sanctuary. Hunting and log poaching became regular occurrences in the Sanctuary. The number of fires increased.

From this time on, fire activity in the Sanctuary was of concern, especially in years when the fires continued through deciduous forests. Nakhasathien & Stewart-Cox (1990, p.40) write of their concern that widespread annual burning in HKK was simplifying mature forests, eliminating fire sensitive species characteristic of SEF and MDF, and encouraging the spread of fire resilient DDF. After working with large cats in HKK Rabinowitz (1990) concluded that seasonal fires and the continuing replacement of SEF with DDF threatened the health and stability of many carnivore populations.

The situation reached a crisis point in the late 1980s when a number of Sanctuary guards were killed, and a highly respected ecologist and Sanctuary superintendent, Sueb Nakasathien, also died. Nakasathien’s death acted as the catalyst for government officials and the people of Thailand to join together to have Huai Kha Khaeng-Thung-Yai (HKK-TY) nominated as a World Heritage site. The nomination was adopted by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1991, and the HKK-TY forest complex became Thailand’s first World Heritage Site. Hmong and Karen hill tribe villages that were inside the Sanctuary were relocated. A buffer zone was established on the eastern side of the Sanctuary to better define the Sanctuary boundary. Increased resources were brought to control illegal activities, including fire.[25]

Into the 1990s fire continued to be an issue in the Sanctuary. Two years in particular, 1994 and 1998, are remembered as being significant fire years when extensive areas of HKK burned (Vibulsresth et al., 1994; Giri & Shrestha, 2000; Akaakara, 2001). The occurrence of large-scale fires in the PA in combination with the public focus on this area brought heavy criticism to the Royal Forest Department (RFD) that it was not doing enough to protect the Sanctuary (Bangkok Post 1998a; Bangkok Post 1998b). Since that time there has been a greater RFD focus on implementing the National fire protection or "no burn" policy, with a disproportionate amount of the resources going to activities related to fire suppression in important PAs such as HKK (pers. obs.).

2.3.3 Current fire situation and management

Today, fire is a near annual occurrence in Huai Kha Khaeng Wildlife Sanctuary (KUFF, 2000). Though fires occasionally occur earlier, the primary fire season is February to April, with March the peak of fire activity (Ofren, 1999). Most fires are caused by people (Kanjanavanit, 1992).[26] Fires are generally considered to start near villages on the eastern boundary, but some are also started in the south, and to some extent north of the

---

[25] More recently, additional parks and wildlife sanctuaries were established around the HKK-TH complex to further 'buffer' the World Heritage area from agricultural development, tourism inflows and other uses (KUFF, 2000)

[26] Though lightning occurs in the Sanctuary, it is usually accompanied by rainfall (Kanjanavanit, 1992).

Sanctuary (KUFF, 2000). In general, people burn to improve grazing and to increase the harvest of forest vegetables such as mushrooms, as well as to poach for wildlife (Kanjanavanit, 1992). The burning is thought to be primarily restricted to deciduous forests and savanna.

Officially, HKK management follows the government's fire elimination policy. There is a fire station on the eastern side of the Sanctuary. During the fire season, suppression crews are trained and deployed (App. 2-2b). A helicopter is brought in for standby from February 1st through March each year depending on the fire season. Further, both government and NGO community outreach programs have been active in the area for some time trying to get people not to burn (App. 2-2c). The increased focus on suppression is considered to be successful:

> *Five forest fire protection units have been placed around the World Heritage Site (Thung-Yai and Huai Kha Khaeng) in the last 3 years. One of these units is a center equipped with a helicopter and fire crew. The work of the fire protection units has proved quite successful in Huai Kha Khaeng by which there have been no major forest fires occurring in the area for the last 3 years. This result is concurrent with the resolutions addressed in the 1998 conservation report after the meeting on the issue of forest fires in the World Heritage (Site).*
>
> (UNESCO, 2003, p. 9)

The fire protection program in HKK is expensive however, and there are also other concerns. Some conservationists argue that the fire elimination policy will have a negative effect on the Sanctuary (e.g., Stott et al., 1990); that ultimately fire suppression will lead to the loss of dry forest types such as open DDF and savanna – which are important graze for the Sanctuary’s ungulate populations. They would like to see a prescribed burn program such as that called for by Stott (1986; 1988; 1990) and Ofren (1999).

The RFD has tried to accommodate the concerns of conservationists by initiating a prescribed burn program. In 2002, a small area of prescribed burning was carried out in savanna in the central southern part of the Sanctuary as a preventative measure against forest fire (Tanpipat, pers. com., 2002). However, HKK has a lot of flammable grasses and bamboos, and a prescribed burning program on the scale required would be extremely expensive. Further, there is also the concern that prescribed burning could get out of control. Ideally, one would like to find a way that allows villagers to maintain historic burn patterns in the Sanctuary without raising the risk that such burns would develop into landscape-scale fires.

CHAPTER 3 OCCURRENCE OF FIRE IN SEASONAL EVERGREEN FOREST

3.1 INTRODUCTION

Current understanding is that seasonal evergreen forest rarely burns (Wharton, 1966; Ogino, 1976). However in recent years there have been increasing accounts of fire in seasonal evergreen forest (SEF). Understanding the extent to which SEF have been burning is important because it indicates whether the concern that SEF is burning and may be having a negative impact on biodiversity is valid.

The purpose of this chapter is to estimate the area of SEF burned in Huai Kha Khaeng Wildlife Sanctuary (HKK) from 1988 to 2002. Satellite data were used to build a fire history of HKK, and field reconnaissance and interviews were undertaken to determine the extent of fire in SEF.

3.2 BACKGROUND

Generally the understanding is that most fires that occur in mainland Southeast Asia occur in deciduous forests or savanna. This is because first, most of the region is deciduous and savanna forests and these forests have relatively high burn frequency. Second, satellite assessment of burning further confirms that fires in recent years have been generally confined to deciduous forests. For instance, Giri & Shrestha (2000) who used Landsat TM to map the 1998 fire in Huai Kha Khaeng Wildfire Sanctuary confirm that most of the burning occurs in deciduous forests. The historic literature also indicates that SEF rarely burn (e.g., Batchelder & Hiri, 1966; Wharton, 1966; Ogino, 1976; Mueller-Dombois, 1981). Like their tropical rain forest cousins to the south, SEF were generally thought to be too moist to burn. Fires stop upon entry to SEF (Batchelder & Hiri, 1966; Stott, 1986, 1988), except in cases of severe drought (Ogino, 1976; Goldammer, 1997a, 1997b, 1999; Rowell & Moore, 2000). Most burning in SEF is limited to forest stands that have been structurally damaged (Fearnside, 1990; Uhl & Kauffman, 1990; Holdsworth & Uhl, 1997; Jones, 1998), or the edges of structurally intact SEF stands (Uhl & Kauffman, 1990; Cochrane, 2001; Laurance et al., 2001; Cochrane & Laurance, 2002; Alencar et al., 2004).

In recent years there have been a growing number of reports of fire in SEF that seem to suggest significant areas of intact SEF may also be burning. For instance Jones (1997) who mapped the fires in mainland Southeast Asia in the 1992-93 dry season using AVHRR[27] one km resolution satellite data, found most fire activity (69%) occurred in the last two months of the dry season (March-April), and that this late dry season fire activity was mostly fire within closed and fragmented evergreen forest. There have also been several reports from protected areas (PAs) of fires penetrating deeply into evergreen forests (Elliott et al., 1989; Pattanavibool, 1999; RFD, 2002). A significant proportion of

---

[27] Advanced Very High Resolution Radiometer (AVHRR)

the forests in PAs are SEF. For example 45 percent of the forest area in HKK is SEF. If intact SEF has been burning, there is potential that these forests would be adversely affected by fire.

3.3 METHODS

The approach used to investigate the extent of burning in SEF was to: i) build a Landsat fire history for SEF in HKK; and ii) undertake field reconnaissance and interviews regarding fire in intact SEF. A fire history is the study and/or compilation of evidence (e.g., historical documents, fire reports, fire scar, tree growth rings, charcoal deposits) that record the occurrence and effects of past wildfires (Merrill & Alexander, 1987). Emphasis was placed on using satellite images to generate a continuous spatial database of fire for a relatively short interval of twenty years.[28] Satellite data, specifically from the Landsat MSS and TM sensors, were chosen as spatial input for fire history. Little other spatial fire data were available as burn areas are largely undocumented (Akaakara, pers. com., 2001).

The Landsat series of satellites offer sensors with adequate spectral and spatial resolution to map HKK. Landsat multispectral scanner (MSS) came online in 1972. This satellite sensor system offered four spectral bands, and a spatial resolution of approximately 80m.

[28] There were few people and therefore fires before 1972 (cf., Ch. 2).

In 1982, the Landsat thematic mapper (TM) satellite sensor system was launched. Landsat TM had an improved spatial and spectral resolution with seven spectral bands, and a spatial resolution of 30 meters. Russell-Smith et al. (1997) used Landsat MSS to map a fire history for Kakadu Park in Australia from 1980 to 1994 and found the sensor to be over 80% accurate in mapping the ground area burned. Vibulsresth et al. (1994) showed that Landsat TM was about 87% accurate for mapping burn areas in forests in HKK, Thailand. In fact, Landsat TM satellite sensor data are used as the primary validation information against which other satellite sensors are compared in the region (Justice et al., 2003; Roy et al., 2003; GOFC, 2005)

Still, there was also mention in the literature that Landsat TM satellite images, which are commonly used to classify burn areas in the region (Vibulsresth et al., 1994; RFD, 1999, 2000), may not be capable of detecting low intensity surface fires beneath broadleaf evergreen forest canopies (cf., Nepstad et al., 1997; Nepstad et al., 1999a; Nepstad et al., 1999b; Peres, 1999). To address this issue, the research was supplemented by including more qualitative information, obtained from personal observations in the Sanctuary in 2000 and 2001, as well as the observations and experience of others who had observed fire in SEF in HKK in previous years.

Methods for the research included data acquisition, building the fire history of HKK, querying for the area of SEF burned each year, as well as interviews and field reconnaissance with Sanctuary guards in intact SEF in HKK. The fieldwork was undertaken between February and April of 2000 and 2001.

3.3.1 Data acquisition

Two types of information were required to build a fire history for HKK: burn area information for a consecutive number of years, and forest type and Sanctuary boundary information. The original plan was to acquire between 10 and 20 near-end-of-fire season images, one per year for sequential years, and then classify the burn areas of each image.[29] However, acquiring the desired image sets was not as straightforward as expected. First, the Landsat TM data were too expensive to obtain. The National Research Council of Thailand (NRCT) is the only agency that offers a suitable selection of Landsat TM scenes for HKK.[30] A set of 10 fire season images, one for each year would have cost in the order of $20,000 (US), financially beyond the scope of the project. The Landsat MSS data which are less expensive could not be obtained because only a few end-of-fire season images were available for HKK from the main agencies, US Earth

---

[29] Images acquired in late March or April were preferred for end-of-fire season images because new growth 'green-up' occurs quickly following rains at the end of April and in early May.

[30] The NRCT has since changed to be the Geo-Informatics and Space Technology Development Agency (GISTDA).

Data Center (EDC) and NRCT, images which had been processed years ago for various purposes.[31]

Fortunately, a suitable secondary source of data was available. Relatively high quality burn area maps that had been produced from Landsat TM imagery for HKK were available for twelve of the fifteen years, between 1988 and 2003. Most of the burn area maps come from a paper written by Vibulsreth et al. (1994). The more recent maps were produced by the Royal Forestry Department (RDF), Remote Sensing Division, Bangkok (Table 3.1). Of note are the following restrictions: i) maps were not available for all the years required making a gap between 1995 and 1997[32]; ii) not all the images acquired were near-end-of-fire season images so the extent of burning in some years may not be fully presented; iii) burn area maps were produced by two different government agencies, and therefore the interpretation of 'burn area' under different classifications might have varied; and iv) most of the burn area maps were available only on paper so there may be considerable placement error expected in the stretching of each map to apply a standardized geocoding (GIS formatting).

[31] While the archived original tapes still exist, there is no longer the capacity to process them. A combination of factors, including tape degradation and the decommissioning of virtually all the Landsat MSS decoders in existence, means that none of the historical Landsat MSS data for the region that had not been previously processed can be retrieved. In 2003, officials from the Earth Resources Observation Systems (EROS) Data Center (EDC) confirmed that the older Landsat MSS had been discarded.

[32] Interviews with RFD staff and review of local newspapers and 'quick look' satellite images indicated that 1995-1997 were not significant fire years in HKK.

Table 3.1 Source data for burn area maps

Image Year	Image Date	Source	Medium	Proportion (%) of Fire Season Represented *
1988	April 6	NRCT	Paper (Vibulsresth et al., 1994)	88
1989	February 20	NRCT	Paper (Vibulsresth et al., 1994)	27
1990	April 12	NRCT	Paper (Vibulsresth et al., 1994)	96
1991	February 26	NRCT	Paper (Vibulsresth et al., 1994)	35
1992	March 16	NRCT	Paper (Vibulsresth et al., 1994)	60
1993	April 4	NRCT	Paper (Vibulsresth et al., 1994)	85
1994	Jan 17, Feb 18, March 6 and April 7	NRCT	Paper (Vibulsresth et al., 1994)	89
1995	Missing			
1996	Missing			
1997	Missing			
1998	March 17	NRCT	Poster (large)	61
1999	March 20	RFD	Digital	65
2000	February 3	RFD	Digital	4
2001	March 10	RFD	Digital	51
2002	April 5	RFD	Digital	86

* Primary fire season Feb 1 – April 15, 74 days

Forest type and Sanctuary boundary location information was obtained from the Royal Forestry Department (RFD), Remote Sensing Subdivision (RFD, 1999; 2000) in the form of a Geographic Information System (GIS). The major feature class maps in the geodatabase included: elevation, topography[33], drainages, forest classification, man-made features, etc. The forest type map was the product of a 1995 Landsat TM image classification.

3.3.2 HKK fire history

The forest burn area for the Sanctuary was determined in four steps. First, the 1988-1994 burn area maps were geocoded and input to a GIS. Geocoding entailed: i) selecting seven identifiable points or 'tics' on the HKK boundary of the figures for which UTM coordinates could be determined; ii) inputting the tic coordinates into ArcView and applying a datum, a projection and coordinate system of UTM Indian 1975 47N Tranverse Mercator[34]; and iii) digitizing the burn area polygons for each year. The root mean square (RMS) error for each map was recorded (App. 3-1), with a final RMS of 0.9 km.

Second, burn areas on the 1998 image (poster) were identified and then digitized for inclusion in the GIS. Definition of the burn area was done under the direction of Dr.

---

[33] A distortion of approximately one km in the original topographic map was noted during fieldwork for the northwest corner of the Sanctuary near Huai Nam Khao (pers. obs).

[34] The projection chosen was the same projection that the RFD uses for HKK GIS.

Surachai Ratanasermpong, a director for the Geo-Informatics and Space Technology Development Agency (GISTDA), who had also classified the burn area maps for the years 1988 through 1994 (cf., Vibulsresth et al., 1994). Burn areas were then traced onto an overlay, and digitized using ESRI Arcinfo. Third, a ‘burn’ field was created in the poly-attribute table and polygons were labeled as either burned area, ‘1’, or unburned area, ‘0.’ Finally, the burn area for each year was queried, results recorded, and burn area maps generated. The fire history for all of HKK is shown in Figure 3.1.

Since the fire history of HKK was to form the basis for the SEF fire history, a check of the fire history accuracy was performed. Interviews with research personnel and review of the literature confirmed that the big fire years were 1994 and 1998 (Vibulsresth et al., 1994; Akaakara, 2002) as shown in the fire history. Further, fieldwork and reconnaissance observation in 2000 and 2001 showed that HKK had few fires in these years. Finally, from newspaper coverage it is known that fires in 1998 were out of control in HKK between March 11 and March 30 (Bangkok Post, 1998a; 1998b; 1998c; 1998d; 1998e; 1998f; 1998g; 1998h) and since the 1998 map was produced from a March 17 image, it is likely that the burn area for 1998 is underestimated. The only years for which there is real uncertainty about the degree of underestimation are 1989, 1991 and 1992. Of the three years, 1991 is the most likely to be underrepresented since a significant area was burning before the February 26 image was taken, and there was still a considerable fire season ahead.

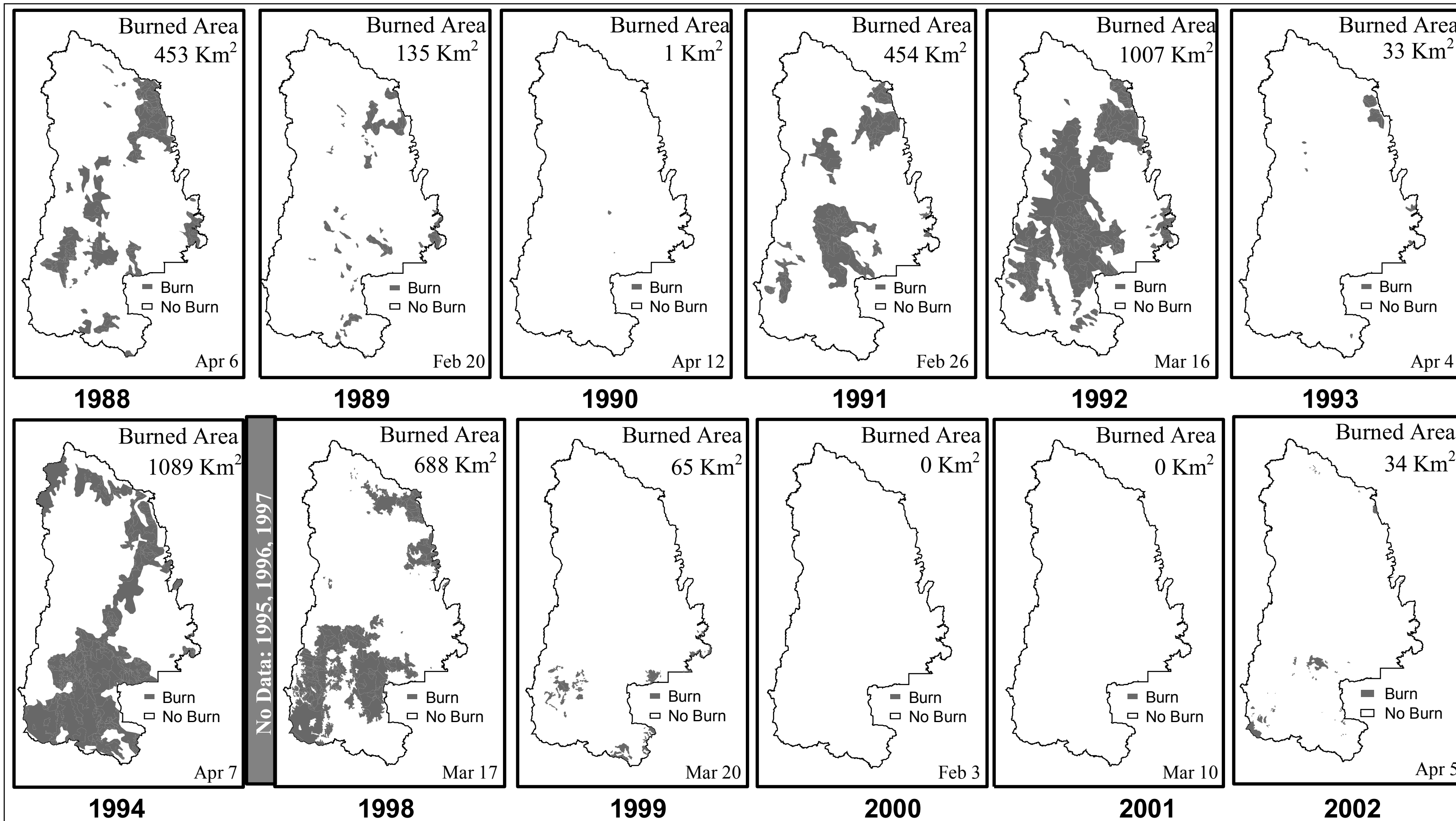


Figure 3.1 Annual burn area for Huai Kha Khaeng (1988-94, 1998-2002). The largest fire years were 1992, 1994 and 1998.

Source: Data for 1988 to 1994 are from Vibulsresth et al., (1994). Data for 1998 to 2002 are from the Royal Forest Department. Data for 1995 to 1997 are missing, though these are not considered to be major fire years. All data were derived from Landsat TM imagery.

Fire history outputs included a HKK fire frequency map, SEF burn area maps, and a graph of SEF area burned versus total Sanctuary area burned. The fire frequency map was generated by overlaying all the burn area maps generated for the fire history (1988-2002) on ArcMap (ESRI GIS) software. Then, an additional field was added to the poly-attribute table so that the number of burns for each polygon could be calculated. Finally, a green to red color ramp indicative of the number of times each area burned was applied and the results presented in Figure 3.2. Burn area maps for SEF were produced by overlaying the forest area map on the burn area maps of HKK and then querying for areas that were identified as being both 'SEF' and 'burn' area for each year. The SEF burn area maps were generated as individual maps and output on a single sheet to provide an overview of the Sanctuary's fire history. The graph of the relationship between the SEF area burned and total area of sanctuary burned was accomplished by using Excel to undertake a simple linear regression for the two data sets between 1988 and 2002.

3.3.3 Field Reconnaissance and interviews

During the 2000 and 2001 fire seasons, field checks were performed and interviews held with researchers familiar with HKK concerning areas burned in recent years. Field checks were done as part of the study plots undertaken in Chapter 4. Field checks included observing trees for burn marks (fire scars),[35] noting forest structure and species

[35] In general fire scars on trees tend to be triangular-shaped, located at the base of the tree, usually on the uphill side, and on multiple trees in the area (Veblen, 2004).

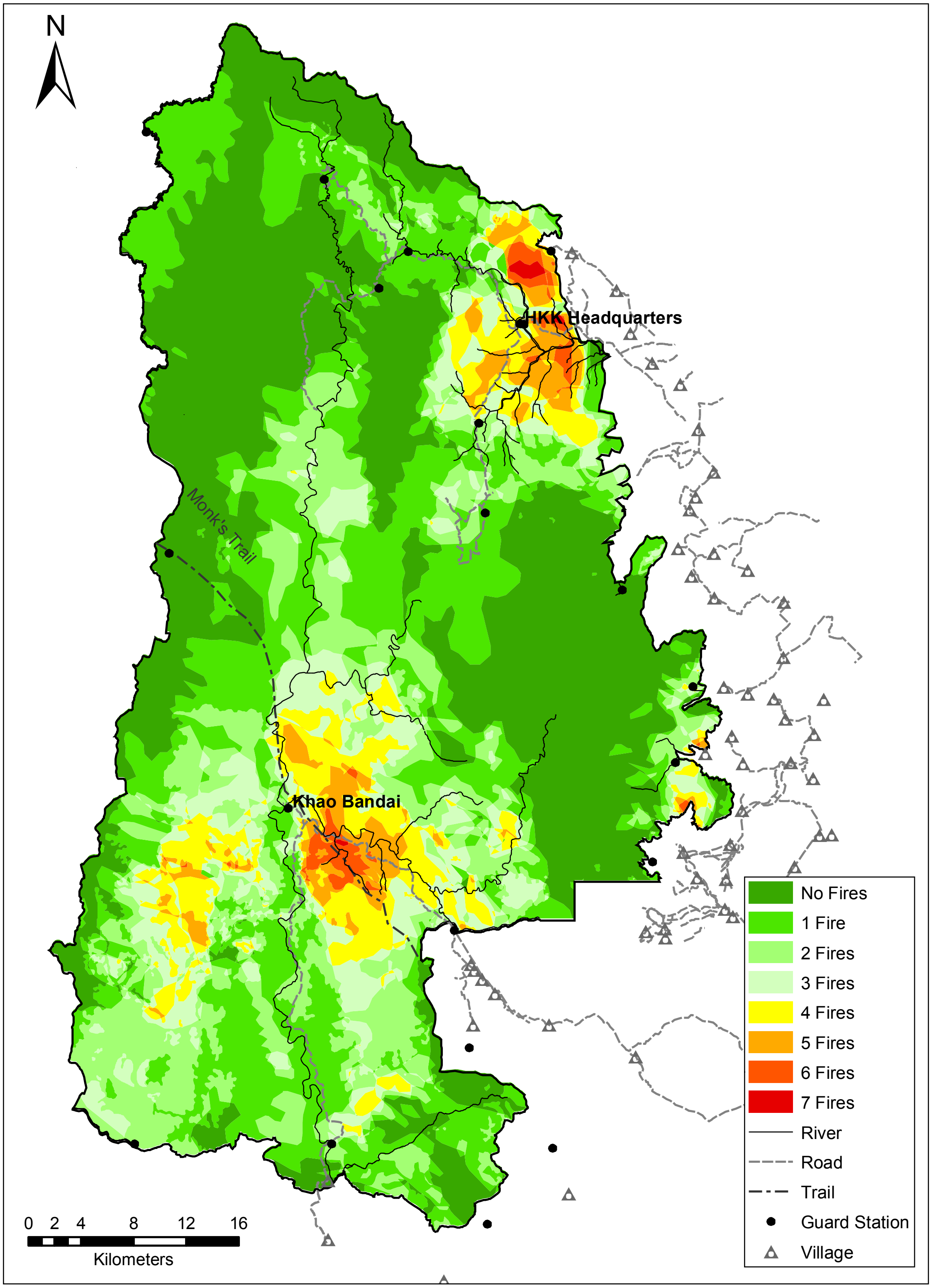


Figure 3.2 Number of fires in Huai Kha Khaeng from 1988 to 2002. Fire frequency is highest near settlements and transportation corridors.

where possible, and interviewing Sanctuary guards.[36] During field reconnaissance, guards were asked to indicate areas where evergreen forests had burned, and questioned as to the year of the fire (Appendices 3-2a, 3-2c).

Interviews were informal in nature, and progressed well in the context of the natural settings in which the fieldwork was being undertaken. Where little or no information was forthcoming, the interviewee was asked if they could suggest a person who might be able to provide insight or information. After that, interviews generally progressed along more general conversational lines, which in turn helped to provide context and depth of understanding to the social and ecological aspects of the fire situation in the Sanctuary. Some interviews were chance events with individuals encountered along the way. Other times considerable effort was undertaken to meet and discuss with specific individuals who might have more detailed knowledge. Where possible, interview topics were revisited as a means of checking the information being provided. In all cases, personal intuition and guidance from the Thai interpreter were used to gauge the quality of the information being gathered. More candid interviews were possible after shared experiences of camping, meals and labour-intensive work with guards.

[36] The GPS locations for live trees with burn marks or fire scars were recorded for possible coring at a later date, though coring was never undertaken.

3.4 RESULTS

The burn areas of seasonal evergreen forests (SEF) in Huai Kha Khaeng Wildlife Sanctuary for 1988 to 2002 are presented in Figure 3.3. The fire history for SEF showed significant burning from 1988 to 2002. The largest years were 1992 and 1994 when appreciable areas of SEF burned, 224 km^2, and 253 km^2 respectively. Smaller areas of evergreen forests were burned in 1988, 1989, 1991 and 1998; little if any SEF burned in 1990, 1993, 1999, 2000, 2001 or 2002. Most of the fires are shown to occur at the edge of SEF. There is also evidence of repeat burning on the forest fringe (Fig. 3.4). Comparison of the area burned in SEF and the area of the entire Sanctuary burned shows a significant relationship. The relationship is shown in Figure 3.5, where the R^2 is 0.94. This means that SEF primarily burned in the most extensive years of fire in HKK - landscape-scale fire years.[37]

The reconnaissance fieldwork revealed that much of the area shown as burned in the SEF fire history seemed to be either degraded, opened SEF or converted to more deciduous forest types. It was difficult to find intact SEF in the vicinity of some guard stations despite the fact that these stations are shown as in or near SEF (Figs. 2.8, 3.4). For instance forests near Huai Mae Tuen seemed be degraded with an opened forest canopy (Fig. 3.6a), while forests in the vicinity of Huai Nam Khao seemed to have been

---

[37] Although the analysis relates primarily to the years where significant areas of SEF burned (1992, 1994, and 1998), of note is the fact that substantial areas of the Sanctuary also burned in several other years specifically, 1988, 1991, 1992, 1994, and 1998 (Fig. 3.1).

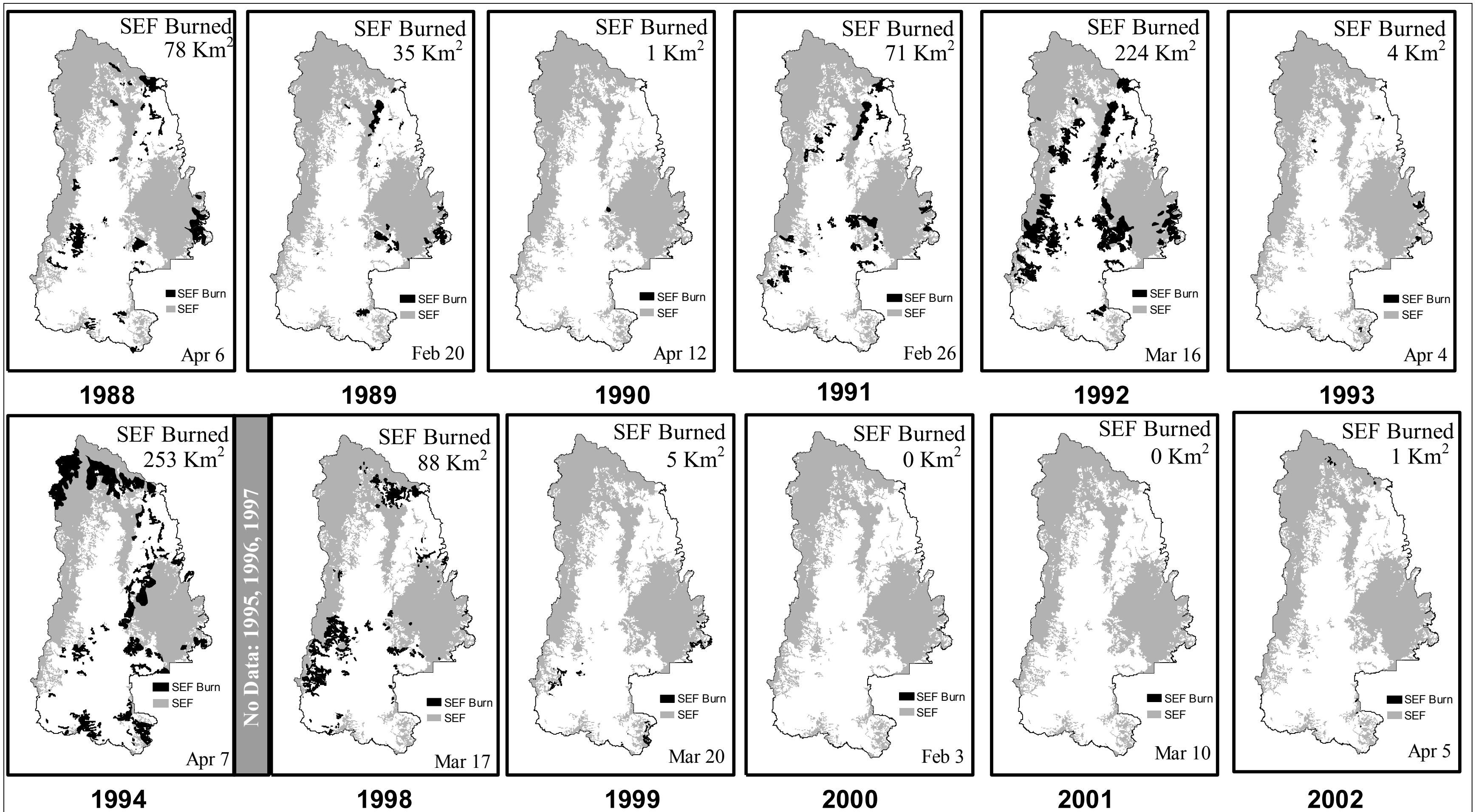


Figure 3.3 Annual burn area for seasonal evergreen forest in Huai Kha Khaeng from 1988 to 2002. Significant areas of SEF are shown to have burned in 1992 and 1994.

Source: Data for 1988 to 1994 are from Vibulsresth et al., (1994). Data for 1998 to 2002 are from the Royal Forest Department. Data for 1995 to 1997 are missing, though these were not considered to be major fire years.

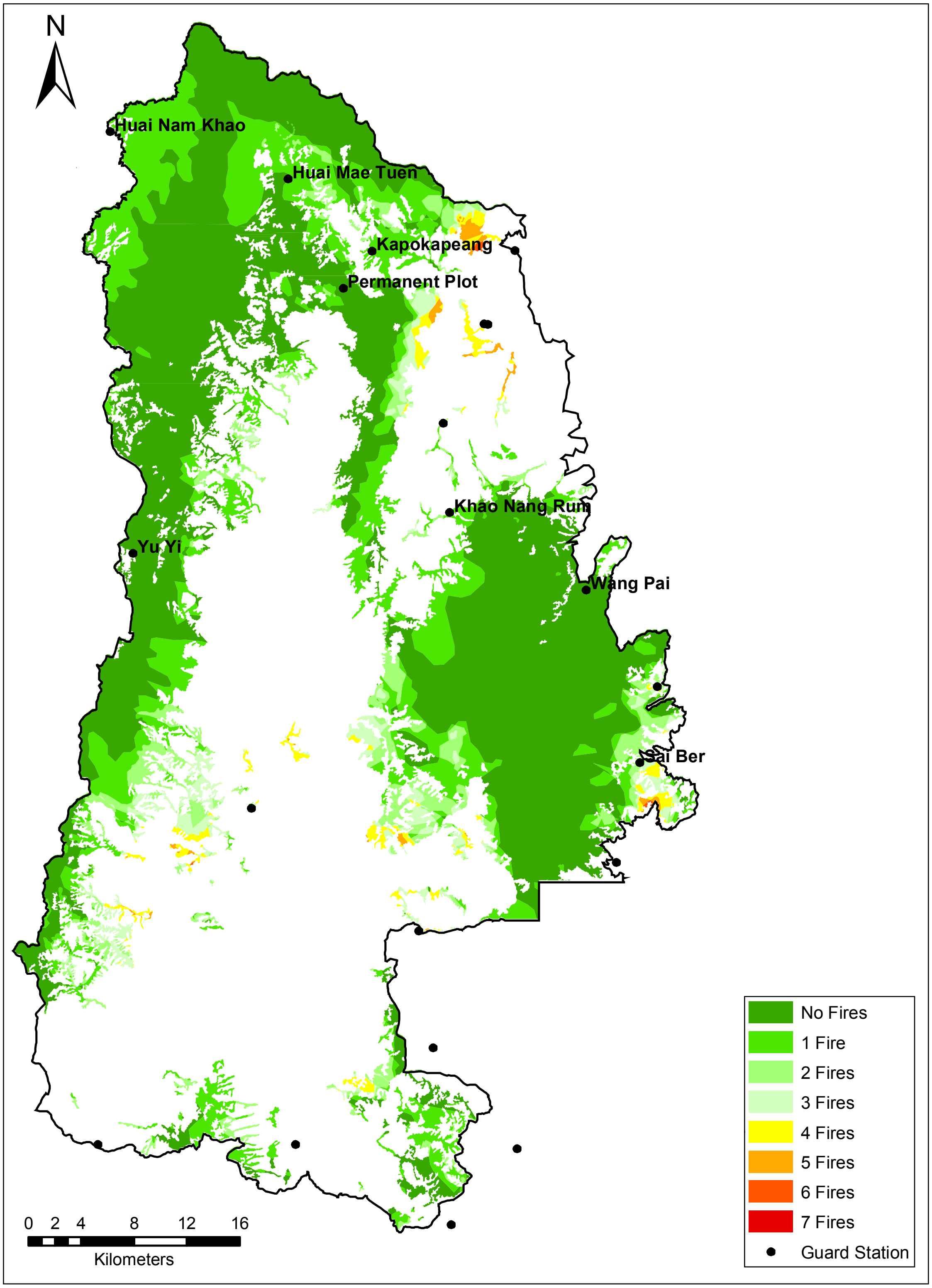


Figure 3.4 Number of fires in seasonal evergreen forest in Huai Kha Kaeng from 1988 to 2002. Some areas along the edge of the evergreen forest formation have burned repeatedly.

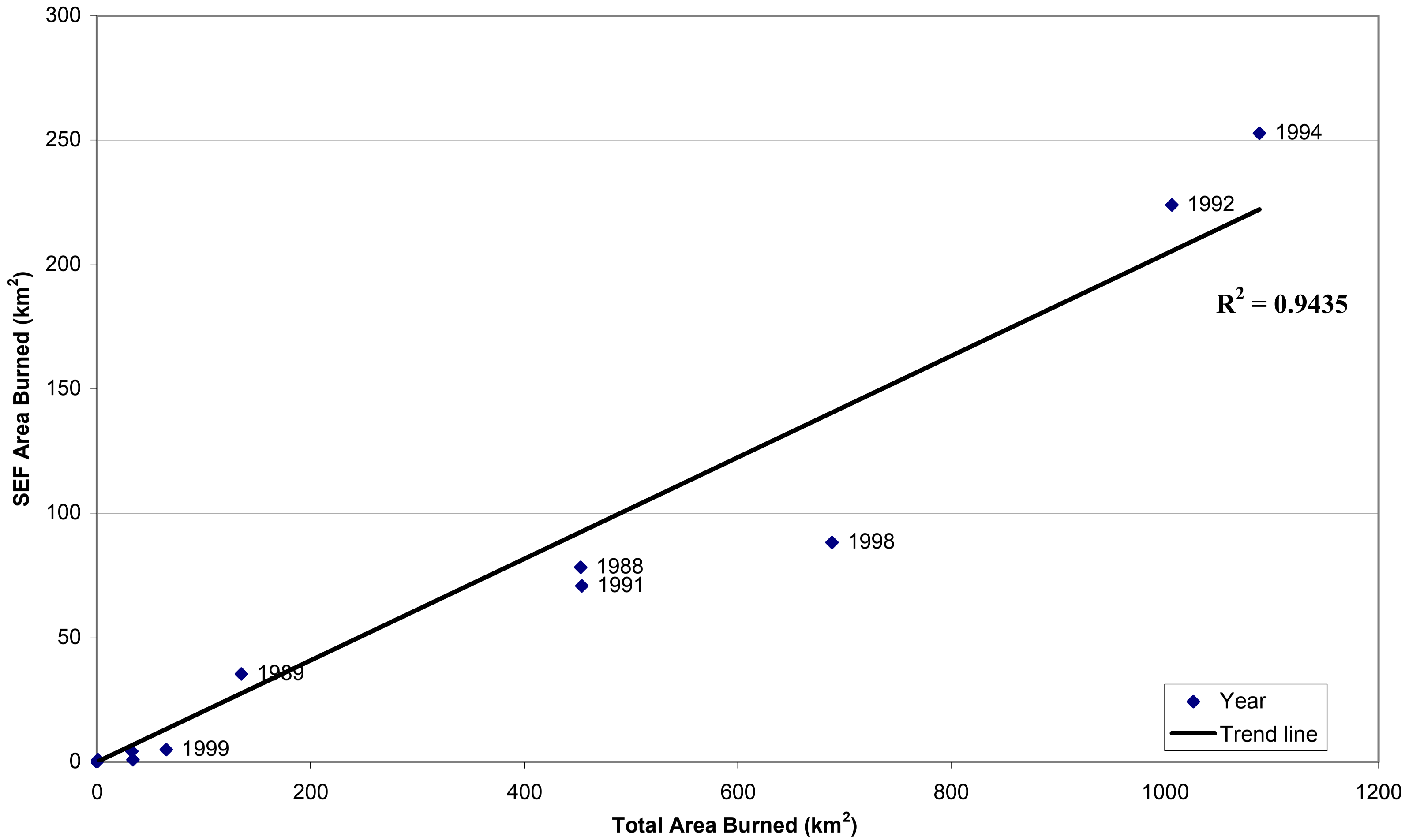


Figure 3.5 Relationship between seasonal evergreen forest area burned and total area burned. The figure shows a near linear relationship ($R^2 = 0.9435$) between the area of seasonal evergreen forest burned and the total area of Huai Kha Khaeng burned for each year between 1988 and 2002.

Fig 3.6a Open canopied SEF near Huai Nam Tuen (2001). This area is near the edge of the SEF vegetation class in HKK and has been burned repeatedly.

Fig 3.6b SEF at the permanent plot in 2001. Fire burned through this area in 1992 and 1998.

Fig 3.6c SEF in the Yuyi area (2001). Fire burned through this area once in 1998.

converted to more of a closed deciduous forest ecotone. Both converted and degraded SEF areas are fairly open and hot in the dry season, and with bamboo frequently encountered. SEF was for the most part restricted to only pockets. By contrast, the SEF encountered at Sai Ber and Yuyi stations were largely intact (Fig. 3.6c). These areas are located in higher parts of the Sanctuary, which receive more rain. Successional elements such as banana, related to past Hill tribe cultivation, were still encountered in these forests; however, the canopy was for the most part closed, and the forest environment moist, with leeches present.[38] In the area of the permanent plot, the forest was also mostly closed SEF; however the interior of the forest was more open and even park-like in some places (Fig. 3.6b). The forest environment in the permanent plot was comparatively dry however and leeches were not present.

The finding that burned areas in the SEF are associated with degraded and converted forests is also supported by evidence of forest change in the forest classifications of the Sanctuary (Fig. 3.7). The area of SEF shown as burned in 1994 in Figure 3.7-left and the area of SEF burned in 1994 in Figure 3.7-right are significantly different. This difference occurs because Figure 3.7-left was based on the 1995 Landsat forest classification for SEF, whereas Figure 3.7-right was based on the 2000 Landsat forest classification. The difference is especially noticeable near Huai Nam Khao and Huai Mae Tuen stations.

[38] Leeches are an indicator species in that they survive in moist environments such as SEF that maintains a relatively closed canopy and comparative high internal relative humidity throughout the dry season (Fogden & Proctor, 1985).

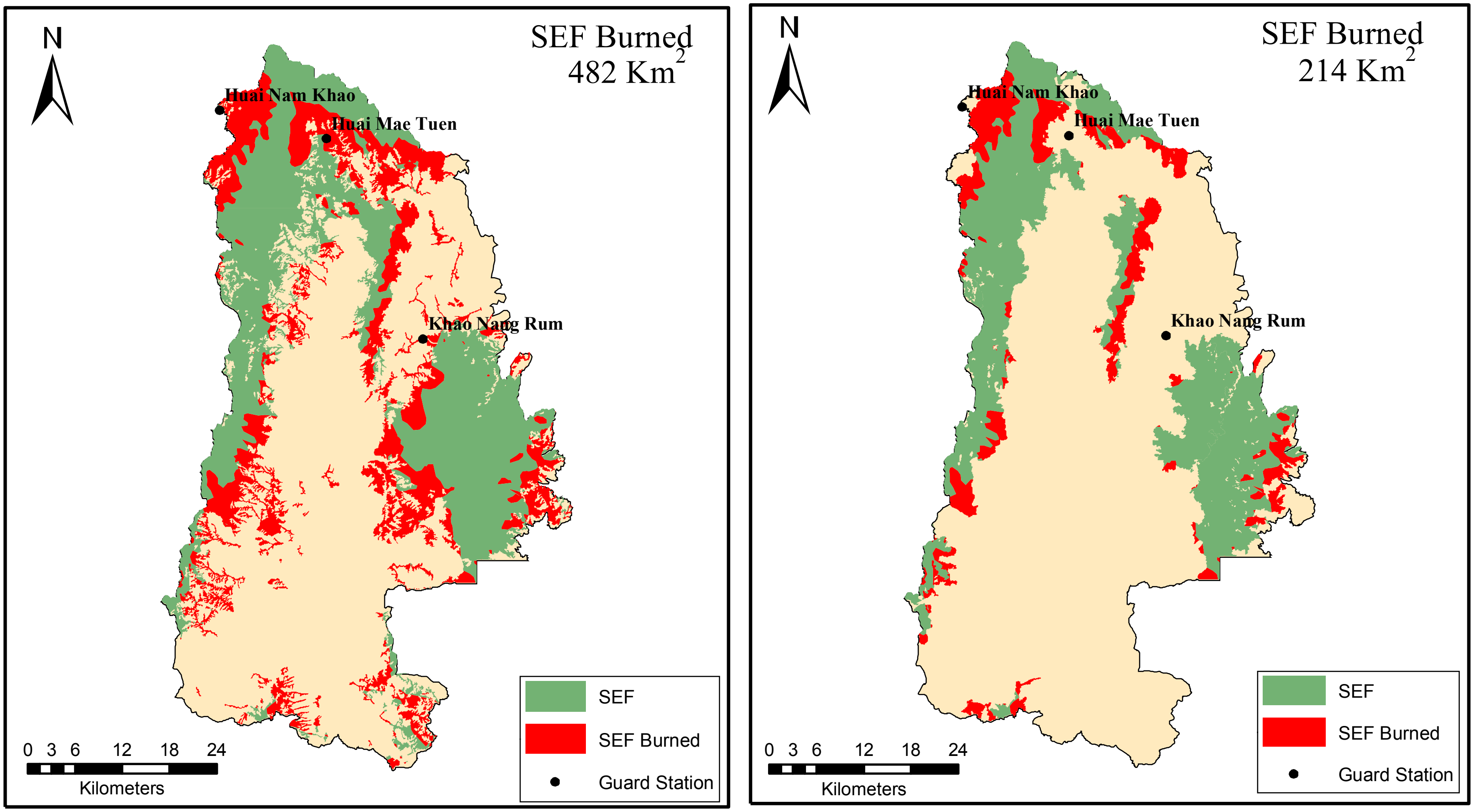


Figure 3.7 Comparison of the 1994 burn area using the seasonal evergreen forest area classification for 1995 and 2000. The burn area from the 1995 classification (left) is larger than that from the 2000 classification, because the area classified as SEF in 1995 was larger; further indication of degradation of evergreen forests to deciduous forest types.

Reclassification of SEF in 2000 was likely done because the area was no longer dominantly intact SEF.

Fieldwork and interviews in areas of intact SEF revealed significant areas of intact SEF had burned.[39] Some areas of intact SEF, which were many kilometers removed from the forest edge, burned. For example in Sai Ber, a site with moist, dense forests, burn marks on trees were frequently encountered (e.g. App. 3-2b). Yah-tek-ho, a Karen hill tribesman and Sanctuary guard, explained that the whole mountain east of Sai Ber burned in 1994.[40] At Yuyi, another moist site, at high elevation (1000-1100m), sanctuary guards indicated that a large fire burned through SEF in the area in 1998. At the permanent plot, a 50 ha research plot near Kapokapeang Station (Fig. 3.4), RFD forest ecologist S. Bunyavejchewin (pers. com., 2002) confirmed that the permanent plot burned completely on two occasions, in 1992 and 1998.[41] Baker who observed the 1998 fire noted that within this context the fires were patchy low-intensity surface fires that burned to a height of less than 1.5 meters (Baker & Bunyavejchewin, In prep).

Further validation of this point is illustrated in Figure 3.8. Whereas the permanent plot is known to have burned in 1992 and 1998, these areas are not really indicated on the

---

[39] The average canopy cover for SEF was 96.5%.
[40] This date was confirmed by Manus Panmon (pers. com., 2004)
[41] Baker and Bunyavejchewin indicate in several papers that the permanent plot has burnt three times, 1990, 1992, and 1998 (cf., Bunyavejchewin & Baker, 1995; Bunyavejchewin et al., 2002; Baker et al., 2005; Baker & Bunyavejchewin, In prep). However S, Bunyavejchewin (pers. com., 2002) clarified that the fire in 1990 which occurred between April 11th and 18th, only burned a small portion of the southeastern corner of the plot.

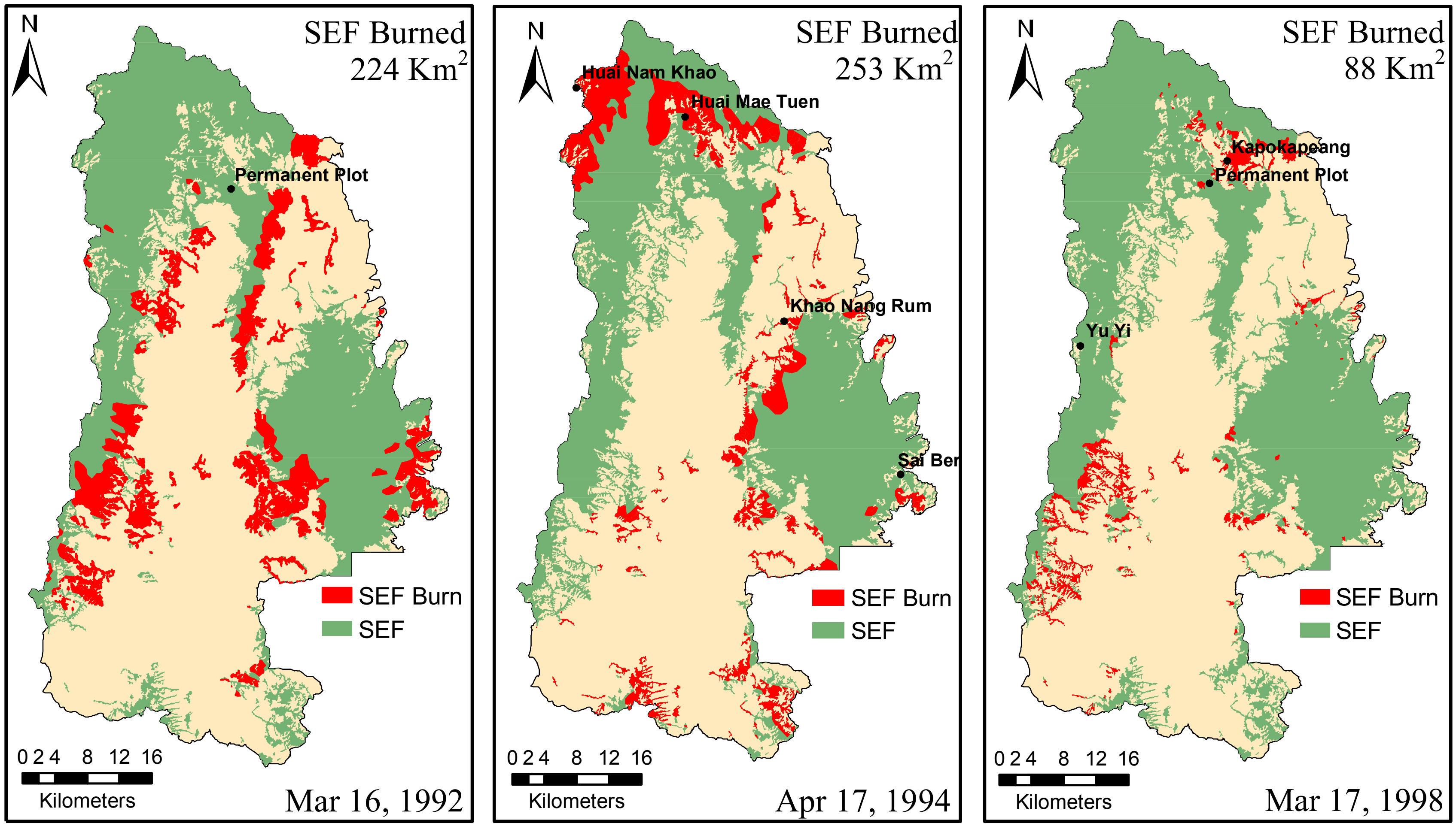


Figure 3.8 Burn area for seasonal evergreen forest in HKK for major fire years. Local reports of extensive burning exist for SEF for the permanent plot in 1992 (left), Huai Nam Khao, Huai Nam Tuen, Khao Nang Rum, and Sai Ber in 1994 (middle), and the permanent plot in 1998 (right), but are not shown on satellite generated burn maps.

Landsat fire history (Figs. 3.8a,c); although the problem could be that the Landsat image was taken before the fire occurred. However for at least the 1998 fire, P. Baker, who was in the area at the time, was able to confirm that the fire burned through the entire permanent plot on March 14th (P. Baker, pers. com., 2002), three days before the image was taken. The same general situation is true for the 1994 fire year. Interviews revealed that the forests around Huai Nam Khao, Huai Mae Tuen, Khao Nang Rum and Sai Ber stations burned in this year, yet the fires at Khao Nang Rum and Sai Ber are not really apparent despite the fact that the burns were documented from a near-end-of-fire season image (April 17, 1994) (Fig. 3.8b).

Finally, comparison of the SEF history, and the reconnaissance and interview findings indicate a significant underestimation in the area burned in the fourteen-year period. The cumulative burn area for HKK over fifteen years, 1988 through 2002, is shown in Figure 3.9. Orange circles indicate locations for which burn marks on trees or fire scars are present, and for which guards were able to confirm the year of burn. If the SEF plot data are considered the cumulative burn area is significantly larger than that shown, suggesting that 90% or more of the Sanctuary may have burned in recent years.

3.5 Discussion

The results show that significant areas of SEF have burned in HKK in recent years. Much of the burning has occurred in more open or degraded SEF, but there is also evidence and reports of fire in intact SEF far removed from the edge and within the forest

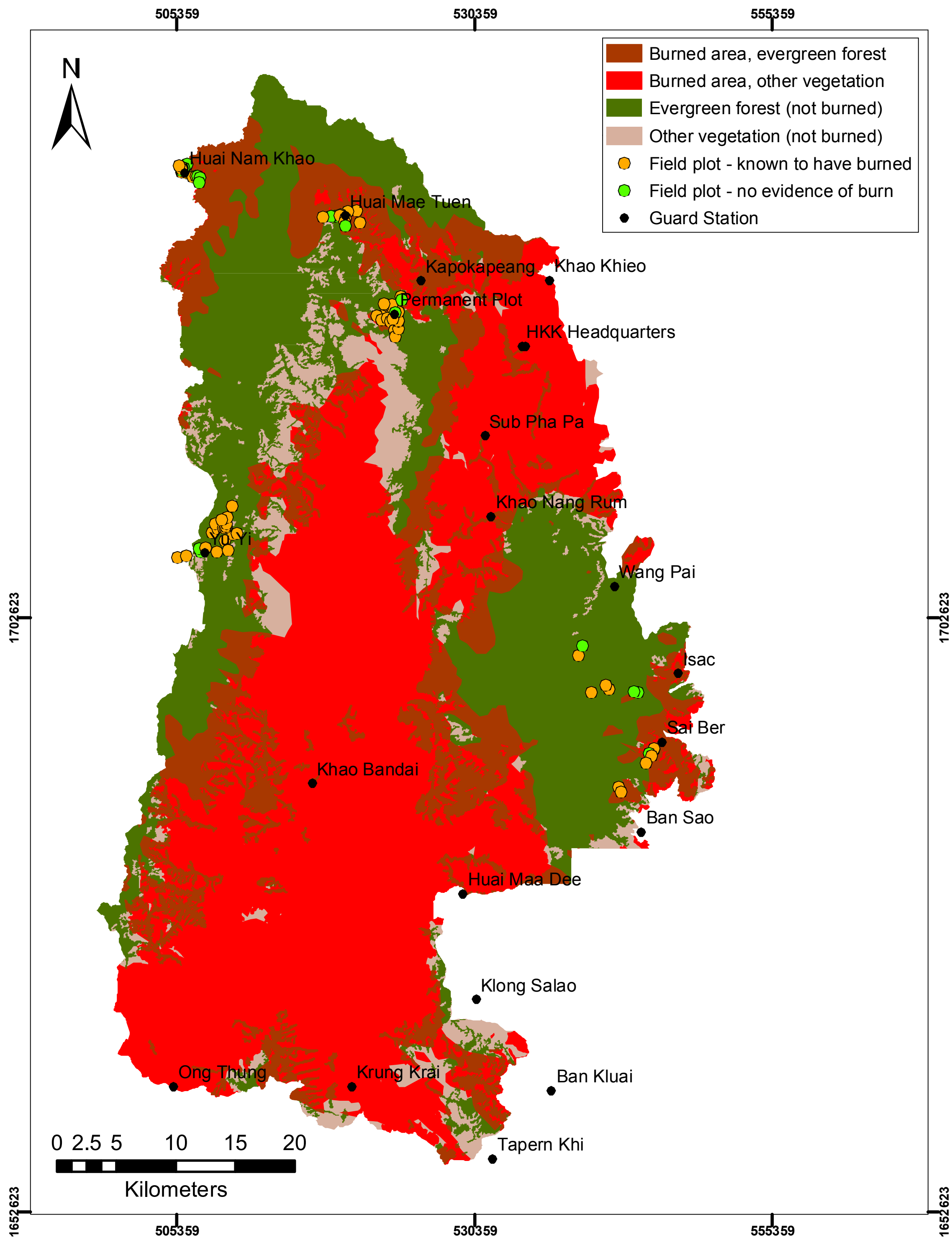


Figure 3.9 Cumulative burn area of Huai Kha Khaeng from 1988 to 2002. Note the burn area does not extend to the field plots in intact SEF (orange circles) suggesting that the total burn area for the Sanctuary is significantly under-represented.

formation. Some intact SEF, such as that in the permanent plot, has burned twice in recent years. This is a different picture of fire in SEF than what is generally presented in the literature. Most of the literature for the region notes only minor burning at the edge of SEF (e.g., Stott, 1988, 1990; Giri & Shrestha, 2000).

Discrepancy between the historic understanding that intact SEF does not burn (e.g., Wharton, 1966; Ogino, 1976) and this research showing that it does, is likely due to a real difference in burn frequency between the past and now. Historically, fire in SEF was probably a rare event as these forests are generally moist and not prone to burn. However an historic lack of fire in SEF does not mean that SEF was not flammable on occasion, but rather, that a source of ignition was not present at the critical time. Historically, there were fewer people living in remote forested areas than at present (TDRI, 1986; Santisuk, 1988); further the landscape matrix was mostly mature forests, quite different from the expanses of more flammable open deciduous forest and savanna vegetation seen today (cf. Ch. 2). In other words, the probability for an ignition source being present in the vicinity of SEF during periods of forest flammability was historically much lower than it is today (cf., figures 2.4 and 2.5).

Discrepancy between more current references indicating SEF does not burn and has not been burning (e.g., Stott, 1988, 1990; Giri & Shrestha, 2000) may reflect more of an assumption of no burning, rather than field-based observation. In part, these references are likely passing on an historic understanding of the fire situation for SEF. However, there may also be problems related to the way observations of fire in SEF are currently obtained. This research suggests the satellite-based technologies (e.g., Landsat) used to document fire occurrence in mainland Southeast Asia are not sensitive enough to detect understory fires in intact SEF. Reconnaissance and interviews undertaken in this research showed that many areas not indicated to have burned in the SEF Landsat fire history had actually burned.

The study is limited in that the methods employed were inadequate to determine the full extent of burning in SEF. While the choice of satellite sensor data, Landsat TM, was spatially and spectrally appropriate and is commonly used to detect burn areas at a local scale in forests in mainland Southeast Asia, it was limited in terms of its capability for mapping surface fire under the canopy of SEF. Additional research is required to determine a more appropriate satellite sensor system or approach for mapping fire in intact SEF.

3.6 CONCLUSION

The purpose of the chapter was to investigate the extent of fire in SEF in HKK. A fire history for HKK was built and reconnaissance and interviews conducted in the field. The results show that in recent years SEF has burned far more extensively than is generally indicated in the literature, and that the burning has not been limited to the edge of SEF or degraded areas. The reason that the occurrence of fire in SEF has not been more widely recognized could be because first, SEF has not historically been considered to be a forest type that burns. Second, Landsat TM, a satellite sensor commonly used to assess the burn area at a local level, has limited capability to detect fire in intact SEF. Additional research is required to determine a more appropriate sensor system or ground-based approach for mapping fire in SEF.

CHAPTER 4 CONDITIONS FOR FIRE IN SEASONAL EVERGREEN FORESTS

4.1 INTRODUCTION

Current understanding is that the primary factor influencing SEF flammability is fuel moisture content (cf., Mueller-Dombois, 1981; Uhl et al., 1988; Kauffman & Uhl, 1990; Holdsworth & Uhl, 1997; Nepstad et al., 1999a), and that SEF burns when leaf litter moisture content is low enough to ignite and spread from fires burning in adjacent open deciduous forest and savanna. However there is some research to suggest that additional factors such as litter load and season may also be important in influencing SEF flammability (cf., Stott, 2000; Cochrane, 2003). Understanding the reasons SEF burns is important as it may help form the basis for a fire management approach in protected areas (PAs).

The purpose of this chapter is to establish the conditions for fire in intact SEF in HKK; specifically sources of ignition as well as the factors that affect the susceptibility of SEF litter to burn including, moisture content, load, continuity, and early versus late dry season timing. The research included undertaking interviews to determine the source of ignition for fire in SEF, and also building test fires to determine conditions for ignition and spread.

4.2 BACKGROUND

Fire occurs when there is a source of ignition and flammable fuels (Nepstad et al., 1999a). The source of ignition for fire in SEF is generally considered to be fires in adjacent vegetation. Studies from the Amazon show that people set fires in fields and disturbed areas and these fires, in some years, spread into adjacent tropical evergreen forests (Nepstad et al., 1999a). This is also considered to be the case in mainland Southeast Asia (cf., Stott, 1988; Stott et al., 1990).

Less is known about the conditions under which leaf litter fuels in SEF become flammable. In general, the understanding is that the primary factor that sustains fire in SEF is low fuel moisture content (cf., Mueller-Dombois, 1981; Uhl et al., 1988; Kauffman & Uhl, 1990; Holdsworth & Uhl, 1997; Nepstad et al., 1999a). As Batchelder et al. (1966, p85) states, “The combination of high humidity beneath the upper canopy, absence of wind, and high moisture content of the forest litter produce an environment inimical to fire from natural causes.” Early research on the leaf litter moisture content for flammability in evergreen forests in the Paragominas, Brazil, suggested the upper threshold for fire to be 12% (Uhl & Kauffman, 1990; Holdsworth & Uhl, 1997).

There are also reasons to believe that moisture content may not be the only factor limiting fire in SEF. For instance, as part of his research, Ofren (1999) sampled fuel conditions including load, moisture content and leaf litter depth in SEF in HKK. His data show litter moisture contents in SEF as low as 9.9% for the 1997 dry season, despite the fact that it was not a particularly dry year or a significant fire year (App. 4-1).[42] The finding seems to suggest that SEF in mainland Southeast Asia may experience moisture contents low enough to burn more commonly than thought, yet fires do not generally occur.

Additional factors that seem to influence SEF flammability in mainland Southeast Asia are: 1) the timing of fires in SEF; and 2) leaf litter load. The timing of fire in SEF is of interest for several reasons. The first reason is reports that indicate most fires in SEF in mainland Southeast Asia occur at the end of the dry season, that is, March and April. Of the 1998 fires, all the fires documented in SEF in national parks (including Doi Inthanon, Huai Kha Khaeng, Khao Yai, and Phu Kadong) took place in March or later (Bangkok Post, 1998a, 1998b, 1998c, 1998d, 1998e, 1998f, 1998g, 1998h; Akaakara, 2002). Also, Jones (1997, p. 3), who used remote sensing to analyze the fires that occurred in mainland Southeast Asia in 1992/3, noted:

> *Most of the fire activity (69%) was in the last two months of the dry season (March-April). This late dry season fire activity is mostly accounted for by increases in the incidence of fire within closed and fragmented evergreen forest…"*

The wider SEF literature also supports the finding of increased late fire season SEF flammability. Biddulph and Kellman (1998), who researched fire in evergreen gallery forests in Gran Sabana, Venezuela, noted that fuels in these forests can reach an ignitable

---

[42] Moisture contents for SEF (and the other forest types) in Ofren (1999) were not calculated with the correct formula. The corrected numbers are presented above in the text, and the re-calculations are presented in Appendix 4-1.

state late in the dry season but that frequent fire entry is probably precluded by the tendency of savanna fires to occur earlier in the dry season and by discontinuities in fuels at the savanna/forest contact. J. A. Carvalho et al (2003) also observed the late fire-season propagation of fire from a forest opening to SEF in Alta Floresta, Brazil.[43] Fire was found to sustain at moisture contents of 13.5% or less and was associated with fire spread rates between 0.16 and 0.26m/min, flame lengths between 15 and 30cm, and flame thicknesses in the order of 10 to 15cm.

A recent, more in-depth investigation of the moisture content threshold was done in the Paragominas, Brazil, however this time with the emphasis on igniting test fires at the end of the dry season. Ray et al. (2005) lit 100 test fires in intact SEF and open SEF forest types at each of five separate sites during the last two months of the dry season.[44] Test fires were carried out by: first, placing a 20cm metal hoop on the forest floor; second, applying 10ml of kerosene to the leaf litter in the center of the hoop; third, igniting the kerosene in the hoop and recording the distance and fire spread rate up to one meter. A combination of regression techniques (nonlinear, stepwise, logistic) was used to identify relationships among variables. Ray et al. (2005) found that the leaf litter moisture content threshold for surface fire in intact SEF was 23%, which is considerably higher than the 12% established by Uhl and Kauffman (1990) and Holdsworth and Uhl (1997) in

---

[43] Confirmation that the fire occurred at the end of the fire-season was obtained through personal communication with J. A. Carvalho (pers. com., 2006).

[44] Rainfall for the region is strongly seasonal. While the average annual rainfall is 1843mm, 75% of this total comes during the six-month wet season from January to June.

the early dry season. During the trials an average litter load of 4.2 +/- 0.2 Mg/ha was measured, and a fire spread rate of 0.076 +/- 0.019 meters/minute (m/min) was reported.[45] In comparison to the early season studies of Uhl & Kauffman (1990) and Holdsworth & Uhl (1997), the high moisture content threshold of Ray's findings seems to suggest that leaf litter may be more flammable later in the fire season even if relatively moist.

Finally, increased late-fire season flammability for SEF was also found by Negreiros (2004). Negreiros undertook Ph D. research to define and quantify the fuel moisture content "threshold" for SEF in Alta Floresta, Brazil. Thirteen experimental plots were set out, each plot containing five subplots within which test fires were conducted. Negreiros (2004) used a test fire method similar to Ray et al. (2005), except that spread events were only recorded to a distance of two meters. Each plot was considered to be one experiment and the five test fires ignited that day between 1300 and 1500 hours. Experiments for each of the 13 plots were conducted on different days between July 17th and August 22, 1999. Negreiros's results showed that although litter moisture contents in the experimental plots varied between 10.5 and 26.5% (at the time of burning) there was no direct correlation between flammability and environmental variables such as litter moisture content. The only obvious result was that high flammability[46],[47] plots were concentrated at the end of the fire season, whereas the low flammable ones were

[45] Mega-grams per hectare (Mg/ha) is the equivalent of tonnes/hectare (t/ha).
[46] According to Negreiros's index, experimental plots of "high flammability" are those where test fires reached the 2 m point on at least 3 of the 5 ignition circles and burned more than 50 % of the total area.
[47] The maximum fire spread rate for the 13 plots was between 0.12 and 0.29 m/min.

observed at the beginning. Negreiros (2004, p. 102) was not able to explain this finding further indicating that,

> *None of the regression analyses resulted in a statistically significant relationship between fuel moisture content and either of the measured environmental variables, burning behavior or flammability (r^2 values greater than 0.22 were not observed. For example, the highest measured FMC (fuel moisture content) of the litter was noted for experimental plot B5; however this was one of the two plots with the highest flammability index. In addition, the second driest litter plot (plot B3) was classified as having a low flammability index. Other measured variables, such as litter depth and mass, surface soil humidity and surface fuel temperature, did not provide additional insight or clarification in the burning behavior of the 13 plots.*

The other factor that has been suggested to be of importance for SEF flammability is fuel load (cf., Stott, 2000; Cochrane, 2003). More, specifically, fuel load is indicated as a potential factor in SEF flammability in mainland Southeast Asia because of the work of Kanjanavanit (1992) in HKK. As part of her research, Kanjanavanit set out to look at the conditions for 'sustainability,' that is, the capacity for vegetation to sustain fire, in closed deciduous forests in Thailand.[48] After lighting fires and burning leaves in closed DDF early in the dry season (January), Kanjanavanit determined that a sustained fire spread of 15cm or more required: i) a leaf litter moisture content below 8.4%; and ii) a litter depth of at least five leaves.[49],[50],[51] She also observed that "fire did not occur at all in the more

---

[48] The primary fuel in closed deciduous forest is also leaf litter. Peak leaf fall for both closed deciduous and SEF forests occurs in February (Kanjanavanit, 1992). Ofren (1999) found similar dry season litter loads in both forest types.

[49] A fuel load equivalent was not available.

closed stands of any Dipterocarpus association and mixed dry dipterocarp forest until March," a factor that she attributed to a combination of higher fuel loads and higher wind speeds at that time of year.[52]

4.3 METHODS

The approach taken to investigating the conditions for fire in SEF in HKK was to: 1) interview guards on how fires in SEF start in HKK; and 2) build test fires and measure fuel conditions for fire spread in SEF.

4.3.1 Source of ignition

Investigating sources of ignition for fire in SEF involved holding interviews with forest personnel during the fire season in 2000 and 2001. Interviews were conducted at each of the guard stations in HKK as well as with forest researchers in Bangkok. Approximately 10 interviews were undertaken primarily with Royal Forest Department officers, and Sanctuary guards. Most interviews were conducted in the field where past burns could be located and discussed. Individuals were asked about fires in SEF, which they had observed in HKK, and how and when these fires started.

---

[50] According to Kanjanavanit (1992), leaf litter depth reached its highest from 1 leaf deep in November to 5 leaves deep in March, and the leaf litter cover value attained 95% in March, in contrast to a mean value of less than 40% in December 1987.

[51] Kanjanavanit ignited most of her test fires in closed deciduous forests early in the fire season; i.e., January and February.

[52] Higher wind speeds would not be a factor in SEF.

4.3.2 Conditions for fire spread in SEF

The conditions for fire in SEF were investigated by recording the fuel characteristics at the site and then lighting test fires. The field fire research was conducted during the fire season from February 1 to April 30 of 2001. Methods included the selection of study sites, sampling strategy, plot layout, measurements, and calculations. More detailed measurements were made in one plot, which is referred to from here on as the ‘detailed plot’.

4.3.2.1 Study sites and sampling strategy

Guard stations located nearest to evergreen forests were used as a base for access to SEF. These stations included: Huai Mae Tuen, Huai Nam Khao, Isac, Kapokapeang, Khao Nang Rum, Sai Ber, Wang Pai, and Yuyi (Fig. 2.8).[53] Field-testing started at Khao Nang Rum on February 14th; however there was difficulty with communications and permission to undertake test fires never reached the station. These first plots helped establish the sampling program, though without the accompanying test fires the plots themselves were not of use. From Khao Nang Rum the field crew drove to Sai Ber station to arrange a date for a traverse of the area, as well as set up the Hobo Sensors for temperature and relative humidity data collection, which will be discussed later (Ch. 6). On February 25th a ride on a helicopter to Huai Nam Khao station was arranged. After initial fieldwork in Khao Nang Rum and Huai Nam Khao a period of time was required

[53] Khao Nang Rum research station area was sampled; however due to a communication mix-up, we were not allowed to set fires, so plots from the area are not included.

to assess the data acquired and needs for the rest of the field season. Between March 2nd and March 6th equipment was obtained, photos developed, fuel samples dried, interviews performed, field students recruited and food bought for reconnaissance in the Sai Ber area. On March 7th the field crew returned to Sai Ber for fieldwork but were interrupted March 10th with heavy rains. Again, the crew went back to regroup, process samples, and organize for the move to the next station.

On March 17th the crew had the opportunity to fly by helicopter to Yuyi station on the west side of HKK, though the forest was not dry. This was a useful time of observation and discussion with guards in the forest, though ultimately these plots were too damp to use. As more rain fell, the field crew left Yuyi guard station on March 27th and remained in Bangkok processing data until April 4th.

It was hoped for a period of drying in the Sanctuary, so fieldwork was abandoned until April 4th. At that time the field crew drove to Kapokapeang station where the area was sampled and the crew then hiked to the Huai Mae Tuen station. The weather was still not very stable, with high winds above the forest, which were generally not felt on the ground, though occasionally trees would blow over.

The last trip into HKK was from April 26th to April 30th. The primary goal of this reconnaissance was to collect the sensors at Sai Ber. Additionally, a substantial trek was made over the mountains to Wang Pai, and additional plot data were collected. The number of plots per vegetation type is provided in Table 4.1 and Appendix 4-2.

Table 4.1 Number of plots per vegetation type

	SEF Closed	SEF Open	Bamboo	Banana	Grass
Huai Nam Khao	12	5	15	12	15
Sai Ber	14	0	3	6	6
Yuyi	31	18	0	0	3
Kapok. - Huai Mae Tuen	57	29	8	0	0
Sai Ber - Wang Pai	10	9	3	0	0
Total	124	61	29	18	24

The sampling strategy was to access areas of intact evergreen forest and sample leaf litter fuel in as many plots over as extensive an area of the SEF as possible. SEF sampling was done in straight lines at an approximate interval of one km. Detours were made to adjacent successional areas, including open SEF_{open}[54], as well as bamboo[55], banana[56], and

[54] Refers to SEF which is more open in character; there may be a sense of more light, a drier environment and some grass may be included in with the surface fuels.
[55] Refers to bamboo in mixed deciduous forest.
[56] Refers to a closed field of mature banana; banana is a successional element in SEF.

grassland[57] so that these areas could be sampled separately and comparative data collected.

Sampling in the field was not straightforward. Access to the guard stations was not always easy to arrange. Some sites such as Yuyi and Huai Nam Khao required helicopter access, which was only occasionally available. Plans had to be shifted quickly in order to take advantage of any opportunities to access remote sites.

Once at a guard station, it generally took some effort to locate areas of intact evergreen forest and to convince guards to go there. Though forest cover maps and topographic maps had been prepared ahead of time, forest types were not always as shown on maps. At many stations the surrounding SEF was considerably more deciduous than expected. Through the use of maps and discussion with station guards, a course would be selected (negotiated) for the following days. Lack of trails, dense bush, water shortages and uncertainty about what would be encountered were all considerations. Early plans were kept flexible; then later with better planning and access to more knowledgeable people, more extensive areas were covered.

Most traverses were day and overnight trips out from the guard station in various directions. Other traverses were extended trips between stations in order to access more

[57] Includes areas where the grasses are short as well as those where the grasses are very tall (+3 m).

remote areas of SEF. Two ‘between station’ trips were from Kapokapeang to Huai Nam Khao and from Sai Ber to Wang Pai; the latter was a four-day overland trip through mountainous terrain (Figs. 2.6, 3.9).

A major limitation to fieldwork was the weather. March 2001 was a rainy month in HKK as a heavy tropical depression hit and 129mm of rain fell between March 5 and March 25.[58] Intermittent rain was encountered throughout the rest of the field season. During these rainy periods access to areas was difficult. Though some sampling continued, most of the plots conducted between March 9 and April 4 were too damp and ultimately had to be deleted from the analysis.

4.3.2.2 Plots

A fire sampling plot usually included three subplots; that is, the center location and two subplots at 50m distances from plot center. After moving an approximate distance of one km, a plot center was randomly selected by turning around and throwing a small wooden sampling frame over the shoulder. Wherever the sampling frame landed was plot center.[59] After the site was described and measurements taken including fuel, canopy closure, and microclimate at plot center, a decision was made on the direction to take each of the 50m subplots. An effort was made to stay in a similar forest and site type

---

[58] Source: Khao Nang Rum Station data acquired from RFD in 2003.

[59] If the frame landed at the foot of a tree the frame was moved two meters away from the tree to facilitate the taking of the hemispheric photos, after Frazer et al. (1997).

(*i.e*., forest structure, slope, etc.). Each plot including three subplots took an hour to an hour and a half to complete, with the setup of the camera for hemispheric photos taking most of the time to position and level the tripod. The hemispheric photos required setting the camera at 1.3 meters, careful leveling, orientation of camera lens mount to north, and multiple shots at different apertures.[60] In all, 124 plots and 256 subplots in the five vegetation types were undertaken. Many of the plots had to be omitted from the data set because the fuels were damp[61], or because a test fire was not conducted. Final subplot data included: 77 SEF_{closed}; 35 SEF_{open}; 25 bamboo; 17 banana; and 7 grass. Plot locations are provided in Appendix 4-3.

4.3.2.3 Measurements

Measurements relating to fuel, canopy gap, site characteristics and fire ignition were collected. The sampling process is shown in Appendix 4-4. A sample of the plot card used to record site measurements and vegetation conditions is presented in Appendix 4-5.

4.3.2.3.1 Fuel

Fuel measurements included: fuel coverage, surface fuel depth (or height in the case of grasses), fuel load (live and dead), fuel moisture content (live and dead). The percent fuel cover was established by placing a rectangular ‘fuel cover sampling frame’ flat over seedlings and ground fuel at plot center as per the recommendations of Dr. B. Anholt

---

[60] Methods for taking the hemispheric photos were after Frazer et al. (1997).
[61] Subplots with leaf litter moisture content over 40% were omitted.

(pers. com., 2001). The 'fuel cover' sampling frame is a small 60 x 40cm wooden frame. The sampling frame is rectangular so that it can be easily carried on the front of a pack. Thin wires are strung across the frame in intervals of 10cm, making 24 squares of 10 x 10cm each. The researcher stands above the frame and counts the number of squares that are primarily filled with a fuel type such as dry leaves, or grasses, or no fuel (e.g., bare soil). An approximate percent cover of each fuel type is then ascertained by multiplying the number of squares filled by a particular fuel cover by four.

The fuel load was established by using a different wooden 'fuel load' sampling frame. The 50cm x 50cm square frame was placed over the plot center where the fuel cover sampling frame had been. The 'fuel load' frame was constructed with a hinge on one side so that the side could open. This style of frame was used so it could be either placed on top of relatively flat surface fuels, or unhinged to surround grass fuels that were sometimes several meters tall. The material within the frame was separated into live and dead fuel, weighed with an Ohaus Compact Scale model CS-200[62], and recorded. Fuel material was weighed in a plastic bowl (or plastic sheet) and the weight of the bowl (sheet) subtracted afterward. If a stick was present (infrequent), the portion inside the frame was cut and weighed and the dimension of the stick inside the frame noted. The square sampling frame as well as the leaf litter material that was previously inside the

[62] Specification accuracy of the scale is +/- 0.1 grams.

frame is shown being weighed in App. 4-4a. The depth of the litter in the frame was measured using a tape measure and measuring from the soil surface to the upper leaf.[63]

The fuel moisture content was measured by first collecting an approximate 30 gram sample of live (seedling, grass) and dead (litter) fuel from the fuel materials that had already been weighed. With dry leaf litter, the sample was not limited to top materials but rather a mix of litter extending to the soil surface. Each sample was then placed into a plastic bag, labeled, weighed on the portable balance and the weight of the sample was recorded. On return to the fire research station in Lansac, the fuel sample bags were placed in a drying oven at 100^{0}C for 24 hours as per the direction of Professor Paul Woodward, University of Alberta (pers. com., 2000). The dried samples were then weighed on an electronic scale and the weight recorded. The difference between the field scale and the station scale was approximately 0.1 grams (g) for weights 30g or less.

4.3.2.3.2 Canopy cover

Methods used to measure canopy cover included both hemispheric photos and densiometer readings. While this work required considerable time and effort, ultimately little use was made of the measurements as focus was placed on determining flammability of intact SEF with complete or almost complete canopy cover (greater than 90%).

---

[63] Grass fuels were measured from the ground to the upper spears.

The methods for taking the hemispheric photos were as follows. First, a tripod was set up over the sampling square at plot center (App. 4-4b). The tripod was set to a height of 1.3m following Frazer et al. (1997). A light reading was taken for the camera and an appropriate speed and aperture setting for exposing film in forest light determined.[64] A manual Minolta camera was used with a Minolta 7.5mm F4 Fisheye Rokkor-x lens. The camera was mounted with the lens facing upward toward the forest canopy, and with an orientation plate mounted over the lens. The camera was turned to reflect a north-south orientation, and the lens carefully leveled. Two pencil thin red lights mounted at 180^0 degrees to each other on the orientation plate were then turned on so that each resultant hemispheric photo would show small dots of red to the edge of the image, two dots indicating north and one dot south. Two photos were then taken, one at an aperture setting of one under what would normally be used to photograph given the light conditions, and another at a setting of two under normal. The photo and film number along with aperture setting and film speed were recorded. At a later date the films were processed, and Gap Light Analyzer (GLA) software (cf., Frazer et al., 2000) used to analyze the percent of canopy cover (App. 4-6).

The densiometer reading was taken by removing the tripod and camera, then standing over plot center with a concave spherical densiometer. Holding the instrument level,

[64] Somewhat underexposed images were required for use with the Gap Light Analysis (GLA) software (Frazer et al., 1997)

between 12 and 18” from the body at elbow height, the mirror in the densiometer was adjusted to reflect the canopy gap. Assuming four equi-spaced dots to each square of the grid, the dots were systematically counted to reflect quarter-square openings. The number of dots was then multiplied by 1.04 to obtain the percent of overhead area not occupied by canopy. Four readings were made per location, one facing each direction (north, southeast, east, and west). The readings were then averaged and recorded. The difference between 100 and the gap was the recorded estimation of overstory canopy cover in percent.

4.3.2.3.3 Plot description

Site description for each plot included: GPS location, habitat type, time, cloud cover, wind estimate, elevation, slope, and aspect. The GPS location was established using a Garmin 12 XL GPS. The GPS was set with a datum setting of Indian/Thailand (1975) and the position was determined after a connection was established with at least three satellites. If a GPS position could not be established due to heavy canopy (not generally encountered), the researcher moved a short distance to a location where a signal could be established and the movement away from plot center noted. The habitat types were classified into the following categories: closed evergreen forest, open evergreen forest, bamboo, banana, and grass. Dominant species were noted and a photo of the stand structure was taken with a person in the shot for scale.[65] The presence of burn marks or fire scars on trees was also noted.[66]

4.3.2.3.4 Test fires

The final work at each plot site was the fire ‘spread’ test, which was conducted by attempting to ignite a fire and allowing it to spread in an undisturbed area near the plot center. The protocol was to hold a cigarette lighter to the leaves for 5 – 6 seconds, and then repeat three times in the same spot if necessary.[67] If the leaves ignited, the progress of the flame was then timed out to 50cm from the point of origin. If the flames extinguished before 50cm, a distance measurement from the origin out to the farthest point burned was recorded. Later after the data were assessed and a clear difference emerged between those fires that burned under 20cm and those that burned to 40 or 50cm, fires that were 40^{+}cm or greater were included as ‘spread’ events. A test fire in bamboo is shown in Appendix 4-4c.

It was not possible to take fuel measurements and ignite fire in the same place because of other sampling requirements. To accommodate this situation, fuel measurements were

[65] An Olympus Stylus 140-zoom camera was used, a compact camera.

[66] Burn marks or fire scars can be recognized as triangular shaped, at base of tree, possibly on twigs, usually on multiple trees, usually on uphill side.

[67] In some of the earlier plots 20ml of gas was used to ignite test fires. However at the time, conditions were hot and dry, the terrain was rough and it was difficult to carry the flammable material without it spilling in packs. I made a decision to ignite test fires via multiple attempts using the cigarette lighter, instead of using an accelerant.

taken at the plot center and the test fires lit as close to the plot center as was practical, usually within one meter.

4.3.2.3.5 Detailed plot

On April 12th a plot (plot 5-38) was established, near the permanent plot (Kapokapeang), where the test fire showed a 'spread' event. To increase the amount of 'spread' data available for the dataset, two additional subplots were conducted in the plot (i.e., 5-38 D and E[68]), and the plot 5-38 identified as the 'detailed plot.' In addition to the stand field data collection, whole leaf litter samples were collected in the subplots for later identification at Kasetsart University, Faculty of Forestry, in Bangkok.

4.3.2.4 Calculations

The following formulas were used to calculate leaf litter load and moisture content (MC) of both the live and the dead fuel samples.

$$Load_{Leaflitter} = weight_{litter+container} - weight_{container}$$

$$MC_{Leaflitter} = \frac{weight_{green} - weight_{dry}}{weight_{dry}} \times 100$$

[68] Subplot 5-38E was incomplete.

4.4 RESULTS

4.4.1 Source of ignition

The primary observation from the field research on sources of ignition was that the SEF fires generally initiate in open deciduous forests and savanna at some distance from SEF. Although lightning-initiated fires do occur, most fires are lit by people burning in grass fuels characteristic of open vegetation types.[69] The RFD fire control unit was observed responding to many fire ignitions in February, just outside the east and southern sections of HKK, near villages. The fire activity with respect to ignitions appeared to increase after February 10th, which is likely to be the case in general since the RFD typically stations a helicopter to assist with fire suppression in the Sanctuary at the beginning of February each year.

Two locations were visited where fire ignitions occurred. In the first case, fire officials took me to a site southeast of Khao Bandai station where a fire was started in 1999. The fire was ignited in a patch of bamboo,[70] and from there spread into adjacent open DDF. The second case was a fire event the researcher came upon one night in April. The fire, which was presumably ignited by local people, was in the buffer zone, just off the main road leading into HKK Sanctuary headquarters. The fire was burning in shrubs and grass

---

[69] Most lightning occurs at higher elevations in the Sanctuary and is generally accompanied by rain (Guard pers. com., 2001).
[70] Bamboo is highly flammable.

in open DDF at a relatively low flame height and spread rate, with occasional flare-ups where more flammable vegetation was encountered. There was music and laughing in the darkness nearby until the people noticed that someone had stopped to assess the fire. It seemed likely the group set the fire an hour or two earlier (App. 4-7a).

Fires also burn into the sanctuary from the northeast and northwest corners of the Sanctuary. A large area of grassland, which is in the neighboring Umpaeng National Park, abuts the northwest corner of the Sanctuary near Huai Nam Khao (App. 4-7b). Guards stationed in the area explained that fires are set annually in the grasslands. Some years these fires will burn up to the station and in the occasional year they will continue into SEF in HKK (Guard, pers. com., 2001). Fires also burn in from outside the northeast corner of the Sanctuary. These fires can affect SEF near Huai Mae Tuen Sanctuary. However no additional information was available on that situation.

An exception to ignitions outside SEF was the case of Yuyi in 1998, where a fire was set in a grassland field directly adjacent to SEF. Guards described the situation at Yuyi whereby a poacher passing through SEF on the Monk trail lit a fire in a field of elephant grass. It is unclear whether the fire was ignited this way or sparked by one of the other fires that were burning all around this Sanctuary that year. Guards who fought the fire reported that the fire moved into the SEF along the forest floor through the root matt, popping up occasionally and fully charring any dead standing trees.[71]

The observation that the ignition source for fires that enter SEF are fires set in grasslands and deciduous forests a long distance from SEF is also supported by the fire history information obtained in Chapter 3. From the fire frequency data (Fig. 3.2), it is apparent that fires occur on a near annual basis in the eastern part of the Sanctuary near villages and along the Sanctuary's transportation corridors. Further, the comparison of the area of SEF burned each year as well as the total area of HKK burned as shown in Figure 3.6 indicates a near linear relationship. This relationship reinforces the conclusion that fire in SEF is very much connected to fire events in deciduous forest and savanna vegetation.

A second major observation is that fires must maintain themselves in grass fuels associated with deciduous forests and savanna until conditions in SEF are right to enter. Two interviews support this observation. First, a guard named Yah-tek-ho at Sai Ber Station in HKK (pers. com., 2001) described how in 1994 fires in HKK moved into SEF. From his description, it was clear that a number of grass fires had been burning at the base of the mountain in the early part of the dry season. Suddenly these came together as one large fire, moved into the SEF and spread up the mountain slope. Second, P. Baker

[71] Biddulph & Kellman (1998) noted that fires move from grassland into broadleaf evergreen forests via the root matt.

(pers. com., 2002) describes how fires in SEF in the permanent plot were initiated in 1998:

> *March 14 the fires burnt through the 50-ha plot. The fires were patchier in the evergreen forest but burnt about 95% of the 50-ha plot.*
>
> *I was at a meeting and got back on Feb 27 and the mixed deciduous and deciduous dipterocarp forest at Kapook Kapiang (Kapokapeang) were already burning. The fires got to the seasonal evergreen forest at Khlong Phuu (the 50-ha plot) about two wks (weeks) later. However, they also came back to KK (Kapokapeang) on March 3 and March 10 each time from different directions.*

4.4.2 Conditions for flammability in seasonal evergreen forest

Several observations arose from the test fires in closed SEF (SEF_{closed}). First, the test fires in SEF in the fire season of 2001 suggest that moisture content is a limiting factor for fire spread in HKK. Of the 77 test fires conducted in SEF between the end of February and late April 2001, the moisture content ranged from 7.4% to well over 50% with a mean of 23.2 $^+/-$1.2.[72] Only five tests resulted in a spread of fire to 40^+cm. All of these ignitions occurred at a fuel (leaf litter) moisture content of less than 19.7%. The fire-spread rate for those fires that burned over 40cm was 0.15m/min $^+/-$ 0.03. Field plot data are presented in Appendix 4-8.

The second observation is that moisture content is not the only factor limiting spread; this is suggested for two reasons. First, it was found that moisture content of less than 19.7%

---

[72] A low leaf litter moisture content of 5.8% was encountered but there was no test fire for this plot.

was not sufficient to ensure a fire 'spread' event. Twenty of the SEF_{closed} subplots had moisture contents of less than 19.7%, yet fires set in these subplots did not spread. Also, comparison with other vegetation types tested showed that the threshold was not as clearly defined for SEF as for other vegetation types measured. Although comparatively few test fires were lit in other vegetation types, those that were indicated the litter moisture content threshold range for spread in bamboo as 7.7 to 13.6%; banana as 9.2 to 12.1%; and in grass as 9.6 to 20.1%. By comparison the moisture content threshold range for SEF_{closed} was 9.0 to 19.7%, which was a broader range of values than for bamboo, or banana.[73] The moisture threshold range for each vegetation type for which spread events occurred is presented in Figure 4.1.

The third observation is that the fuel load for SEF_{closed} seems to be an important factor for spread. The research suggests that subplots with the higher loads were more likely to burn once ignited. The mean leaf litter load for test fires in SEF was 9.1 $^{+}/-$ 4.0 Mg/ha, whereas the mean load for test fires that showed fire spread was 10.9 $^{+}/-$ 1.4 Mg/ha. This observation was also supported by the work done in the detailed plot 5-38. In the detailed plot, five subplots were tested of which two had spread events to threshold (40-50cm) and three showed little spread at all (Figs. 4.2a, 4.2b, 4.2c).[74] Comparison of four of the five subplots (5-38) suggested that high fuel load was the only obvious difference

---

[73] The grass category included a wide range of grass species and grassland structure, from fine short grass similar to lawn to coarse two and three meter stalks associated with fields of elephant grass.

[74] All of the subplots were done between 11:15 and 12:40 pm on April 12, 2001

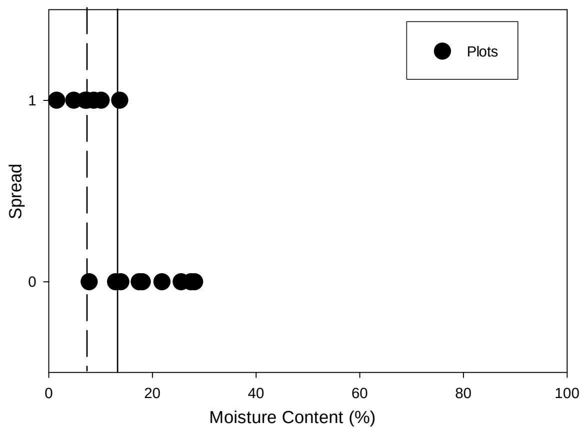


Fig. 4.1a Spread tests for bamboo litter

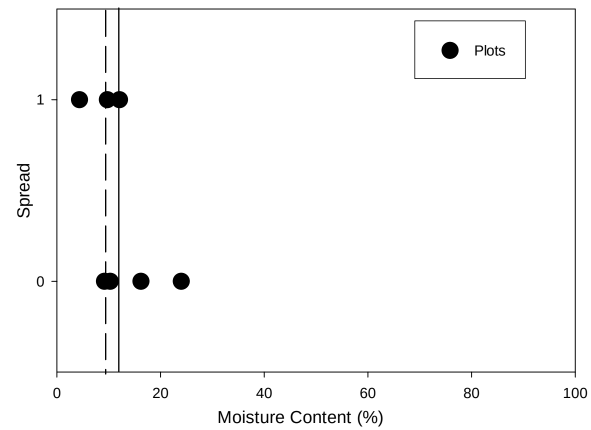


Fig. 4.1b Spread tests for banana litter

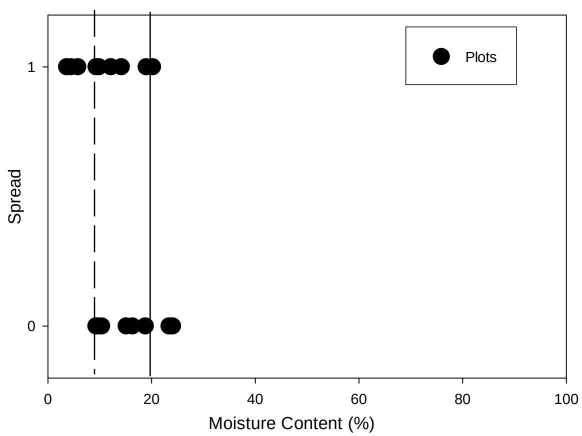


Fig. 4.1c Spread tests for grass

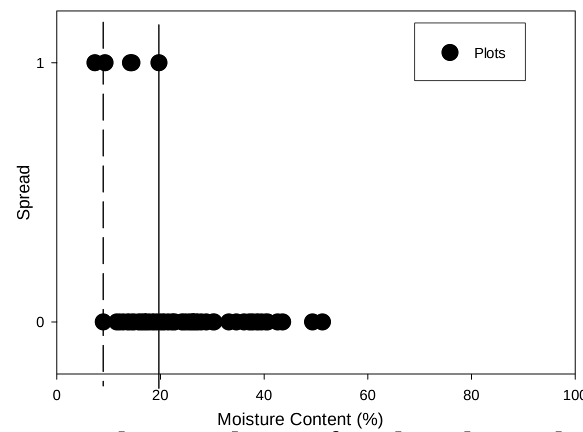


Fig. 4.1d Spread tests for closed SEF litter

Figure 4.1 Observed range in the moisture content threshold for fire spread in four vegetation types. There is a substantial range in the litter moisture content threshold for SEF compared to bamboo and banana leaf suggesting other factors may also be important for fire spread in this vegetation type.

* 1 - fire spread to (or almost to) the 50cm limit. ** 0 - fire did not spread

Fig 4.2a Seasonal evergreen forest (permanent plot) at Plot 5-38A at 11:15 am on April 12, 2001. The test fire in the subplot spread to 50cm in 4 minutes 40 seconds.

Fig 4.2b Leaf litter load for plot 5-38B at 11:45 am on April 12, 2001. The test fire in this subplot with a load of 7.1 t/ha only spread a couple of centimeters.

Fig 4.2c Fire spreading in leaf litter at Plot 5-38D at 12:15 pm on April 12, 2001. The fire in the subplot spread to 50 centimeters in less than 4 minutes

between those that spread and those that did not. The leaf litter loads for the subplots with fire-spread events were 9.8 Mg/ha[75] and 13.3 Mg/ha, whereas the loads for those that did not have spread events were 5.3 Mg/ha and 7.1 Mg/ha (Table 4.2).

The final observation is that fires in SEF are unlikely to occur in the early dry season (February). There are two reasons for this conclusion. First, the moisture content for ignitions was much lower for the first half of the fire season than it was for the second half. The highest leaf litter moisture content for a successful fire spread event between February 26 and March 8 was 14.2%, while in April, test fires were sustained at up to litter moisture contents of 19.7%. Second, the first part of the field season (February 22 – March 8) was exceptionally dry, yet there were few spread events, and none of these fires would have continued to burn in the forest. Figure 4.3 shows the minimum daily relative humidity for SEF ($Rh_{min,SEF}$) for the field season compared with the $Rh_{min,SEF}$ for the year with the driest February on record, 1995, and the three major fire years in HKK 1992, 1994, and 1998 (Fig. 4.3).[76] Leaf litter moisture contents as low as 7.4% with a mean of 12.7% $^{+}$/-3.4 were encountered for eight test fire subplots between February 26th and March 8th, yet for the most part, fire in SEF did not spread.

---

[75] Megagram (Mg) is equivalent to tonne (t).
[76] Figure 4.3 was derived from the work done in Chapter 6, specifically Figure 6.6.

Table 4.2 Detailed plot data 5-38[*†]

Subplot	Fire Spread	Moisture Content (%)	Litter Load (t/ha)	Continuity (%)	Canopy Gap (%)	Temp (°C)	RH (%)	Leaf litter species
A	yes	19.7	9.8	100	4.4	28.6	69	*Hopea odorata Roxb, Harpulai arborea Radlk., Saccopetalum lineatum Craib., Cinnamomum sp.*
B	no	14.6	5.3	92	4.2	29.3	67	missing
C	no	14.9	7.1	100	4.4	30.5	61	*Cinnamomum sp, Dimocarpus longan Lour, Saccopetalum lineatum Craib, Harpulia arborea Radlk., unknown*
D	yes	14.5	13.3	100	4.7	31.3	59	*Harpulia arborea Radlk., Cinnamomum sp.*
E	no	missing	missing	missing	missing	missing	missing	*Cinnamomum aurea-saracen Koster*

[*] Subplots A-E performed between 11:15am and 12:40pm on April 12, 2001.
† The detailed plot was located in the vicinity of the permanent plot.

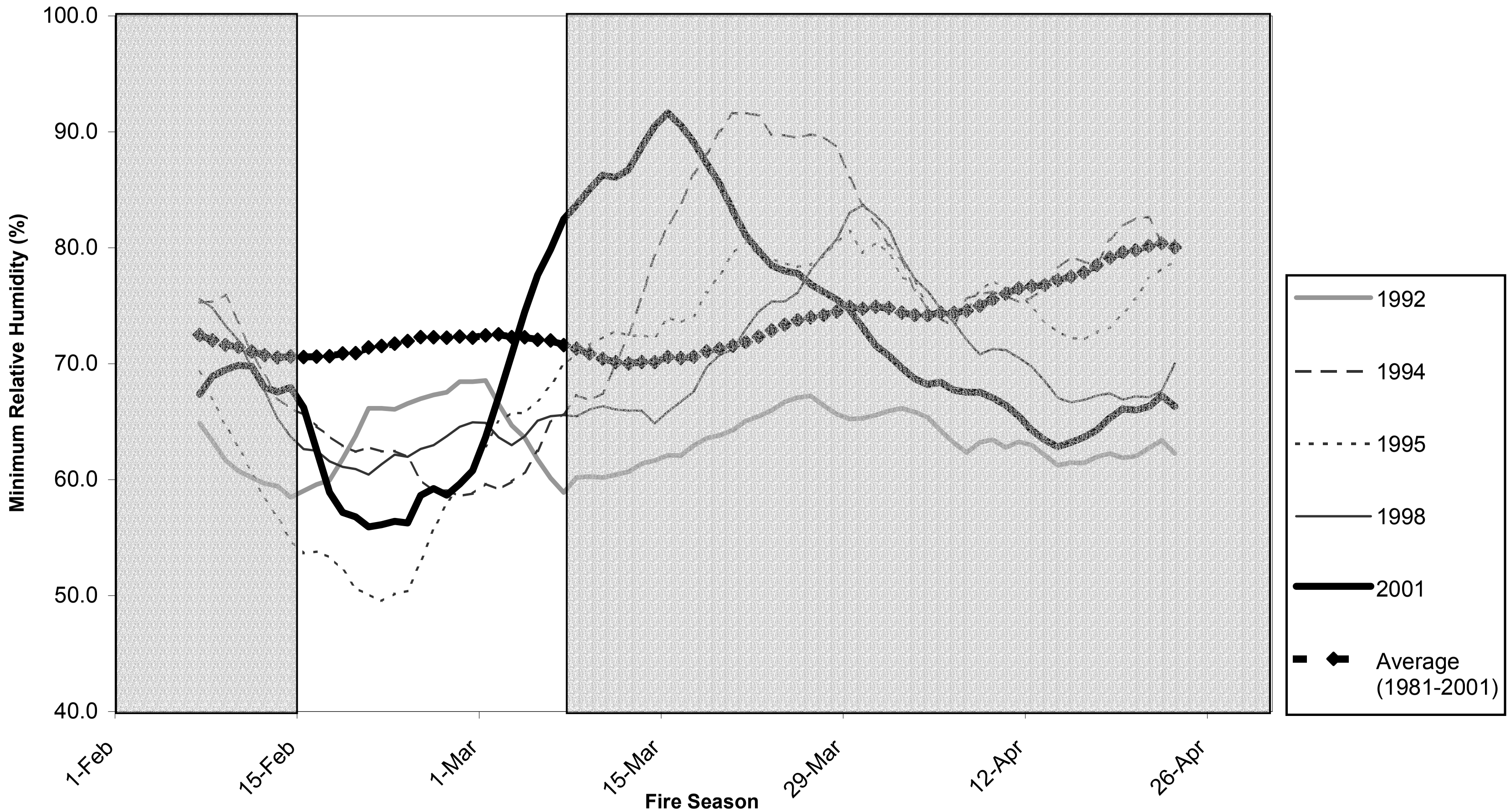


Figure 4.3 Minimum seasonal evergreen forest relative humidity values for field season year (2001) compared to lowest February relative humidity year (1995), and years SEF burned (1992, 1994, 1998). Test fires lit between February 26 and March 8, 2001 did not show signs of developing into uncontrolled burns despite the fact that this was the second lowest relative humidity year on record (1981 - 2003).

4.5 DISCUSSION

The research showed that SEF burns when there is an adjacent source of ignition in March and low litter moisture contents at that time. The ignition source was usually fires set in the first part of February at some distance from SEF. The month of March was found to be important for SEF flammability for three reasons. First, the available records and literature for fire in SEF showed late season burning in March and April. Second, increased fuel load was found to be associated with fire in SEF, and litter loads are highest in SEF in March. Finally, the leaf litter itself seemed more flammable in March and April, than in February; test fires in leaf litter with moisture contents as low as 12% did not burn in February, whereas those with moisture contents as high as 20% burned in April. Since most fires that affect SEF are set at the beginning of February, conditions must be such that fires continue to burn in grass fuels until SEF fuels become flammable in March. Grass can sustain fire as long as there is sufficient fuel and no rain from mid-February to March, and the SEF litter is likely to be dry enough to burn at 15%[77] or less at that time.

The research findings are similar in two ways to previous interpretations. First, the source of ignition for SEF fires is grass fires adjacent to SEF. Second, moisture

---

[77] Although the research showed some fire spread at moisture contents of 19.7% in April, a moisture content threshold of 15% or below is considered more likely in terms of sustaining fire in SEF.

content is an important factor for fire in SEF. In fact, the upper moisture content threshold for fire in SEF this research was 20% which is comparable to the 23% threshold found by Ray et al. (2005). The major difference between the findings of the model presented by the literature and the results of this study is that literature on the subject tends to present moisture content as the only major limiting factor for SEF flammability (cf. Ofren, 1999), whereas the research findings revealed timing of fire as an important factor for SEF flammability, and possibly fuel load too.

It is interesting to note that while the tropical literature does not directly identify the factors of timing of dry season and fuel load, supporting documentation can be found. For instance, Ray et al. (2005) specifically set out to conduct research in the Paragominas towards the end of the dry season, though the rationale for selecting this timing was not explained. Interestingly, the results of Ray et al. (2005) showed a much higher flammability threshold for the latter part of the dry season (23%), when compared to work done in the early part of the dry season for the same forest area (12%) (cf., Uhl & Kauffman, 1990; Holdsworth & Uhl, 1997). Negreiros (2004) too found high late season SEF flammability in the Amazon. Accounts of March fires in SEF in mainland Southeast Asia also support the timing factor. Kanjanavanit's work (1992) supports the requirement of heavier fuel loads.

It is not clear why late season timing (March and April) is an important factor for SEF flammability in HKK. The position presented in the literature is that the reason SEF tends to be more flammable later in the dry season is because the forests have had more time to dry out (e.g., Biddulph & Kellman, 1998), or that external factors such as increases in wind speed in March may influence SEF flammability (Kanjanavanit, 1992). This study did not support these positions. In the 2001 field season year, unseasonably low moisture contents were experienced in February, much lower than in March. In one test-plot in February, moisture contents as low as 7.4% were found; and while a fire spread was documented, the test fire would not have continued to burn on in the forest. Also, increased wind speed does not have much impact on the flammability of intact SEF because relatively little wind is experienced at the forest floor.

It is suspected that increased flammability in the latter part of the dry season may have to do with two other factors. It is possible that the leaf litter itself may be more flammable later in the fire season. The leaves on the ground are still relatively fresh in February but towards the middle of March this quality has changed. By then the leaves may well have been on the ground for four to six weeks, and six weeks of decomposition in a tropical forest is a significant period of time (Preston, pers. com., 2005). With decomposition, cellulose is likely to be removed leaving higher concentrations of lignin, phenols, and tannins behind, leaf compounds that decompose more slowly (Loranger et al., 2002). One study which was conducted shows that phenols take approximately eight weeks to decompose in tropical forests (Scheid et al., 2003). The potential flammability of phenols is not known, but the decomposition process may be responsible for the release of other potentially more volatile materials. Unfortunately, as yet little research has been done in this area making it difficult to speculate (Preston, pers. com., 2005).

A specific hypothesis for why high fuel load may be important for SEF flammability is not suggested here. In general, fuel litter load would probably be considered limiting if fuel loads are very thin or discontinuous. However, this was not generally the case in HKK. The mean litter depth for SEF in February, March and April seemed sufficient (6.7, 9.9, and 26.2 Mg/ha respectively) with no obvious discontinuities in February, suggesting that an increased litter load aids flammability for some other reason. However leaf litter loads are higher later in the fire season. For whatever reason fuel load is important, say for example the release of volatiles through decomposition, the greater abundance of litter on the forest floor in March and April may further facilitate flammability.[78]

The most significant limitation of the research conducted in this chapter is that it was not possible to determine the statistical significance of any of the factors considered. Although the original sampling objective had been to collect sufficient data during the field season to be able to perform a logistic regression on fire spread events, only five sustained fire spread events were obtained. A minimum of ten successful spread events would likely have been needed to test the significance of fuel variables using logistic

[78] The height of litter accumulation on the forest floor in closed deciduous forests is considered to be March in Thailand (Kanjanavanit, 1992).

regression (J. Zhou, pers. com., 2005). The other significant limitation of the study is that only one moisture content sample was taken per test fire subplot. Leaf litter moisture content can be quite point sensitive (B. Hawkes, pers. com., 2002). Since the litter sample and the fire test cannot be conducted on the same point, it would have been prudent to obtain more moisture content samples for each test fire conducted.

4.6 CONCLUSIONS

The purpose of the research in this chapter was to investigate the source of ignition as well as fuel conditions for fire spread in SEF. Interviews were conducted to determine the source of ignition for fire in SEF. Test fires were built and fuel conditions monitored to assess factors for spread. The findings indicate that SEF in HKK burn when there is a source of ignition adjacent to SEF in March, and the SEF leaf litter moisture content is below 15%. The research was limited in that there were not enough fire spread events in the test plots to determine the statistical significance of potential factors that influence March SEF flammability, specifically timing of fire and fuel load. Additional research is required in order to improve confidence in the identified factors.

CHAPTER 5 EFFECT OF FIRE ON SEASONAL EVERGREEN FORESTS

5.1 INTRODUCTION

Current understanding is that fire has a negative effect on seasonal evergreen forest (SEF), converting them permanently to more deciduous forest forms (cf. Cochrane, 2003). However preliminary research from mainland Southeast Asia suggests that these changes may only be temporary, and that fire at an intermediate frequency serves to increase tree species' diversity (Baker & Bunyavejchewin, In prep). Understanding whether SEF has been adversely affected by the landscape fires of recent years is important because it indicates whether intervention (suppression) is needed in protected areas (PAs).

The purpose of this chapter is to determine the change in the area of SEF in HKK from 1989 to 2000. A Landsat TM change detection was undertaken and interviews carried out to investigate the change in the area of SEF that occurred in the eleven-year period.

5.2 BACKGROUND

In recent years there has been more research showing that fires in tropical evergreen forests have a serious impact, altering the forest composition and structure (Cochrane et al., 1999; Gerwing, 2002; Cochrane, 2003). Tropical evergreen forest species have thin bark and are vulnerable to fire (Kauffman & Uhl, 1990; Uhl & Kauffman, 1990; Nepstad et al., 1999b). Studies done in the Amazon and Indonesia show that even low intensity surface fires can weaken dominant trees leaving them to die months or sometimes years after a fire (Cochrane & Schulze, 1999; Cochrane, 2003). Common tree species suffer the greatest total mortality (Slik et al., 2002) but rare species are most likely to be locally extirpated (Cochrane & Schulze, 1999). The situation is considerably worsened with repeated burning (Cochrane & Schulze, 1999; Cochrane, 2003).

Some of the research suggests the negative effects of fire on SEF can be expected to be long-term. Even 15 years after burning Slik et al. (2002), who did research in tropical evergreen forests in East Kalimantan, Indonesia, found the forests show no evidence of regaining lost species. According to Cochrane (2003) and others, there are several reasons to suspect the effects of repeated fires are long-term. First, the mechanisms of regeneration are diminished: specifically, the seedling bank is significantly diminished by fire (Van Nieuwstadt et al., 2001), as well the number of flowering and fruiting trees in the near-burned forests is reduced (Kinnaird & O'Brien, 1998). Second, there is increased likelihood of repeat burning, further reducing seed and seedling source as well as surviving unburned forest fragments (Cochrane et al., 1999; Cochrane & Schulze, 1999; Van Nieuwstadt et al., 2001). Third, burned sites may be invaded by wind-borne light-demanding pioneer species that further hamper regeneration and increase forest flammability (Woods, 1989; Swaine, 1992; Cochrane et al., 1999; Gerwing, 2002). Finally, there are physical changes in soil properties and biota abundance and diversity which can impact the soil’s moisture-carrying capacity or otherwise inhibit evergreen forest species from re-establishing (Kinnaird & O'Brien, 1998; Abdulhadi et al., 2000; Laurance, 2003). These factors together increase the likelihood of a permanent loss of evergreen forest species and increased dominance of deciduous forest species and grasses.

The scant literature on the effects of fire on SEF in mainland Southeast Asia suggests that fire may not have a long-term effect on SEF. Baker and Bunyavejchewin (2001; In prep) who observed fire in SEF in HKK in 1998 and subsequent regeneration in the following years, found that other than killing the seedling bank and the occasional emergent tree, fire in SEF did not seem to have any significant irreversible effect. Gaps in the canopy created by fire were quickly re-occupied by surviving poles and trees or by vigorous sprouts. They concluded that at an intermediate interval, fire may promote tree species diversity by eliminating super competitors, such as *Hopea ordata*, that dominate after more extreme disturbance conditions.[79]

There is also evidence that adverse effects of fire to SEF may not be long-term. Local studies have shown that if successional DDF is left unburned for a period of time SEF species start to return within ten to twenty years (cf. Kanzaki et al., 1985; Lamotte et al., 1998).[80] Holdsworth et al. (1997), working in the Amazon, also showed that it only takes

---

[79] Intermediate interval is not defined in the paper.

[80] Kanzaki et al. (1995) found 13 seasonal evergreen forest elements re-introduced themselves to DDF over a 27-year period of fire protection.

four years after a fire to start to see enough cover develop to change structure and microclimate conditions of a site towards a more sheltered SEF environment.

5.3 METHODS

The approach taken to assess the change in the area of SEF in HKK from 1989 to 2000 was to undertake ‘change detection’ using Landsat TM satellite images. Digital change detection is the quantification of temporal phenomena from imagery acquired by satellite multi-spectral sensors on different dates (Coppin et al., 2004). Also, a limited number of interviews were also conducted with people knowledgeable about the Sanctuary to verify “on the ground” changes detected using satellite images.

A remote sensing approach was taken because it allowed the flexibility to look back in time as well as provide continuous spatial data on the landscape. Further, the approach also allowed for a different perspective on forests since the only work that had been done on the effects of fire in SEF in the region was ground-based (cf., Baker, 2001).

A four-step approach to change detection was developed with the guidance of Dr. Joji Iisaka, an adjunct professor of Geography (Remote Sensing), University of Victoria. This approach involved: first, undertaking an unsupervised classification using an isodata[81] clustering classification technique on each of the images available to the project. Unsupervised classification is a method that examines a large number of unknown pixels and then divides the pixels into a number of cluster classes based on natural groupings present in the image values. Other approaches such as supervised classification using training sites are commonly used for classifying forest types in the tropics, but would not have been suitable for this work since the SEF in the Sanctuary is a mosaic of forest types and it is not possible to select pure training areas.

The second step was determining spectrally similar classifications that were suitable for multi-temporal comparison. Differences in sensor type, sensor noise, and atmospheric conditions between images can skew change detection results. In addition, the red band (B3) and near infrared band (B4) which are commonly used for vegetation typing, Normalized Difference Vegetation Index (NDVI), are particularly sensitive to differences in atmospheric moisture such as haze due to effects of scattering of shortwave radiation. Atmospheric corrections are generally seen as a mandatory pre-processing procedure in order to put data collected from different sensors or at least different dates on the same radiometric scale (Song et al., 2001; Liang et al., 2002; Trisirisatayawong & Samchimchom, 2002).

[81] Iterative Self-Organizing Data

In this case there were two difficulties in applying atmospheric corrections to available images. First, since the precise atmospheric conditions at the time an image was taken were not generally known, one or more generalized atmospheric corrections such as correction to a black body feature, would have had to have been applied to each image (i.e., scaling the values down so that DNs associated with deep water are at or close to a value of zero). Such an approach would be suitable for a situation where distinct changes in forest class are apparent such as the difference between clear-cut and forest areas. However the focus here was in detecting changes in forest types in a forest mosaic situation where changes between DN are subtle, and there was concern that applying fairly general atmospheric correction algorithms might adversely affect the product (J. Iisaka, pers. com., 2004).

The second reason for not wanting to use an atmospheric correction is that for the unsupervised classification it was important to try to preserve the original digital numbers as far as possible (J. Iisaka, pers. com.). Atmospheric corrections, as with preprocessing, would alter the original DNs. Instead, a post-classification check was used to determine image classifications that were radiometrically ‘comparable’ and could be included for change detection. The post-classification check involved comparison of cluster classes and cluster class definition among images, as well as comparison of cluster class means to determine spectrally similar ‘like’ classifications.

The third step was differentiating change classes of specific interest. One approach to identifying the change that has occurred between two images is simply to assess the difference or subtract two classifications. This approach is limited in that there are several factors that may differ between images. One of the most significant differences is sun angle and the resultant shadows, especially in images of areas with mountainous terrain. A change image produced from a simple subtraction of images would include all aspects of change between the images including changes in shadow, which could skew results considerably. For the research, only the change classes associated with changes of significance were considered (i.e., the movement of pixels from one forest type to another). The methods employed in this step were adapted from the work on change vectors in Neuner (2002) and Johnson et al. (2005).

The final step of the change detection was producing dot density maps of SEF in HKK for 1989 and 2000, as well as the 'change' density map. A dot density map is a particular type of thematic map in which a dot is used to represent certain numbers of things in an area (Tatian, 2000). In this case the dot density maps were generated in order to provide visual representation of the change results (i.e., where the change is happening in the SEF and how much change has occurred). This approach was particularly useful in that it provided a map of change, which could then be compared with the SEF historical burn data (Ch. 3).

Methods for the change detection included data acquisition, pre-processing, isodata classification, classified image selection, creation of change classes and identification of change classes of significance, change area calculation, and generation of dot density maps. Fieldwork from the 2000 and 2001 field seasons supported the change detection exercise, as did interviews with people familiar with the Sanctuary.

5.3.1 Data requirements and acquisition

Change detection requires comparison between 'like' images, and several criteria were taken into account before selecting the images for comparison. The first criterion was that the selection of satellite images be suitable for classifying forest types in HKK. Landsat images were chosen since these are commonly used for forest classification at a local scale in the seasonal tropics (Lucas et al., 1993; Vibulsresth et al., 1994; Giri & Shrestha, 2000; Lung & Schaab, 2004). There is good availability of these images in Thailand from late 1988 onward and at reasonable cost.[82]

The second criterion was that the selected scenes be dry season images, preferably February images. February is the month when most of the deciduous tree species have lost their leaves (Kanjanavanit, 1992) and forest types can be most easily discerned. The third criterion was that images be post-1988. All of the villages inside the HKK

[82] The cost of a Landsat scene from the GISTRA is approximately $2000 (US), although some images may be available from other sources such as Tropical Rain Forest Information Center (TRFIC) for a minimal charge.

boundary were removed and protection efforts increased in 1988, leaving fire as the only major landscape disturbance in HKK since 1989. The fourth criterion for image selection was to acquire images that were as near a common anniversary date as possible. The use of images taken at the same time of year minimizes seasonal differences such as sun angle. The fifth criterion was to use cloudless images, if possible. Clouds in images must be removed using a mask, which leaves holes in an otherwise continuous data set. The final criterion was that the images acquired needed to be from non-drought years. Drought can influence the fullness of the forest canopy, as well as the timing of leaf drop, which may skew results. In this regard, January through March images of 1992, 1994, 1995 and 1998 were of concern as these were dry years. Additional materials were also required for this part of the work, including maps of the Sanctuary and field data.

Images used are presented in Table 5.1. All of the scenes but one are cloud free. The 1992 image shows less than one percent cloud, most of which is in the high mountain areas of Huai Kha Khaeng.[83,84] A geocoded image was also obtained from the RFD as a master image for geometric correction. GIS related maps, including topography, forest, and the Sanctuary boundary and guard stations, were obtained from the RFD Remote Sensing division. Field data were collected during the reconnaissance of evergreen forest

[83] 1992 is not a drought year.
[84] Images were provided by the Tropical Rain Forest Information Center, Michigan, USA, and the Royal Forest Department, Remote Sensing Division, Bangkok, Thailand.

areas undertaken between February and April in 2001, discussed previously in chapters 3 and 4.[85]

Table 5.1 Landsat data

Sensor	Year	Date	Path/Row	Cloud
Landsat 4 TM	1989	Jan-11	130/49	0
Landsat 5 TM	1992	Dec-31	130/49	<1%
Landsat 7 ETM+	1999	Dec-25	130/49	0
Landsat 5 TM	2000	Feb-03	130/49	0

5.3.2 Preprocessing

Preprocessing for the research included image geocorrection, subsetting, and cloud removal. Preprocessing was undertaken using PCI Geomatica, version 8.1 developed by PCI Geomatics, Canada.

Geometric correction and image rectification was undertaken using PCI Geomatics's GCP Works software, version 8.1. The geocoded Landsat TM image (1999) was used as the master image against which the other images, Landsat TM 1989, 1992, 2000, and Landsat ETM 1999 were corrected. Between 15 and 18 geographically referenced

[85] Some fieldwork was previously done in the fire season of 2000.

control points (GCPs) were used for each image. GCPs were placed within, or just outside, the HKK boundary with a few additional control points distributed around the larger scene. Images were corrected to the ¼ pixel as per the recommendations of Lillesand & Kiefer (1994). A second-order polynomial model was used for the geometric correction and a nearest neighbor resampling method selected. The RMS error associated with the GCP points was less than 0.24. Geocorrected images were output to a single file with 30 bands.[86] Images were then visually compared for spatial correlation, and the spatial displacement between images found to be less than or equal to one pixel.

The geocorrected file containing the four images was subset using PCI's Image Works module and utility function. The subset image files were then separated into either seven or nine channel image sets and exported to an ERDAS software format for use in Multispec, the chosen software platform for image classification.

Cloud removal was required for the 1992 image. Isodata classification was used to remove clouds from the image. The methods for cloud removal are detailed, and as such have been included in Appendix 5-1.

[86] Earth model UTM 47 E013

5.3.3 Isodata classification

Images were classified in Multispec[87] software using image bands one through five and seven for each image and an isodata algorithm classifier. Isodata classification involved determination of the number of classes and definition of the evergreen zone forest classes.

5.3.3.1 Determination of the number of cluster classes

The objective was to choose the number of classes that produced a classification result which differentiated major land and vegetation features, and particularly evergreen forests as a major zone. Both visual and numeric assessments were used to determine the number of classes. Visual assessment entailed experimenting with the number of cluster classes (10-30) to determine the approximate subset that most clearly differentiated the evergreen forest zone or formation[88] within the scene. Numeric assessment entailed reviewing the number of pixels in each cluster class as well as the separability of clusters of interest. Trials run using 20 cluster classes produced a classification result that clearly highlighted the evergreen forest zone and presented six evergreen zone cluster classes, consistent with the researcher's understanding of topographical and ecological conditions in the area.[89] Thus, 20 cluster classes were used for the final classification.

---

[87] Public domain image analysis software

[88] The evergreen forest zone included cluster classes representing both evergreen species and deciduous species.

[89] The researcher's knowledge of conditions in HKK included both map-based and field-based experience.

5.3.3.2 Definition of evergreen forest zone classes

The objective was to define or describe each spectral class that had been identified as part of the evergreen forest zone. Cluster classes do not represent a particular feature such as a forest type per se but rather a combination of land-based features that together have been distinguished as a spectral class. Spectral class descriptions were determined by visually comparing individual evergreen zone cluster classes with: i) various band combinations of the original Landsat imagery; ii) GIS based topography and forest type maps; and iii) field data. The primary descriptors for the evergreen zone cluster classes included dry soil, deciduous species, evergreen species, elevation, sun, and shadow. In this step the Multispec-linked shift key was used to highlight an individual cluster so that it could be distinguished. Once a classification was isolated, reference data were used to help define each spectral class. At the same time, other image windows were opened and reference images loaded for comparison. Two types of reference data were used for comparison. First, different band arrangements and composites of the original Landsat TM image (*i.e*., pre-classification) were used; for example, of the seven Landsat bands, bands 4,3,2 and 4,5,3 (false color composites) were loaded in the red, green, blue, colors to highlight vegetation features. Second, hard copy base GIS maps of the topography map and forest type were used to help define the spectral classes. After each cluster class was identified then personal knowledge of the Sanctuary and particularly data points from the fieldwork were used to help confirm the identification. Accordingly, the names used to identify each cluster class represent the features most responsible for the general spectral response or 'cluster class' being observed.

The final isodata classification for the 1989 Landsat image, and the evergreen zone cluster classes are presented in Figure 5.1. In the isodata classification 20 classes are shown with the evergreen forest zone differentiated from other major landscape zones by pink and purple colors. In the evergreen zone six spectral cluster classes are shown (clusters 11, 13, 15, 17, 18, 19); four of the classes contain evergreen forest species, one class contains dry deciduous species (class 11), and another class is a combination of evergreen and deciduous species (class 18). Definitions for each of the evergreen zone cluster classes are shown in the legend.

5.3.4 Classification selection

Determination of 'like' classifications was made by comparing the number of classes as well as the definition of each cluster or spectral class which were comparable. The spectral class means of the images with similar classifications were then compared by plotting the Landsat band 4 (B4) versus Landsat band 3 (B3) cluster class mean values for the evergreen zone classes in each image. These two bands are of particular importance for differentiating vegetation features, and are the primary input variables used to establish NDVI, a commonly used band ratio (cf., Sader & Winne, 1992; Stoms & Hargrove, 2000; Hayes & Sader, 2001; Iisaka, 2004). Preliminary comparison of the images showed that only the 1989 and 2000 images share similar evergreen zone spectral classes and spectral class definitions (Table 5.2). The evergreen zone cluster classes for the 1992 and 1999 images show entirely different sets of spectral classes, being clusters

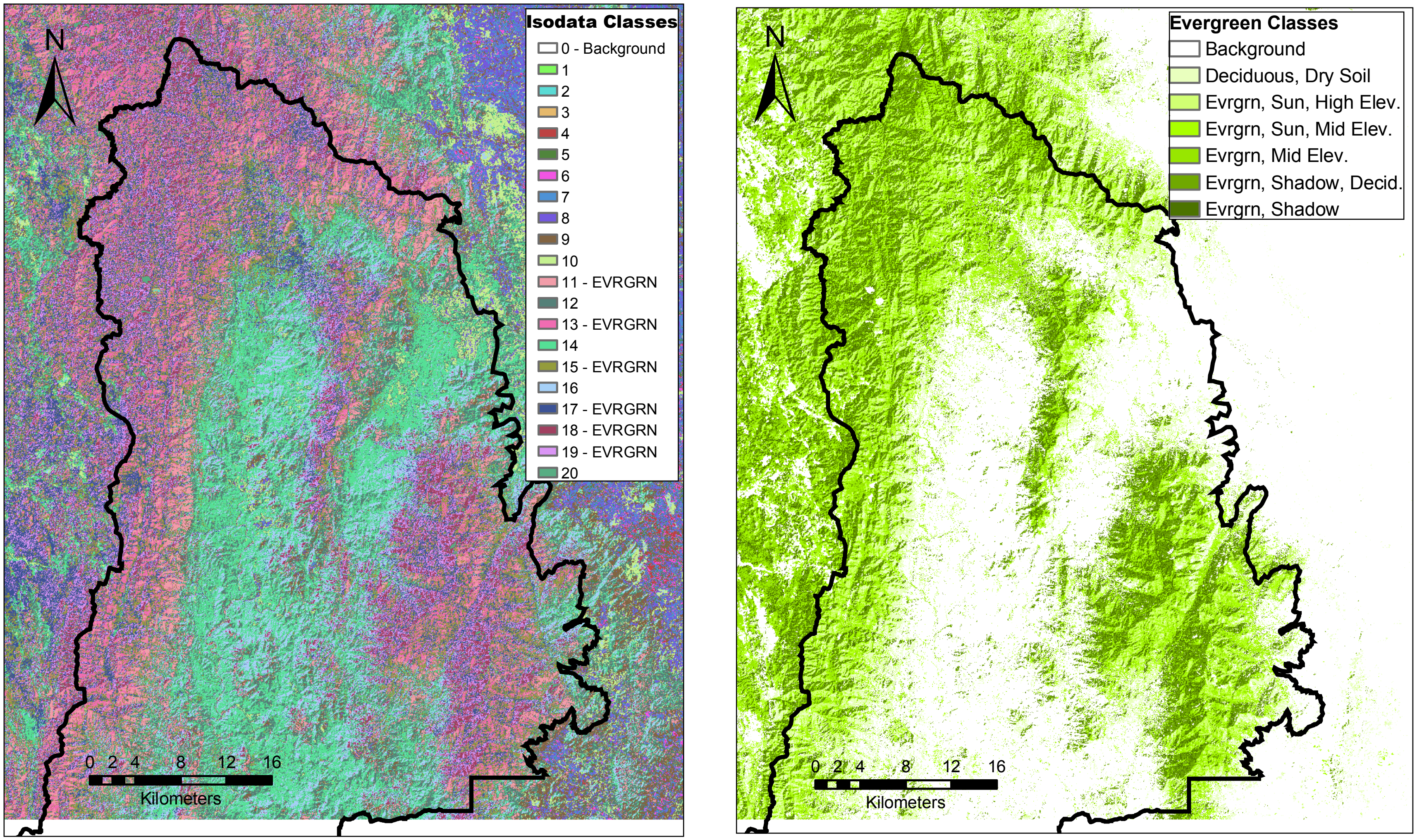


Figure 5.1 Unsupervised classification of 1989 Landsat TM image: Isodata cluster classes (left), and identified evergreen zone cluster classes (right)

Table 5.2 Comparison of seasonal evergreen forest cluster classes among four classifications

Cluster #	Landsat TM 1989	Landsat TM 1992	Landsat ETM 1999	Landsat TM 2000
0				
1			Evergreen	
2				
3			Evergreen	
4				
5				
6				
7			Evergreen	
8			Evergreen	
9				
10		Evergreen		
11	Deciduous, Dry Soil		Evergreen	Deciduous, Dry Soil
12			Evergreen	
13	Evergreen, Sun, High Elevation			Evergreen, Sun, High Elevation
14		Evergreen		
15	Evergreen, Sun, Mid Elevation			Evergreen, Sun, Mid Elevation
16		Evergreen		
17	Evergreen, Mid Elevation	Evergreen		Evergreen, Mid Elevation
18	Evergreen, Shadow w/ Deciduous	Evergreen		Evergreen, Shadow w/ Deciduous
19	Evergreen, Shadow			Evergreen, Shadow
20		Evergreen		

10, 14, 16, 17, 18 and 19, and 1, 3, 7, 8, 11 and 12, respectively. It is suspected that higher atmospheric moisture in the 1992 image as evidenced by the need of minor cloud removal, and improved sensor capabilities for the 1999 image (*i.e.*, Landsat ETM+) account for the discrepancies in the unsupervised classification results for those images.

Plotting of B4 and B3 cluster class means for 1989 and 2000 images further confirmed the two images were radiometrically comparable. A comparison of the cluster mean values of Band 4 versus Band 3 is shown for the two images (1989, 2000) in Figure 5.2. A near equidistant shift is observable between the six cluster class means in each classification. Since the distance between each cluster class mean pair (time 1 (1989) and time 2 (2000) cluster class means) is roughly the same, the two image classifications can be said to be comparable (J. Iisaka, pers. com., 2004). Thus the 1989 and 2000 images were determined to be suitable for inclusion in the change detection.

5.3.5 Change class identification

Determination of the change between the 1989 and 2000 isodata classifications was a multi-step process. First, the six evergreen cluster classes of the 1989 and 2000 classifications were recoded using Erdas Imagine, version 8.7. The 1989 spectral classes 11, 13, 15, 17, 18 and 19 were recoded as 10, 20, 30, 40, 50 and 60 respectively; and the 2000 spectral classes 11, 13, 15, 17, 18 and 19 were recoded as 1, 2, 3, 4, 5 and 6 respectively. Second, the two images, 1989 and 2000, were combined using the raster union operation to create 36 possible pixel change combinations. Finally, change classes

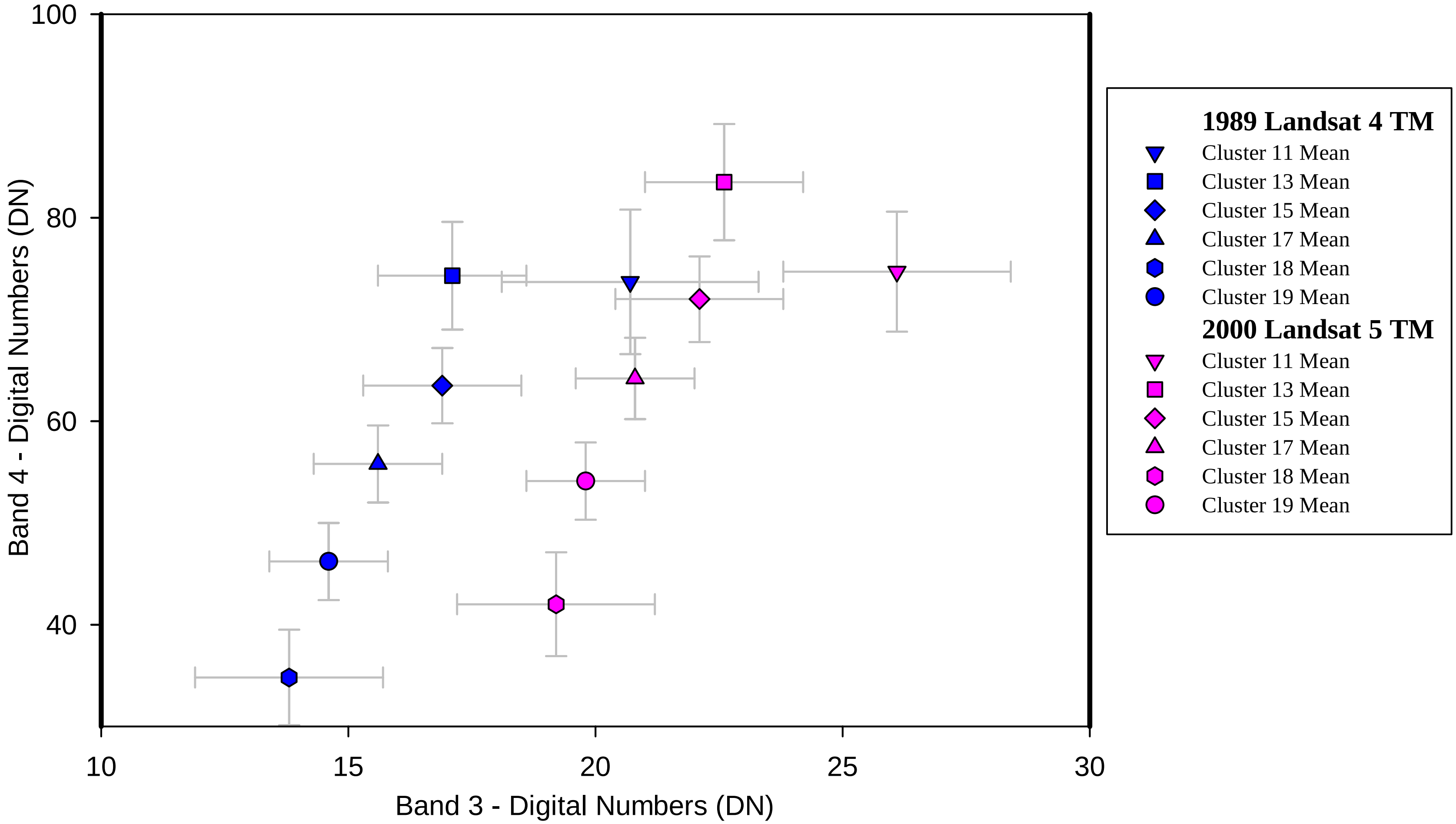


Figure 5.2 Comparison of band 4 and band 3 cluster class values for the Landsat TM 1989 and 2000 images. The graph shows a near equidistant shift between 'like' evergreen zone cluster classes. Error bars represent one standard deviation from the mean.

of significance were identified. In this final stage, only change classes where the dominant change was viewed to be between forest types were considered (*i.e.*, evergreen to deciduous species types or vice versa). Other change classes such as classes involving change in shadow to sun, or in elevation were not included. A union operation was then used to create 'change' cluster classes. The addition of six cluster classes was made to create 36 new cluster classes as shown in Figure 5.3. Only some change classes are of significance, notably classes 12, 13, 14, which represent change from deciduous to evergreen forest species, and classes 21, 31 and 41, which represent change from evergreen to deciduous forest species. Pixel calculations for the change class analysis are presented in Appendix 5-2.

5.3.6 SEF area calculation

The area of SEF for the 1989 and 2000 images was derived by adding the number of pixels in the evergreen species cluster classes (i.e., clusters 13, 15, 17, 18 and 19)[90] and then multiplying by the size of pixel, 30 x 30 meters (Table 5.3).

5.3.7 Dot density map generation

Three maps were produced: a 1989 and a 2000 evergreen dot density map, and a change dot density map. The input cluster classes for each image were selected and input into Erdas Imagine. The input cluster classes for both the 1989 and 2000 forest maps were

[90] The dry deciduous species cluster class 11 was not included in the SEF area calculation.

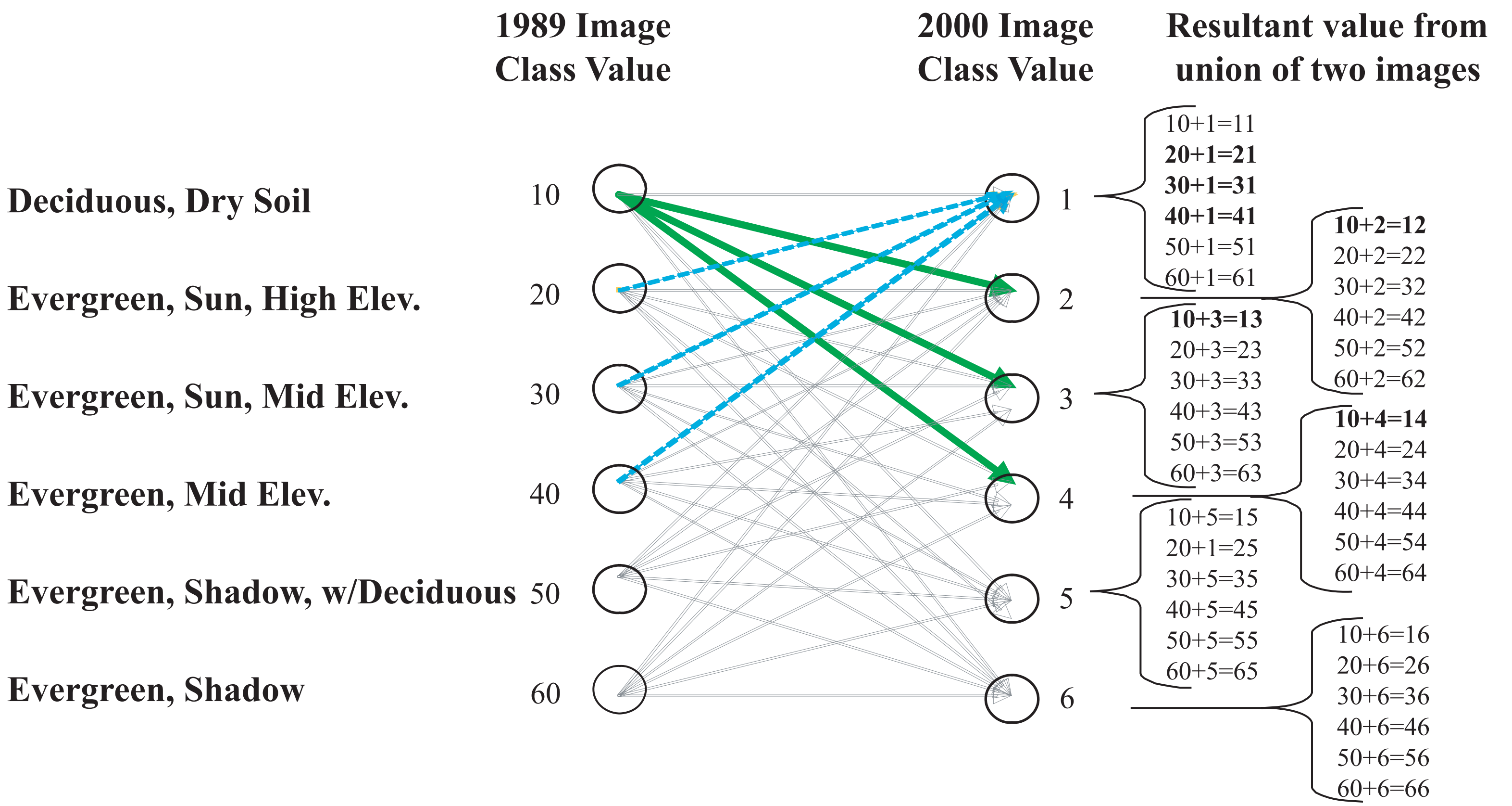


Figure 5.3 Creation and identification of change classes of significance. Change classes 12, 13 and 14 show the direction of pixel change from deciduous to evergreen related spectral classes, while classes 21, 31 and 41 show the direction of pixel change from evergreen to deciduous forest spectral classes.

Table 5.3 Area calculation for SEF in HKK in 1989 and 2000

1989	**Multispec Clusters**	**Imagine Recoded Clusters**	**Pixels (30mx30m)**	**Area (km^2)**
Background	0	0	2886263	2598
Deciduous, Dry Soil	11	10	233313	210
Evergreen, Sun, High Elev.	13	20	309658	279
Evergreen, Sun, Mid. Elev	15	30	521099	469
Evergreen, Mid Elev.	17	40	557466	502
Evergreen, Shadow with Decid.	18	50	269316	242
Evergreen, Shadow	19	60	406075	365
Grand Total			**5183190**	**4665**
Total Evergreen			**2063614**	**1857**

2000	**Multispec Clusters**	**Imagine Recoded Clusters**	**Pixels (30mx30m)**	**Area (km^2)**
Background	0	0	3062012	2756
Deciduous, Dry Soil	11	1	384712	346
Evergreen, Sun, High Elev.	13	2	250892	226
Evergreen, Sun, Mid. Elev	15	3	497556	448
Evergreen, Mid Elev.	17	4	481940	434
Evergreen, Shadow with Decid.	18	5	187676	169
Evergreen, Shadow	19	6	320832	289
Grand Total			**5185620**	**4667**
Total Evergreen			**1738896**	**1565**

the evergreen forest zone cluster classes *(i.e.*, 13, 15, 17, 18 and 19). The input cluster classes for the change map were the cluster classes of significance for evergreen forests becoming deciduous (i.e., 21, 31 and 41).

Next the dot density maps were created in ArcGIS, ArcMap using the Spatial Analyst utility. This was done by first, converting each of the newly assembled images from raster to feature class data (points) and then importing into ArcMap; and second, running trials to determine suitable inputs for the parameters in Spatial Analyst. Ultimately, a cell output size of 100 m and a search radius of 500 km^2 were selected for each of the maps.

Finally, threshold levels were established for each of the maps. Threshold levels for the 2000 evergreen forest density map were established first since field data were available for 2001. Field sample plots established in chapters 3 and 4 were also used to help establish appropriate threshold levels for the density classes for the 2000 map. Field plot data were used to differentiate the three evergreen forest zone density classes (Table 5.4). The data seemed to fall naturally into categories that differed in orders of magnitude of density. Figure 5.4 shows the use of plot data and evergreen density dots to establish threshold levels for the 2000 evergreen density map, while the inset figure shows the resulting 2000 density map. Green colored areas are considered to be ‘closed’ or dense SEF, whereas yellow areas are either more open deciduous forests or evergreen forests with a significant presence of deciduous forest species.

Table 5.4 Definition of SEF dot density categories

Dot class	Category description
0 – 13	Not SEF
13 – 130	Open SEF
130 - 1,300	Dense SEF

The 1989 evergreen forest density map was created following the above methodology. As field plot data were not available to help differentiate evergreen threshold levels for the 1989 map, the same evergreen forest threshold levels were used as were established for the 2000 density map. For the change map, four change density classes were delineated. The upper threshold for ‘no change’ was set at 250, which was judged to be consistent with personal field knowledge of the extent of evergreen forests in 2000. Thresholds for the upper three categories were divided fairly evenly between the 250 and 700 dot density range (Table 5.5).

Table 5.5 Definition of forest change dot density categories

Dot class	Category description
0 – 250	No Change
250-400	Low Change
400-550	Medium Change
550-700	High Change

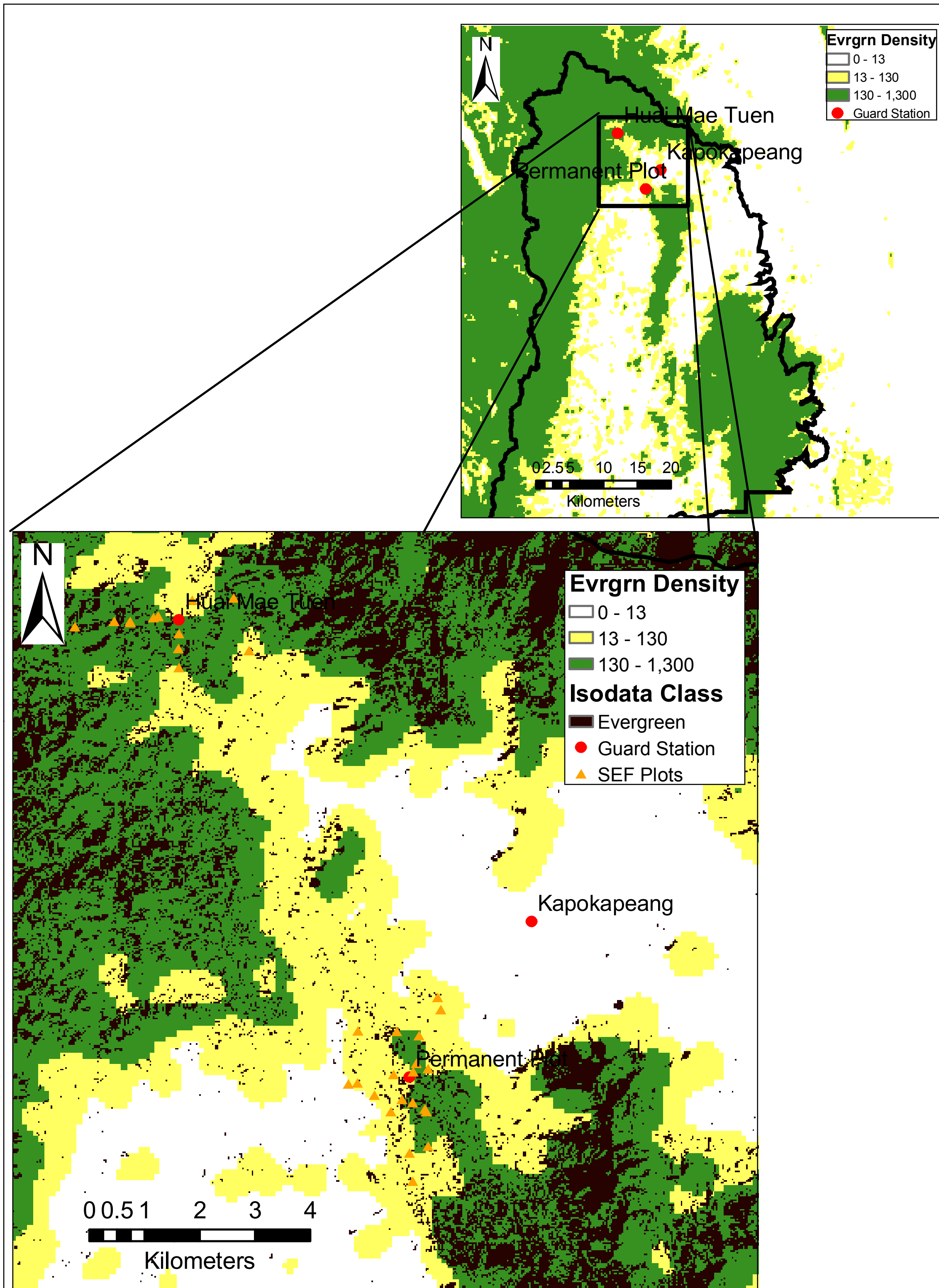


Figure 5.4 Creation of 2000 evergreen forest dot density map (top). A combination of evergreen forest dots or pixels and field plot data were used to establish an appropriate dot density threshold for evergreen forest (bottom) .

5.3.8 Comparison with burn data

The accuracy of the change detection was checked in two ways. First, the SEF change image was compared to the SEF fire frequency data generated in Chapter 3 (Fig. 3.5). The comparison was made by using a ‘recode’ and ‘union’ operation technique similar to that previously described. The change density categories were recoded to 10 (no change), 20 (low change), 30 (moderate change) and 40 (high change). The SEF fire frequency values were recoded as 1 (no fire), 2 (one fire), 3 (two to three fires) and 4 (four or more fires). The frequency figure was then converted to raster. A union operation was then applied to the raster image and twenty-eight classes. Finally, the results were grouped on the basis of whether or not a change in the forest type was associated with fire occurrence.

Second, interviews were undertaken with researchers, RFD officers, and guards familiar with HKK to obtain information on the effects of fire in evergreen forests. Approximately ten interviews were conducted in Bangkok with senior researchers and RFD foresters who had observed fire in evergreen forests in HKK. Interviews were also conducted with guards at each of the stations visited in the Sanctuary. Interviewees were asked whether they noticed changes in SEF in HKK caused by fire.

5.4 RESULTS

The change detection analysis showed a decrease in the area of SEF in Huai Kha Khaeng Wildlife Sanctuary from 1858 km^2 in 1989 to 1565 km^2 in 2000. Between 1989 and 2000 there was a net difference with 15% of the pixels of significance going from tropical evergreen forest to deciduous forests (Table 5.6). Seven percent of the pixels at higher elevation moved from an evergreen class to a deciduous class, and eight percent[91] of pixels at mid-elevation moved from evergreen class to a deciduous forest class. The change in pixels between the various evergreen zone spectral classes is presented in a results matrix (Table 5.7).

A spatial representation of the area of change is presented in Figure 5.5. Figures 5.5a and 5.5b are SEF dot density maps for 1989 and 2000 respectively, while Fig. 5.5c is the dot density map for the pixels that changed between the two years. There is considerably more evergreen forest in 1989, than in 2000. Areas of high-density change are shown in dark purple (Fig. 5.5c). A dot density map showing the trend in change from evergreen to deciduous forest is shown in Figure 5.6. In this figure the dot density map of evergreen forest (1989) has been overlain with a dot density map of the change classes for evergreen to deciduous forest (1989-2000). The area of highest density of change is shown in yellow and located in the vicinity of the permanent plot.

---

[91] Includes 7 + 1

Table 5.6 Percent change in the number of pixels from evergreen to deciduous classes and vice versa

1989 Classification	*2000 Classification*	*Percent*
Evergreen in sun at high elevation converting to dry, deciduous forest		
Evergreen	Deciduous	20%
Deciduous	Evergreen	13%
Evergreen	***Deciduous***	***7%***
Evergreen in sun at mid elevation converting to dry, deciduous forest		
Evergreen	Deciduous	10%
Deciduous	Evergreen	3%
Evergreen	***Deciduous***	***7%***
Evergreen at mid elevation converting to dry, deciduous forest		
Evergreen	Deciduous	1%
Deciduous	Evergreen	0%
Evergreen	***Deciduous***	***1%***
Total Conversion from Evergreen to Deciduous		
Evergreen	***Deciduous***	***15%***

Table 5.7 Results matrix of change classes for 1989 and 2000

	Deciduous, Dry Soil	**Evergreen, Sun, High Elevation**	**Evergreen, Sun, Mid Elevation**	**Evergreen, Mid Elevation**	**Evergreen, Shadow with Deciduous**	**Evergreen, Shadow**
Deciduous, Dry Soil	**84%**	13%	3%	0%	0%	0%
Evergreen, Sun, High Elevation	20%	**46%**	27%	5%	0%	1%
Evergreen, Sun, Mid Elevation	10%	16%	**53%**	19%	0%	2%
Evergreen, Mid Elevation	1%	4%	27%	**53%**	2%	14%
Evergreen, Shadow with Deciduous	0%	1%	2%	8%	**54%**	35%
Evergreen, Shadow	0%	1%	7%	34%	11%	**47%**

The most obvious area of change is the north-central section of HKK. It is known that SEF burned two times in this area between 1992 and 1998. Change is also apparent along the edge of the SEF formation in the transition zone with other vegetation classes. This observation seems to make sense since areas around the edge of SEF are likely to burn commonly, and are often the source of ignition for fire in SEF. Edges are also likely to be the area most affected by a mis-registration error, which was up to one pixel displacement in some places.

While it is difficult to estimate an error associated with the mis-registration of pixels between images, change detection results were validated to a considerable degree by comparison with burn area data. Comparison of the areas of forest change and areas

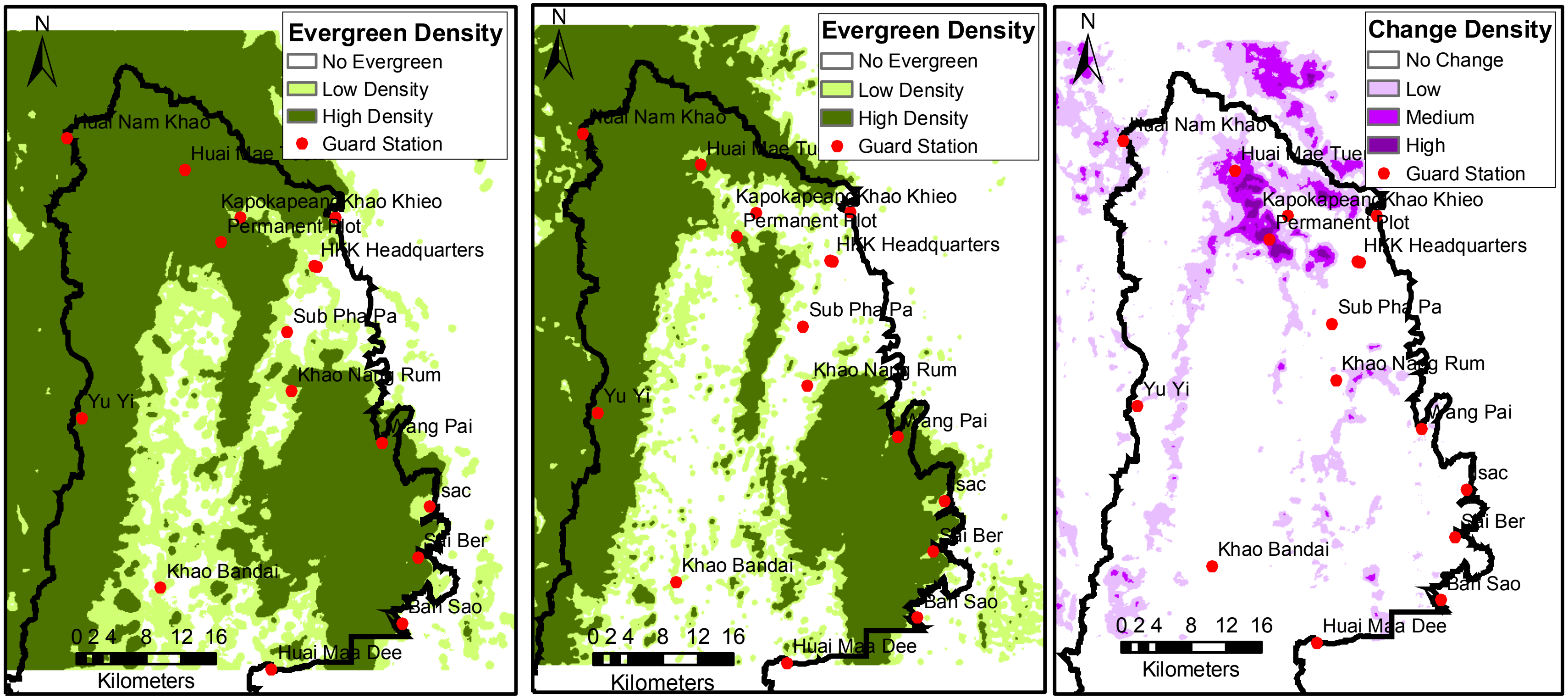


Figure 5.5 Comparison of three dot density maps. A reduction in the area of evergreen forest is apparent between the 1989 density map (left) and the 2000 density map (middle), as well as in the 1989-2000 change density map (right).[1]

[1] The change density map is not a difference figure but rather a separately generated dot density map (see section 5.3.7).

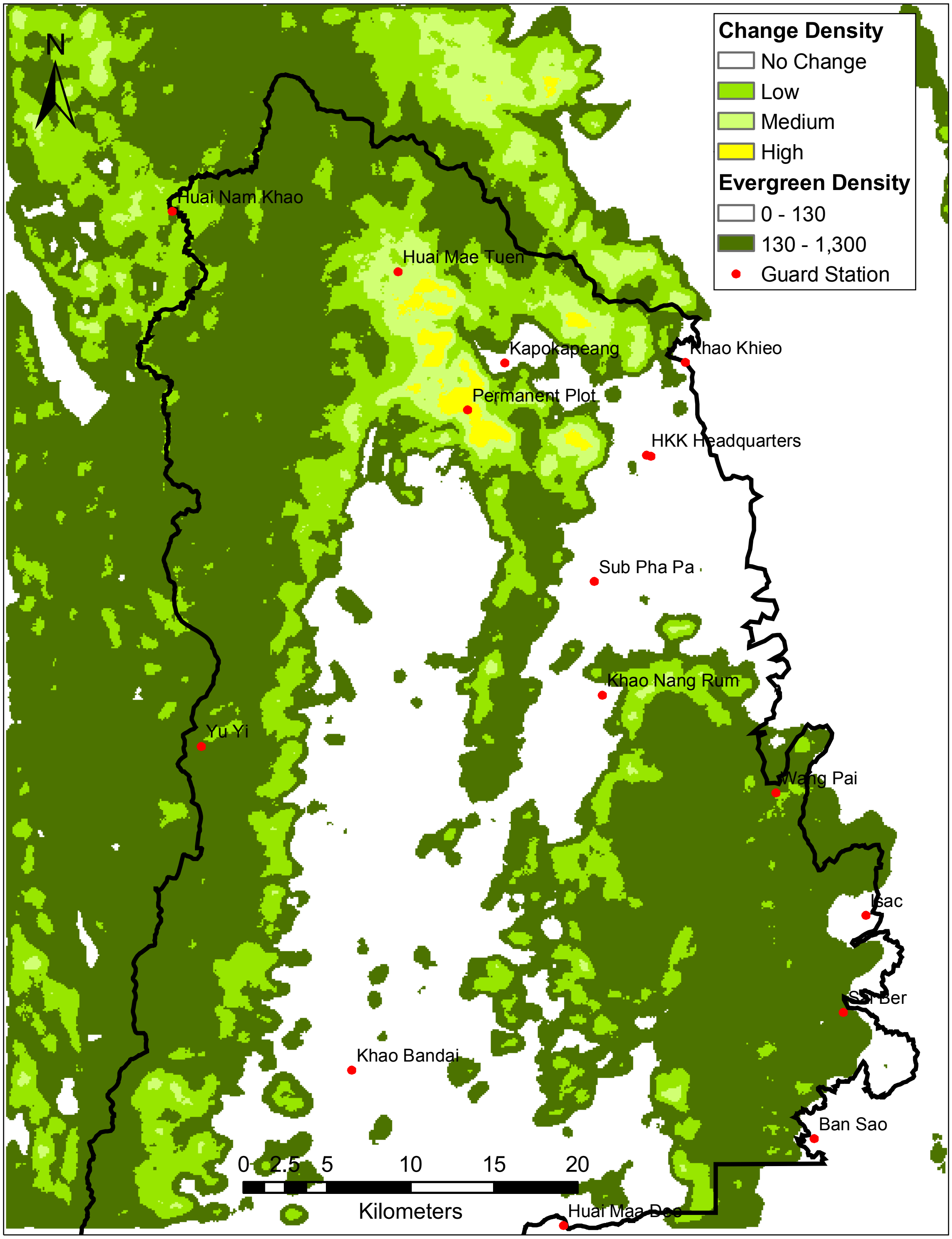


Figure 5.6 1989 evergreen dot density map with 1989-2000 change density map overlain. The most significant change has occurred in and around the permanent plot.

burned showed a 70% agreement between the spatial representation of the change area in SEF and the burn area (Fig. 5.7). Details of the spatial correlation between fire frequency and change density in the evergreen forest zone are provided in Table 5.8.

Table 5.8 Correlation between fire frequency and forest type change

Correlation Between Fire Frequency and Forest Type Change		
Fire Frequency	***Forest Type Change***	***Percent***
No Fire	No Change	53%
Fire	Change	17%
Correlation		***70%***
No Correlation Between Fire Frequency and Forest Type Change		
No Fire	Change	17%
Fire	No Change	13%
No Correlation		***30%***

While there is a good match in the transition zone, spatial differences between the two maps are obvious near the center of the Sanctuary. This discrepancy is probably because the burn area in the fire frequency figure is more accurate at the edges than in the center area of more intact SEF. As discussed in Chapter 3, burn areas can be effectively mapped in disturbed SEF, but not mapped as effectively in intact SEF. Low intensity understory fires can burn undetected by Landsat imagery. The SEF in the north center of Figure 5.6, at least in the permanent plot, is relatively intact, yet it has burned twice completely during the time period considered. While this burn information is not apparent in the fire frequency map, it is suggested in the change map.

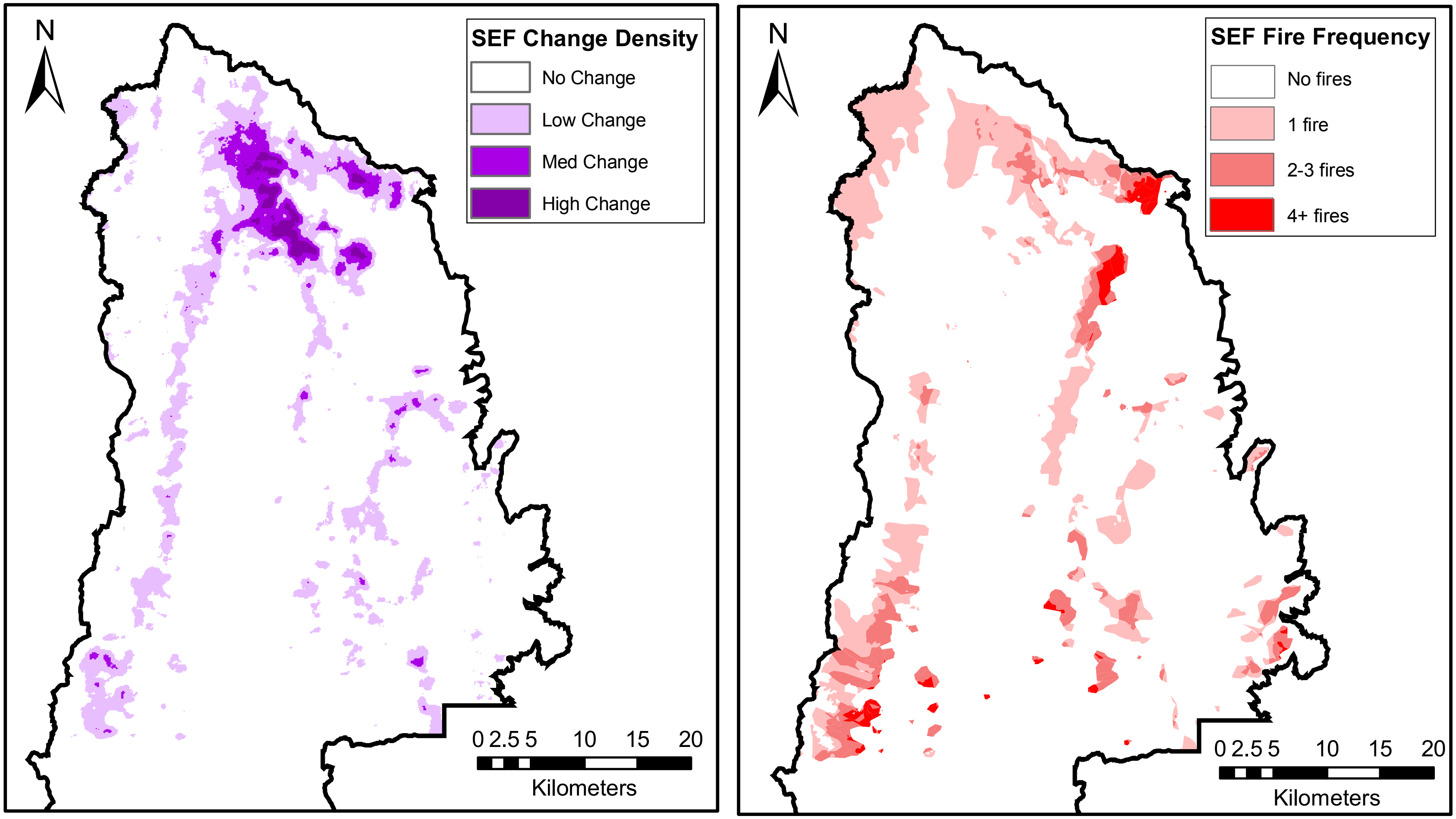


Figure 5.7 Comparison of the SEF fire frequency map and the SEF change density map. There is a 70% agreement between the change area in the 1989-2000 change density map (left) and the burn area in the 1988-2002 fire frequency map (right).

The results of the change detection work were also supported to some degree by the interviews. One guard who has been working in HKK for many years noted that SEF in the vicinity of the permanent plot was much drier now than in the past, and he observed that there are no longer leeches in that area. Another interview with Mr. Nopparat (2001), past Chief of the Khao Nang Rum Wildlife Research Station, suggested that the forests in HKK in general are now much drier. He explained that the flow to the HKK River seems to be much reduced, though dry season river flow has not been monitored. However, it is difficult to say whether this latter observation is directly associated with fire in SEF.

The comparative openness and associated dryness of SEF areas that have burned two or more times in recent years is shown in Figure 3.7. Note the darkness of the forest at Yuyi (Fig. 3.7c) which is only known to have burned on one occasion in comparison with the other sites at Huai Nam Khao (Fig. 3.7a) and the permanent plot (Fig. 3.7b) which have burned two or more times. While the choice of images for Figure 3.7 was subjective, the images are representative of the researcher's impressions of the forests at various sites for which the fire history in recent years was more or less known.

5.5 DISCUSSION

The findings indicated that fires have had a significant adverse effect on SEF in HKK in recent years. Over the eleven-year study period, pixels with spectral signatures associated with SEF decreased by 15% and were replaced with pixels associated with

DDF (i.e., dry soil, open canopy). This ‘replacement’ may not actually represent the conversion of evergreen forest to deciduous forest, but could also include gaps or openings in the forest canopy. Still even where new gaps in the forest canopy have emerged as mature trees have died, there is still a sense of breakdown of the evergreen forest cover. This change is particularly notable in the vicinity of the permanent plot, an area that has burned twice completely during the period assessed.

In general the findings of the study are comparable with the larger body of research indicating a negative effect of frequent fire on SEF. Trees die leaving holes in the forest canopy. Each time a fire burns through SEF the mechanisms for regeneration become further disturbed. As Cochrane (2003) indicates there may be less seed and fewer seedlings after subsequent burnings. Also, seed sources become more distant. As well, soil may have become drier or hardened as a result of burning and may be less able to support moisture-sensitive SEF species. Further, there is increased likelihood of competition with grass and other early successional species.

However Baker and Bunyavejchewin (In prep) would argue that the creation of gaps in the forest canopy is not always detrimental. The death of the odd emergent opens the forest canopy and creates opportunities for other species, which ultimately increases the diversity of SEF stands. As long as fire frequency is at an intermediate frequency SEF may not be adversely affected because gaps created are quickly filled by surviving poles and seedlings. Still, Baker and Bunyavejchewin do not specify a period of time that is ‘intermediate’, and it seems likely that it will probably be longer than the current frequency of every six years (i.e., the permanent plot burned twice in fourteen years).

Ultimately, the study was limited in two ways. First, there were inherent limitations in the approach of using unsupervised classifications for the change detection. Cluster classes of an unsupervised classification do not represent specific vegetation types such as SEF or DDF, but rather distinct spectral features, which might include a combination of elements such as forest-cover type, soil moisture, and elevation. As such the data only reflect something about the change in spectral classes associated with SEF, and not SEF per se. Second, only a short time period of 11 years was considered in the study. Eleven years is not a long enough interval, nor is the analysis in-depth enough to determine how effectively gaps are filling in, or what the trend will be in terms of the effects of fire in SEF. Additional research is required in order to determine the long-term effects of surface fires on SEF.

5.6 CONCLUSIONS

Research was undertaken to determine whether the area of SEF in HKK changed between 1989 and 2000 as a result of fire. Unsupervised classification followed by selection of like images, and determination of change classes of significance was used to determine change in the SEF formation. The results showed that in 11 years approximately 292 km^2 of SEF has been opened-up, developing into forest gaps or areas dominated by more open deciduous and savanna vegetation. The study was limited in that the period of time covered in the study was relatively short. Additional research is required to determine the long-term effects of fire in the Sanctuary, and the region.

CHAPTER 6 PREDICTING THE FREQUENCY AND OCCURRENCE OF FIRE IN SEASONAL EVERGREEN FOREST

6.1 INTRODUCTION

Current understanding is that the litter moisture content in seasonal evergreen forest (SEF) is rarely low enough to burn (cf., Uhl et al., 1988; Kauffman & Uhl, 1990; Uhl & Kauffman, 1990; Holdsworth & Uhl, 1997), and that it is not possible to predict fire in SEF in mainland Southeast Asia. However, there is also literature to suggest that: 1) low dry season SEF leaf litter moisture contents in mainland Southeast Asia may be more common than is generally thought; and 2) fire in SEF can be predicted by monitoring soil drought. Understanding how commonly the conditions for fire in SEF occur and our ability to predict years when the conditions for fire in SEF are likely to occur is important because it provides an indication of whether the problem of fire in SEF might be managed by focusing the suppression effort on the years that SEF is likely to burn.

There are two objectives for this chapter: 1) to determine the frequency of fire season years between 1984 and 2001 with the conditions for fire spread in SEF (i.e., fire in the vicinity of SEF in March and estimated SEF litter moisture contents less than 15% at that time (Ch. 4)); and second, to determine the relationship between January 31st (i.e., pre-fire season) Keetch-Byram Drought Index (KBDI) and Canadian Drought Code (DC) values and identified SEF fire season years for 1981 to 2003.[92] Determination of the frequency of years with the conditions for SEF fire spread, the first objective, involved building an historic minimum relative humidity data set for SEF. Establishment of the relationship between January 31st drought code values (KBDI and DC) and SEF fire season years, the second objective, involved the generation of values for the two drought codes for 1981-2003 and logistic regression analysis.

6.2 PART 1: THE FREQUENCY OF YEARS WITH THE CONDITIONS FOR FIRE IN SEF

6.2.1 Background

Research from Chapter 4 showed that indicators of conditions for fire in SEF are: 1) fire in grass fuels from mid-February to the beginning of March; and 2) a SEF leaf litter moisture content below 15% in March. Although the literature for mainland Southeast Asia suggests that conditions in open deciduous and savanna fuels may commonly be dry enough to sustain fires set in February, SEF litter moisture contents of 15% or less are generally thought to rarely occur (Ogino, 1976; Kanjanavanit, 1992).

Still, the limited amount of local moisture content data available for mainland Southeast Asia suggests that low litter moisture contents may occur more commonly than thought. For instance Ofren (1999) recorded moisture contents under 10% in SEF towards the end

---

[92] Excluding 1983 and 2002.

of the dry season in 1997, and this present research (Ch. 4) showed low moisture contents in that same range in February in 2001.

6.2.2 Methods

The approach used to determine the frequency of years with conditions for fire in SEF was to build an historic relative humidity history. The relative humidity history was needed to meet two separate conditions. The first condition was to establish years when fire was likely to be burning adjacent to SEF. While there is little historic observation data available to this effect, what is known is that most fires that affect SEF are initiated in open deciduous forests and grasslands (grass fuels) on an annual basis (cf. Ch. 4). The literature suggests fires ignited in open DDF and savanna are likely to continue burning as long as it does not rain and the average relative humidity ($Rh_{ave,grass)}$ is maintained below 50% (Mather, 1978; as cited in Kanjanavanit, 1992).[93] Since most fires are set in February[94], relative humidity levels need to be below 50% from the time of ignition, say mid-February, until SEF fuels become flammable in mid March. [95] Thus the historic relative humidity record was used to identify years between 1984 and 2001 where the

---

[93] Kanjanavanit (1992) indicates that such conditions are common in grasslands in the dry season in mainland Southeast Asia. She also indicates that grasses are ready to burn from November, which suggests they cure early in the dry season, possibly in November and December.

[94] Increasing incidents of fire ignition in and around HKK from February 10th (pers. obs, 2000, 2001).

[95] This assumes sufficient grass fuels to carry fire in DDF_{open} and savanna to interface with SEF; a reasonable assumption in HKK where roughly 1/3 of the area contains grass fuels (cf. Ch2).

average relative humidity for open deciduous forests and grasslands was maintained below 50% between February 15th and February 28th. [96]

Second, there was a need to establish years when SEF was likely to have litter moisture contents under 15% in mid-March. Little daily dry season SEF litter moisture content information was available for SEF in mainland Southeast Asia. However some preliminary research on the relationship between litter moisture content and relative humidity was available for the Amazon. This research shows that it takes 13 to 16 days at a minimum relative humidity of less than 65% for SEF litter to dry to the point of flammability (Uhl & Kauffman, 1990; Holdsworth & Uhl, 1997).[97] Thus the historic relative humidity record was used to determine years between 1984 and 2001 when the SEF minimum relative humidity had been maintained below 65% between March 1st and March 15th.

The required relative humidity data for February and March (1984-2001) were obtained through interpolation. While a fairly continuous relative humidity record was available for open grass areas in HKK, a relative humidity record for SEF was not.[98] Thus, the

---

[96] Actually, relative humidity conditions in grass fuels need to be below 50% until mid-March, but the second requirement, that the relative humidity conditions in SEF litter need to be below 65% for the first two weeks of March is more stringent than that for grass fuels, so the relative humidity conditions for grass in March do not need to be considered further here.

[97] The flammability threshold referred to is 15%.

[98] Some SEF daily relative humidity data are presented in Thompson & Landsberg (1975); however the in-stand SEF relative humidity data and the forest clearing (field) data are presented as combined values, and as such cannot be used.

focus was placed on building a SEF minimum relative humidity record ($Rh_{min,SEF}$). There are several techniques for estimating missing weather data including methods based on series mean, ordinary least squares regression, and time series (Benton, 1990; Tuller, pers. com., 2005). For this research, missing weather data were determined using a least squares linear regression, which estimates a best fitting straight line through a set of data points. The linear least squares fitting technique was chosen because it is the simplest and most commonly applied form of linear regression. The average relative humidity values for grass ($Rh_{ave,grass}$) were then converted to SEF minimum relative humidity ($Rh_{min,SEF}$) equivalents so they could be graphed and read off the same scale.

A seven-step process was used to determine the frequency of fire season years between 1981 and 2003 with the conditions for fire spread in SEF as follows: i) acquisition of SEF relative humidity data from Hobo sensors ($Rh_{min,SEF,sensor}$) during the 2001 field season; ii) interpolation of the $Rh_{min,SEF}$ data values for 1994-2001 and 2003; iii) extension of the daily $Rh_{min,SEF}$ data back to 1981; iv) application of a fifteen-day moving average; v) determination of the $Rh_{min,SEF}$ threshold equivalent for an average relative humidity of 50% in grass; vi) identification of years when sustained $Rh_{min,SEF}$ values were below the determined thresholds for grass and SEF litter fuels in February and March.

SEF temperature and relative humidity data were obtained using miniature, battery-powered data loggers. The HOBO Pro Temperature/RH Data Logger Series Sensor, Onset Computer Company, USA were used. These sensors were chosen because they are portable, inexpensive and have an accuracy of $^{+/-}0.2\ ^{o}$ C and $^{+/-}3\%$ RH for the temperature and relative humidity range experienced in the field. HOBO sensors were mounted on a stick 20cm off the ground, as the original intent had been to correlate relative humidity with fuel moisture and not with other weather stations (App. 4-4d).[99] The sensors were suspended inside a white Polyvinyl Chloride (PVC) cap as shelter from direct sunlight and set to record temperature and relative humidity every 15 minutes.

All the sensors were in the field and in position by February 18, 2001, and stayed in their location until April 29th. The original intention had been to move the sensors to other locations every two weeks; however, this was not possible due to access and time problems caused by rain and logistics. Six HOBO sensors were taken to the field, but only three sensors provided relative humidity data. The relative humidity sensor on two of the HOBO instruments malfunctioned: it is believed that the sensors got wet just prior to deployment in the field. Another sensor was crushed, it was assumed by an elephant, and all those data for the field season were lost. The useful sensor data from the three valid sensors were downloaded into Onset Boxcar software and ultimately graphed using Microsoft Excel software.

There are two weather stations in HKK, one at Khao Nang Rum Station (KNR) and one at Kapokapeang Station (Fig. 6.1). They both have an approximate elevation of 500m

---

[99] Weather stations are set to a standard height of 1.20 m in Thailand

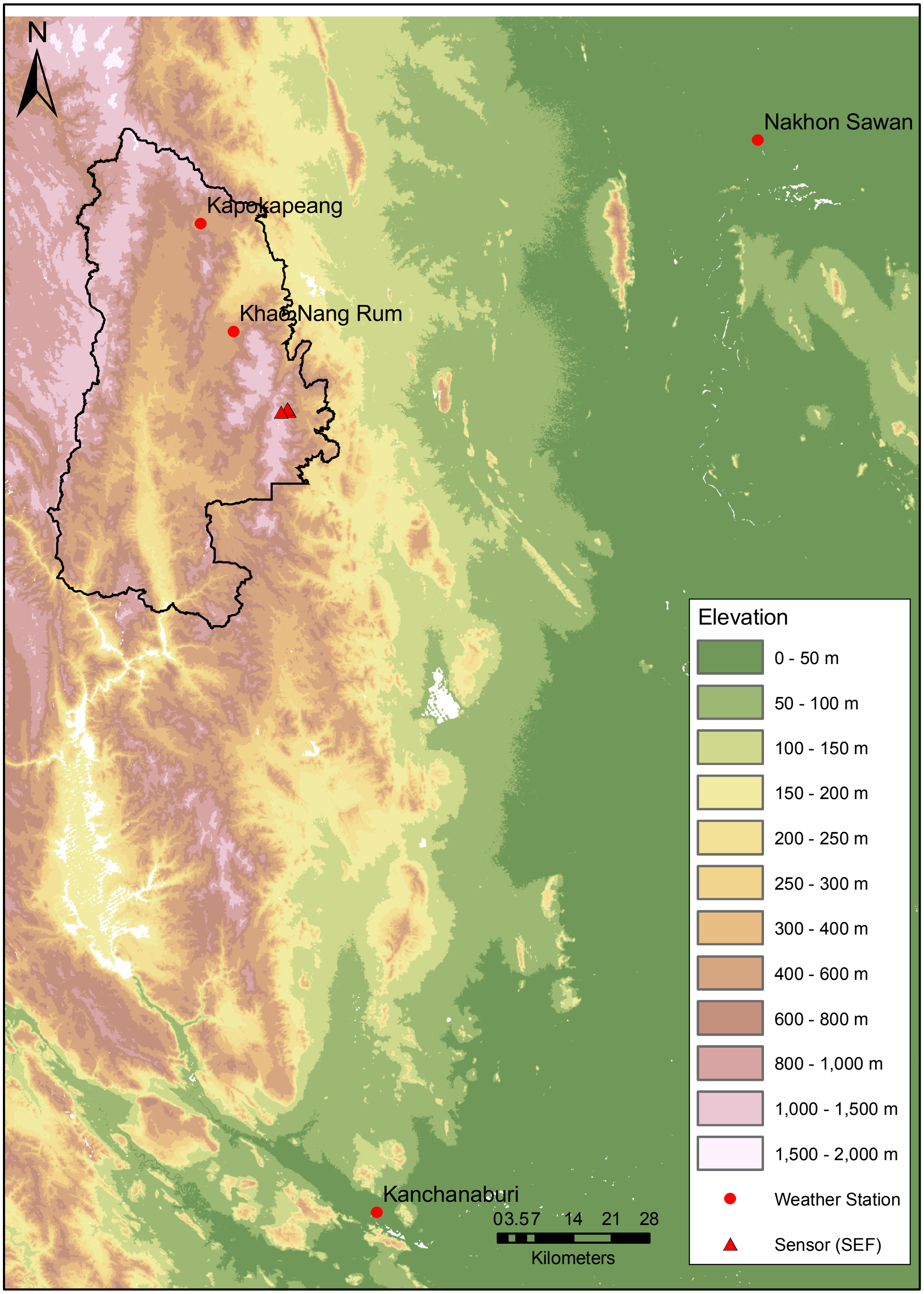


Figure 6.1 Hobo Sensor and weather station locations

and are set up in the station clearing, which is approximately 100m in diameter and surrounded by a mosaic of deciduous and evergreen forests. The weather station at Kapokapeang is a newer and more sophisticated automatic Campbell Scientific type 012 weather station, compared to an older automatic Sato Japanese-brand relative humidity logger.[100] Temperature instruments on both stations are sheltered and set up approximately one meter above the ground and over grass. The station at Kapokapeang had sensor data from 1992-1999, while the station at KNR had data from 1994-2001 and 2003.[101] The decision was made to use the KNR relative humidity data since it was both a longer and more consistent data set.[102]

Daily minimum relative humidity data were also available from stations outside HKK. The two closest weather stations for which relative humidity data back to 1981[103] are available are the Nakhon Sawan and Kanchanaburi weather stations (Fig. 6.1). Nakhon Sawan weather station (15^{o} 48’00’’N, 100^{o} 10’ 00’’E) is located at 34masl[104] in an open grass area approximately 200m x 200m surrounded by a ‘built’ community setting. Kanchanaburi weather station (14^{o} 01’ 00’’ N, 99 ^{o} 32’ 00’’ E) is located at 28 masl in an open area of 8m x 8m surrounded by sparse forest (savanna). Both weather stations use

[100] Detailed information on the type of weather station at KNR was not available.
[101] The weather station at Khao Nang Rum is still operational however they have a backlog of data to process (Sukmasuang, 2004, pers. com.).
[102] The weather station at Kapokapeang has broken down a number of times over the years that have resulted in lengthy gaps in the data set and concern over the quality of some data (Bunyavejchewin, 2002, pers. com.).
[103] Except 1983.
[104] Masl = meters above sea level.

the same type of instruments, shelter and methods. Temperature is measured manually using wet and dry bulb thermometers after which both values are converted to relative humidity by using a standard conversion table. Thermometers are installed in a "screen box" (60 x 60 x 70cm) and located 1.20m above ground. The box has "slatted windows" which allow for air circulation while limiting wind flow (Paiboon, pers. com., 2005; Satidporn, pers. com., 2005). The minimum relative humidity data from these stations ($Rh_{min,field}$) were available back to 1981 and were of high quality; i.e., the data were a continuous day record with few gaps.[105]

The HOBO sensor data were checked for comparability to establish the relationship between $Rh_{min,SEF}$ and $Rh_{min,field}$. This was done by first, averaging the three $Rh_{min,sensor}$ results for SEF. The three sensors have comparable readings (Fig. 6.2). Second, SEF sensor data were cleaned by limiting high $Rh_{min,SEF}$ values to a maximum value of 98%.[106] The forest clearing (Khao Nang Rum weather station) data were cleaned by limiting low $Rh_{min,field}$ values to a minimum of 4%.[107] Third, rainy days between March 9 and March 25, 2001, were deleted. Fires will not ignite or spread on these days, and inclusion of an unseasonable period of rainy weather during the dry season could skew results (S. Tuller, pers. com., 2005). Fourth, a check was made to ensure that relative humidity minimums

---

[105] The exception was 1983, which had a large dry season relative humidity gap.
[106] Several days of unseasonable rainy weather led to inaccurate sensor readings of 100% or more.
[107] There were two or three days in the KNR data set that registered as low as zero, which is not possible.

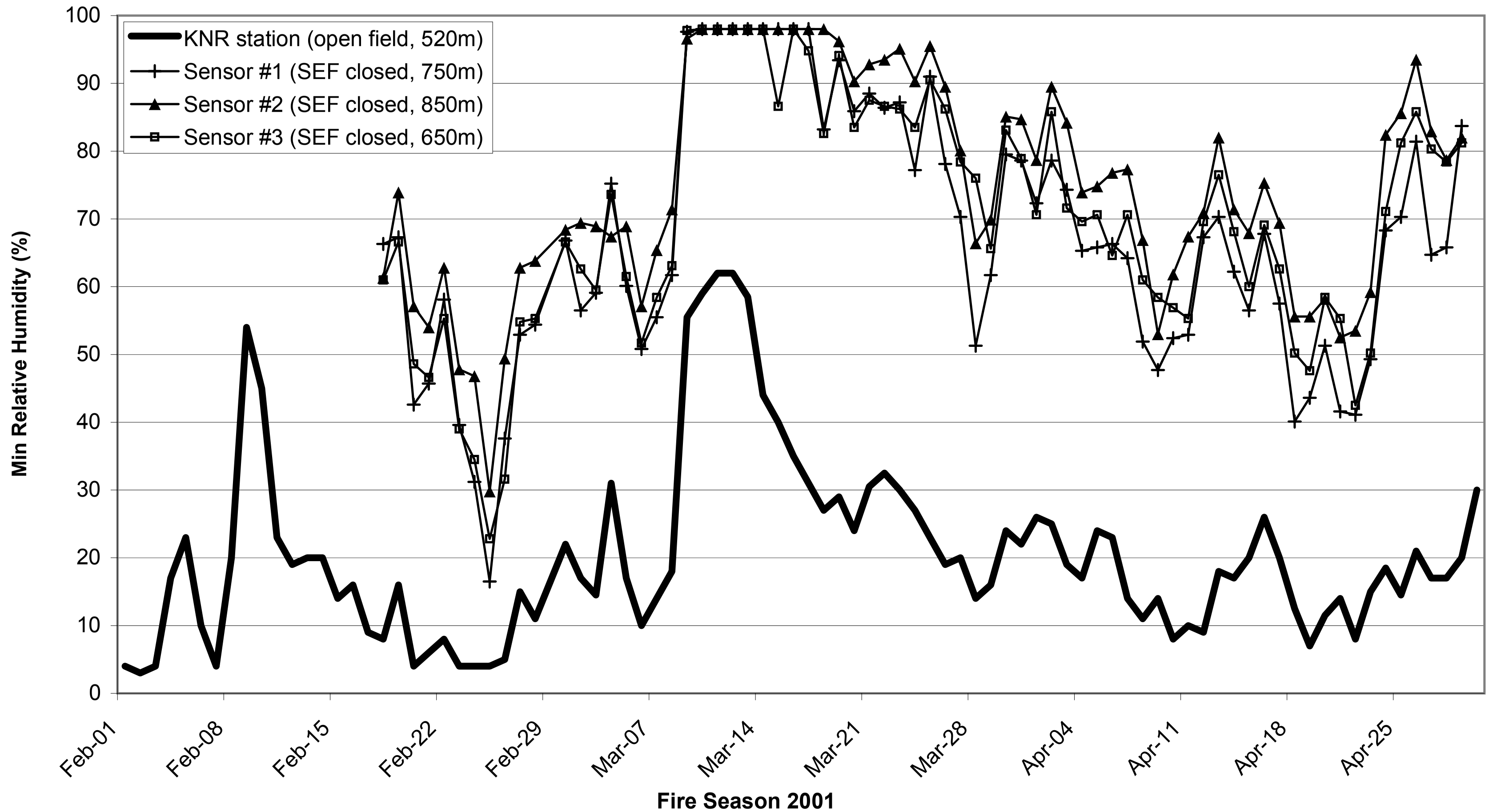


Figure 6.2 Comparison of the fire season minimum relative humidity values for sensors in closed seasonal evergreen forest and weather station in open at Khao Nang Rum. Rh_{min} values for the sensors were comparable despite the placement of sensors at different elevations.

for SEF occur at about 1300 hours.[108] A histogram developed from the sensor values shows that the minimum relative humidity in SEF in HKK generally occurs between 1300 and 1400 hours (Fig. 6.3).

Interpolation of the $Rh_{min,SEF}$ data set for 1994-2003[109] was accomplished as follows. First, the relationship between $Rh_{min,SEF}$ and $Rh_{min,field}$ was determined by inputting the $Rh_{min,SEF,sensor}$ and $Rh_{min,field,KNR}$ data into an Excel spreadsheet. Specifically, 2001 fire season $Rh_{min,SEF,sensor}$ data for SEF (February through April) were regressed against 2001 fire season $Rh_{min,field,KNR}$ data. The results showed an R^2 of 0.70, for the equation $y = 1.44x + 43.07$, where y is the $Rh_{min,field,KNR}$ and x is $Rh_{min,SEF,sensor}$ (Fig. 6.4a). Next, $Rh_{min,SEF}$ values for 1994-2003 were generated by entering $Rh_{min,field,KNR}$ values into the equation (above). Finally, $Rh_{min,SEF}$ dry season data were validated by comparing 'predicted' $Rh_{min,SEF}$ values for 2001 with 'actual' $Rh_{min,Sensor,SEF}$ values for the 2001. The two data sets showed similar curves (Fig. 6.4b).

The $Rh_{min,field,KNR}$ data set was extended in an effort to lengthen the $Rh_{min,SEF}$ data set as far back in time as possible. The approach taken was to determine whether a relationship exists between daily $Rh_{min,field,KNR}$ values in HKK and those from an average of two lowland weather stations outside the HKK boundary, Nakhon Sawan and Kanchanaburi

---

[108] Kauffman et al. (1990) and Uhl et al. (1990) used 1300 data as the relative humidity minimum for tropical evergreen forest in the Amazon.

[109] $Rh_{min,field,KNR}$ data were not available for 2002 so this year was omitted from the data set.

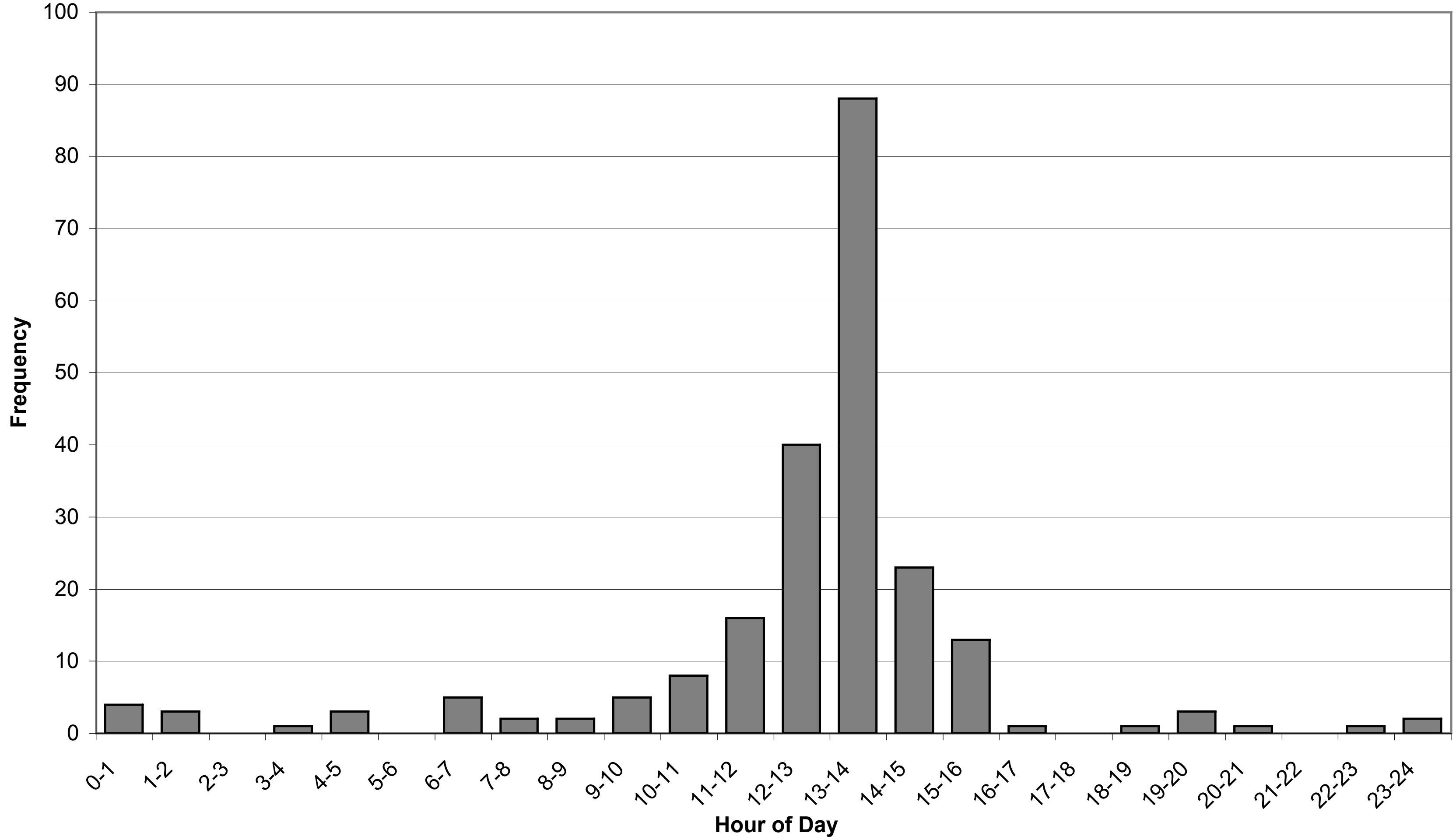


Figure 6.3 Histogram for the time of daily minimum relative humidity occurrence in seasonal evergreen forest from February to April, 2001

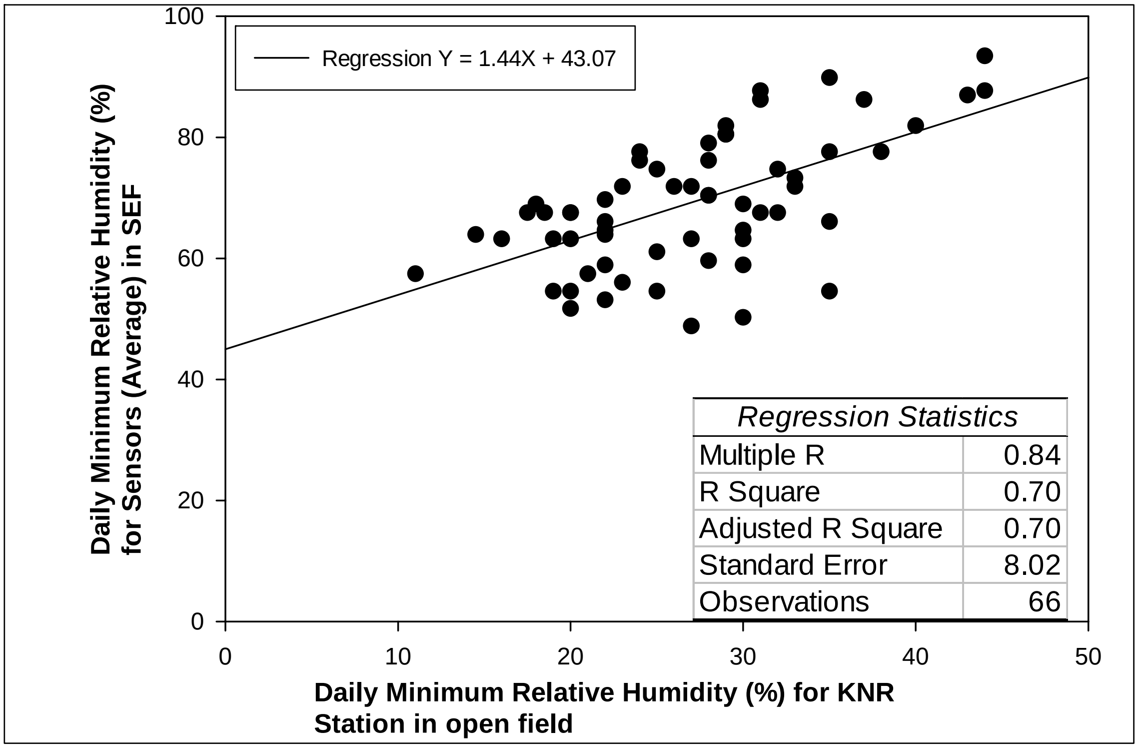


Fig. 6.4a Regression of open field relative humidity to seasonal evergreen forest relative humidity minimums for 2001 fire season

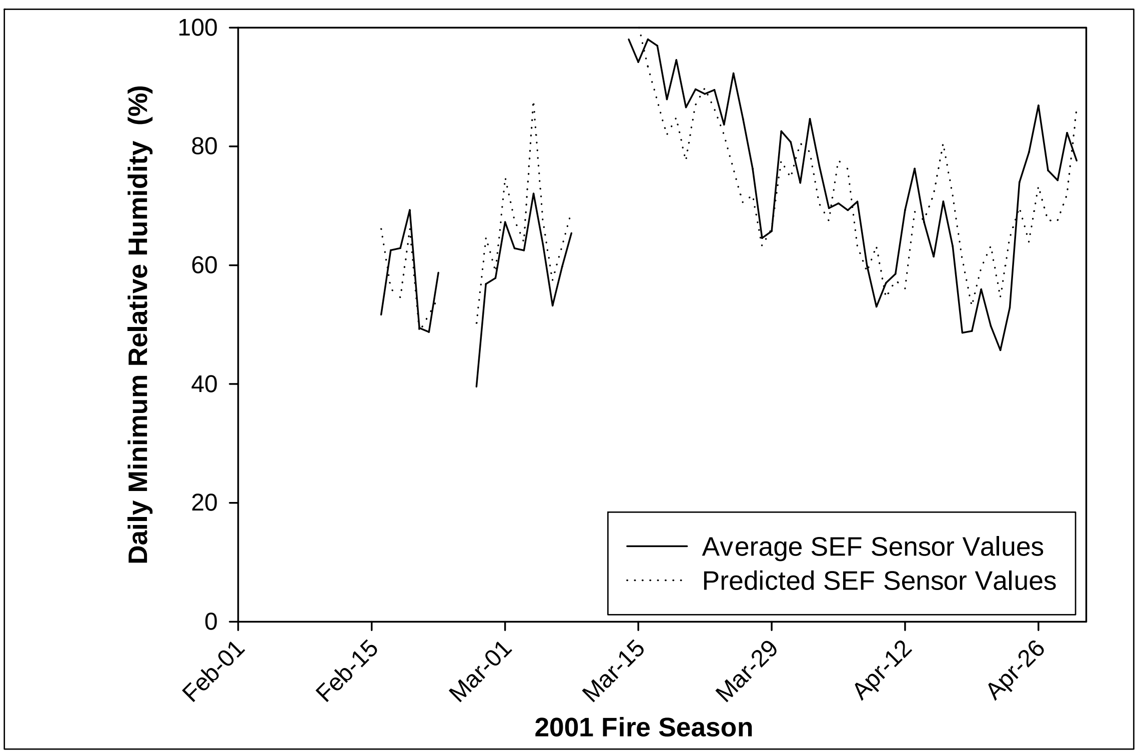


Fig. 6.4b Comparison of predicted and average sensor relative humidity minimums

($Rh_{min,field,N\&K}$) (Fig. 6.1). Station values were regressed both individually and in combination using the overlapping data sets for 1994 to 1999. The regression between $Rh_{min,KNR}$ and $Rh_{min,N\&K}$ was found to fit best with an R^2 of 0.68 (Fig. 6.5a). Then, the daily $Rh_{min,KNR}$ values were interpolated back to 1981. Finally, the data were checked by comparing predicted $Rh_{min,KNR}$ values for 2001 with actual $Rh_{min,KNR}$ values for 2001 (Fig. 6.5b).

A fifteen-day moving average was then applied to the 1981-2003 daily $Rh_{min,SEF}$ data set. The work was carried out in Excel using the 'moving average analysis tool.'

Determination of the $Rh_{min,SEF}$ threshold equivalent for an average relative humidity of 50% in grass was calculated in the following manner: First, the $Rh_{ave,field,KNR}$ values for the 1994-1999 fire seasons were regressed with the $Rh_{min,field,KNR}$ values for the same period. The regression equation produced was y = -36.15 + 1.15x with an R^2 of 0.60, where x is $Rh_{ave,field,KNR}$ and y is $Rh_{min,field,KNR.}$ Next, the predicted $Rh_{min,field}$ threshold was calculated using the 50% relative humidity value as follows: y = -36.15 + 1.15(50). From the calculation the $Rh_{min,field}$ value is 21%. Finally, the predicted $Rh_{min,SEF}$ threshold value was calculated using the earlier $Rh_{min,field,KNR}$ to $Rh_{min,SEF,sensor}$ equation (Fig. 6.4a) as follows: y = 1.44 (21) + 43.07, where y is the daily $Rh_{min,SEF,sensor}$. From the above calculation a February threshold value applicable to the SEF data was found to be 73.3%.

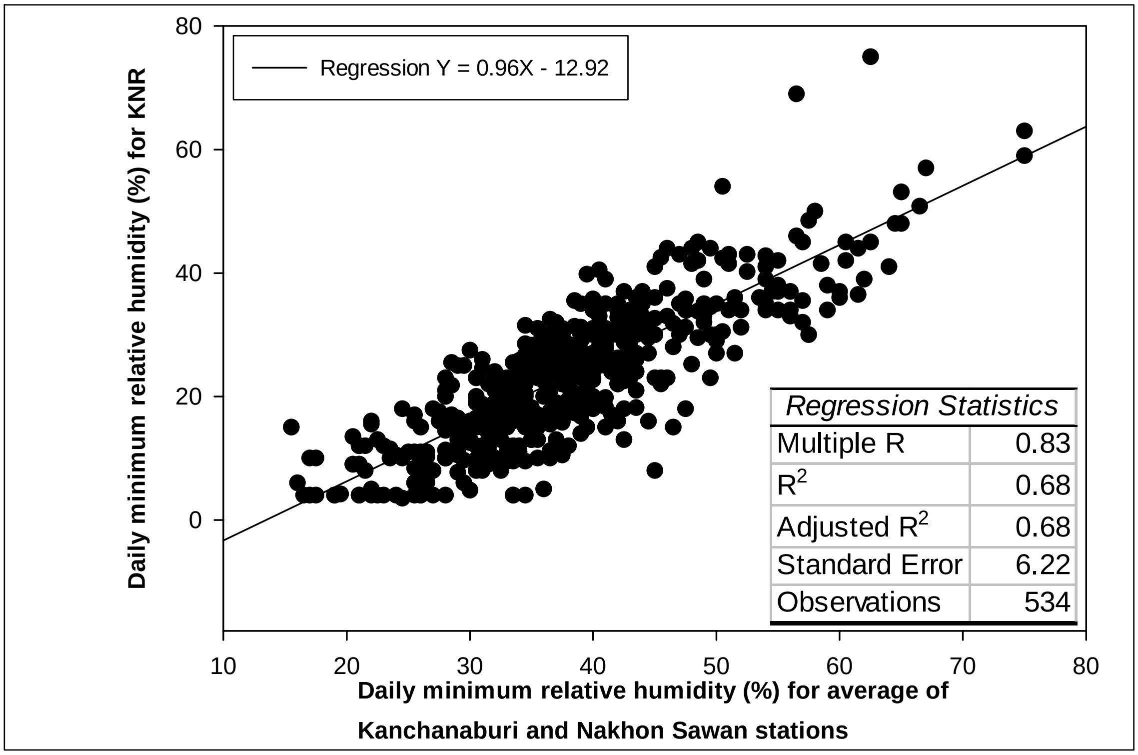


Figure 6.5a Regression of Kanchanaburi and Nakhon Sawan relative humidity minimums to Khao Nang Rum minimums for fire season years from 1994 to 1999

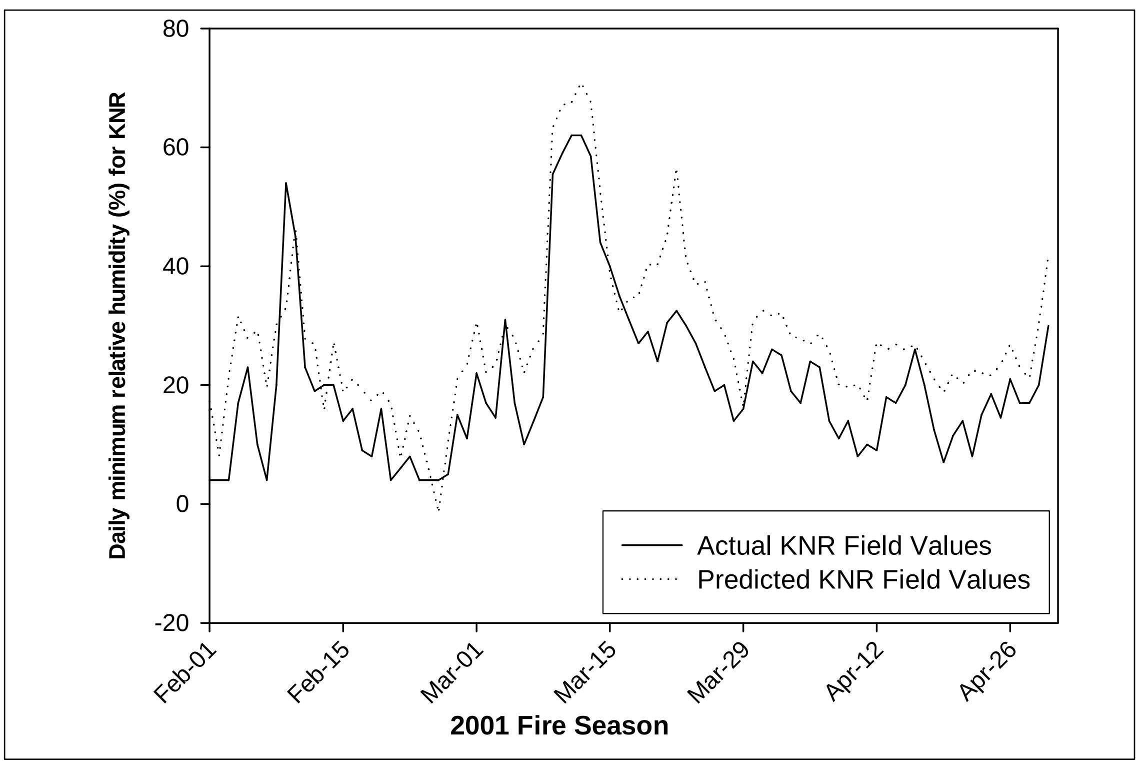


Figure 6.5b Comparison of predicted and sensor relative humidity minimums

Identification of fire season years when the daily relative humidity values were sustained below February and March thresholds was made by first, plotting the dry season $Rh_{min,SEF}$ values in HKK for 1981 to 2003[110]; and second, identifying years where $Rh_{min,SEF}$ values for the last two weeks of February were sustained below 73%, and the $Rh_{min,SEF}$ values for the first two weeks of March were sustained below 65%. Finally, the fire frequency was calculated by dividing the number of identified SEF fire spread condition years by the 17-year interval (1984-2001).

6.2.3 Results

The results showed that sustained $Rh_{ave,grass}$ below 50% ($Rh_{min,SEF}$ equivalent 73%) occur commonly in open deciduous forest and savanna from February 15th to February 28th. Specifically, 10 of 17 years met this standard including 1985, 1986, 1990, 1991, 1992, 1993, 1994, 1995, 1998, and 2001. However there were only four years with a sustained $Rh_{min,SEF}$ below 65% for the two-week period between March 1st to March 15th. These were 1985, 1992, 1994, and 1998 (Fig. 6.6). In fact, both the conditions for fire spread in grass for the last two weeks of February and for fire spread in SEF for the first two weeks of March were met in these same four years. The fire frequency for SEF between the years of 1984 and 2001 is 4.25, indicating that the conditions for fire occur on average once in every four years.

---

[110] Excluding 1983 and 2002.

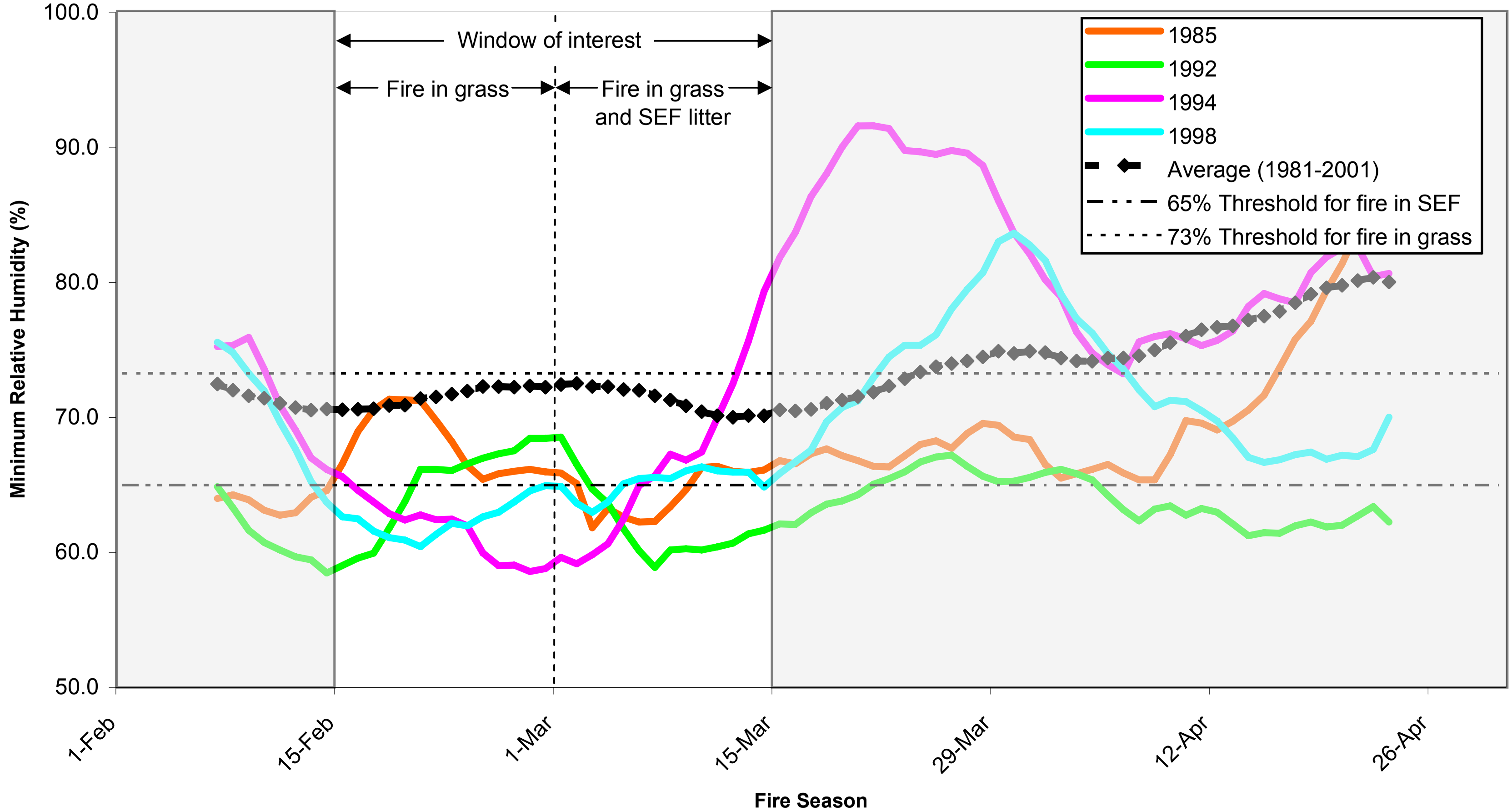


Figure 6.6 Sustained low seasonal evergreen forest (SEF) relative humidity years between 1984 and 2001. Fire seasons of 1985, 1992, 1994, and 1998 had relative humidity minimums (Rh_{min}) below the 73% threshold necessary for fires lit in grass in mid-February to continue burning and the two weeks of Rh_{min} below 65% threshold necessary to prepare SEF litter to burn in March.

The results were supported by the fire history data generated in Chapter 3. Substantial areas of SEF burned in HKK in 1992, 1994, and 1998. These years were also the sustained low $Rh_{min,SEF}$ years (Figs. 3.4, 6.7). With regard to 1984, while little burn area data were available for SEF from 1981-1987, Rabinowitz (2002) did indicate that a major fire year occurred in the mid-80s; however the precise year was not documented.

Other years that presented minor burning in SEF are shown in figures 6.8a and 6.8b. The years 1991 and 1995 had low $Rh_{min,SEF}$ in February. The burning that was noted for 1991 probably occurred in open SEF near the beginning of March. Also, 1988 and 1989 showed relatively low sustained $Rh_{min,SEF}$ later in the dry season. It seems likely that these fires started later in the field season (i.e., late March or early April).

6.2.4 Discussion

The research in this first part of this chapter suggests that in HKK the conditions for fire (i.e. fires burning in and around SEF in mid-March and litter moisture contents below 15%) occur comparatively frequently, on average once every four years. This frequency was far higher than that indicated in most of the literature, which suggests that SEF litter is rarely dry enough to burn. However, this study result was not unexpected since some published research had indicated that low litter moisture contents in SEF do occur in some years (e.g., Ofren, 1999).

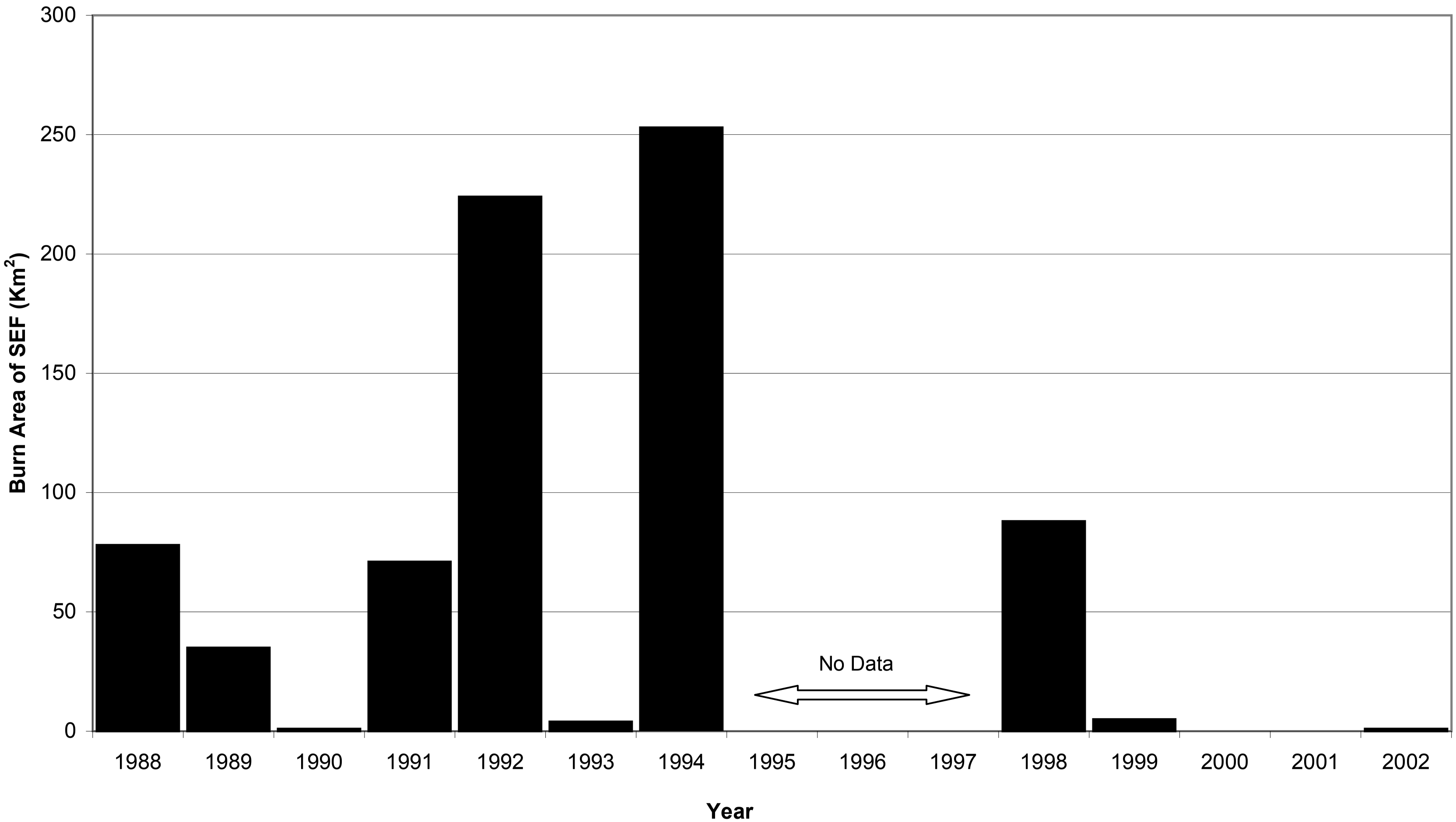


Figure 6.7 Annual burn area in km² for seasonal evergreen forest in Huai Kha Khaeng between 1988 and 2002.*

* Data generated from Landsat TM analysis in Chapter 3.

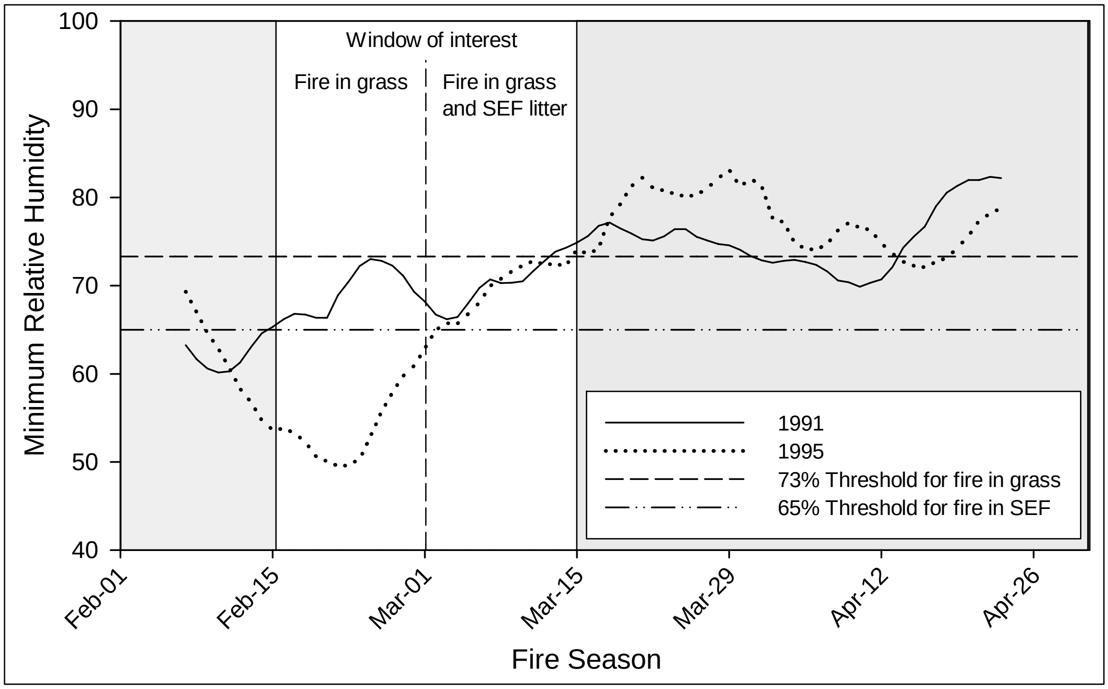


Fig. 6.8a Relative humidity minimums for 1991 and 1995. Relative humidity in seasonal evergreen forest ($Rh_{min,SEF}$) is not below the 65% threshold necessary for fire in SEF litter. Grass will burn in February but not spread to SEF in March.

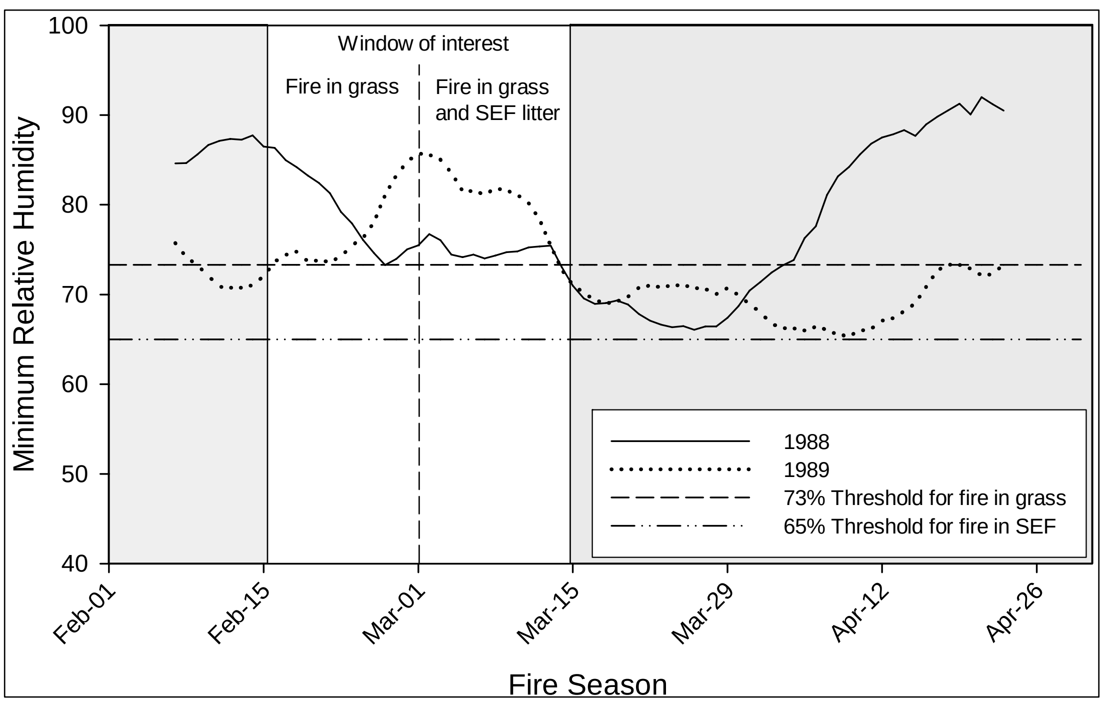


Fig. 6.8b Relative humidity minimums for 1988 and 1989. SEF values are not low enough to maintain fire in February, but are marginally low enough for fire in SEF in late March or early April, provided a source of ignition at that time.

This part of the study had two limitations in terms of predicting the frequency of fire in SEF. First, the study relied on relative humidity thresholds established from published literature (much of it from the Amazon region of Brazil) rather than through local experimentation. If the threshold is not consistent with conditions in the region, it is possible that the fire frequency results will be skewed, although there is no evidence of this being the case. Second, the fire frequency was established for only one locale, HKK. Additional research is required to confirm the frequency with which fire in SEF is likely to occur in the wider region.

6.3 PART II: RELATIONSHIP BETWEEN SUSTAINED LOW SEF RELATIVE HUMIDITY YEARS AND DROUGHT CODES

6.3.1 Background

Until recently, relatively little research had been done in predicting years when SEF would burn. Fire in SEF was known to be linked with drought (Nepstad et al., 1999a; Nepstad et al., 2004). Further, a clear relationship between drought and El Nino had been established for some parts of the world (Ropelewski & Halpert, 1986; Goldammer, 1993). However this relationship has not proven to be significant for the mainland Southeast Asia region (Goldammer & Siebert, 1990).

More recently, research involving the prediction of the required conditions for fire in tropical evergreen forests has come from the Amazon Basin, and specifically the work of

Daniel Nepstad (cf. Nepstad et al., 1994; Nepstad et al., 1995; Jipp et al., 1998; Nepstad et al., 1999a). Nepstad, a senior researcher at Woods Hole, Massachusetts, USA, undertook research to determine whether fire season years with low SEF litter moisture contents could be predicted by monitoring deep groundwater reservoirs. Nepstad (1999a) reasoned that it should be possible to use groundwater levels to assess years with low litter moisture contents since in-stand relative humidity, a controlling factor for litter moisture content, is dependent on tree roots being able to readily access water. Evergreen forest species in the Amazon region have been shown to have deep root systems which are capable of obtaining water from depths of 8 to 12m (Jipp et al., 1998).[111] Provided there is sufficient groundwater, evergreen forests maintain high internal relative humidity levels throughout the dry season. Conversely, depletion of deep groundwater reservoirs, which can occur after a prolonged drought (e.g., several concurrent years), may result in low internal evergreen forest relative humidity levels and associated low litter moisture contents.

On this basis Nepstad (2004) developed a model to enable the early detection of evergreen forest fire risk in the Amazon Basin. RisQue is a geographic information system-based soil water balance model that produces a map of maximum plant-available soil water (PAWmax) (10m depth).[112] As described by Nepstad, PAW is depleted using

---

[111] Tropical evergreen trees were previously thought to be shallow rooted (Jordan, 1985; Jordan, 1991).

[112] The RisQue model was developed using 1565 soil texture profiles and empirical relationships derived from soil texture and critical soil water parameters.

monthly evapotranspiration estimates derived from the Penman-Monteith equation and satellite-derived radiation inputs, and recharged using monthly rainfall estimates derived from 266 meteorological stations. Preliminary assessements of RisQue suggest the model has promise in terms of detailing the spatial and temporal patterns of drought in the Amazon basin.

Similar SEF prediction research has not been undertaken for mainland Southeast Asia. It would take several years to obtain the required input parameter of daily deep groundwater baseline data in HKK, or for the larger region (Tangtham, pers. com., 2001). The only currently available tools for monitoring soil moisture status are drought codes or indices that represent soil moisture deficiency as a continuous variable. Index values generally range from zero, in which the soil and duff (organic matter) are saturated with water, up to a maximum value (e.g. 100s or 1000s) that corresponds to the absence of available moisture in the soil and deep duff layers. In other words, the upper portion of the scale corresponds to those situations when the moisture deficiency is "abnormal" or "unusual" (cf. Werth, 2005). Drought codes are readily accessible since they require only basic weather information, such as temperature and precipitation in order to generate them.

Nepstad (1996) argues that drought codes or indices are inadequate for predicting long-term drought because they use comparatively shallow soil moisture reservoir depths. However recent research by Negreiros (2004) suggests that it is the upper soil layer (top

10cm), and not deep soil water reservoirs, that influence SEF litter moisture contents. Regardless, it is seems useful to determine if there is a relationship between available drought codes or indices and sustained low relative humidity years since no deep soil moisture reservoir codes or indices are currently available.

6.3.2 Methods

The relationship between pre-fire season drought codes and low relative humidity conditions during February and March in SEF was determined using logistic regression. Logistic regression is a type of ordinary regression[113], useful when the observed outcome is restricted to two values, which usually represent the occurrence or non-occurrence of some outcome event, (usually coded as 1 or 0, respectively). It produces a formula that predicts the probability of the occurrence as a function of the independent variables (Pezzullo, 2005).

Two drought codes were selected for the research, Keetch-Byram Drought Index (KBDI) and Canadian Drought Code[114] (DC).[115] Drought codes such as KBDI and DC are indices that produce a number that represents the net effect of precipitation and evapotranspiration in producing cumulative moisture deficiency in the deep duff or upper

---

[113] Ordinary regression deals with finding a function that relates a continuous outcome variable (dependent variable y) to one or more predictors (independent variables x_1, x_2, etc.). Simple linear regression assumes a function of the form: $y = c_0 + c_1 * x_1 + c_2 * x_2 + ...$ and finds the values of c_0, c_1, c_2, etc. (c_0 is called the "intercept" or "constant term").

[114] Drought Code is one element of the Canadian Fire Weather Index (FWI) System.

[115] Excluding 1983 and 2002.

mineral soil layers. These two drought codes were chosen because both have been used with respect to fire-related research in the Southeast Asia (Weidemann, 2002; Weidemann et al., 2002; FDRS, 2004). The reservoir thickness for KBDI is 20 cm, while for DC is 10 cm.

Two sets of data were generated for the logistic regression. The first data set was the January 31st drought code values for KBDI and DC (independent variable), while the second set were designated SEF 'fire spread condition' and 'non-fire spread condition' years (dependent variable). Data requirements for generating the two drought codes values were as follows. The KBDI requires daily twenty-four-hour total rainfall at 1500 hours standard time, and daily maximum temperature for a continuous period of several months[116] (Hoffmann, 2002; Weidemann, 2002). The DC requires daily twenty-four-hour total rainfall recorded at 1200 hours Standard time, and the daily temperature readings at 1200 hours Standard time (Turner & Lawson, 1978).[117]

Rainfall and temperature data were acquired from Khao Nang Rum Wildlife Research Station (KNR), HKK. Twenty-four-hour total rainfall from 0800 to 0800, and maximum daily temperature were available from 1981 to 2003.[118] Noon temperature readings were also available but only from 1994 to 2003. For the most part the continuity of the

---

[116] The time lag for KBDI is 88 days.
[117] The time lag for DC is 48 days.
[118] Excluding 1983 and 2002.

weather data sets was quite high, though significant gaps were apparent for the 1983 and 2002 dry seasons. Where an occasional daily maximum temperature value was missing, the average of the two closest values was used.

Both drought codes were calculated in pre-programmed Excel worksheets. The KBDI calculation worksheet was obtained from a GTZ[119] Project, "*Integrated Forest Fire Management*" based in Samarinda, East Kalimantan. The KBDI worksheet formula was slightly modified (i.e., the units were changed from imperial to metric) with the result that the index scale was also readjusted from 1-800 to 1-2000 (Hoffmann, pers. com., 2002; Weidemann et al., 2002). A DC calculator was obtained in the form of a Fire Weather Index Excel-based Addin Utility from the Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. The calculator included an adjustment for latitude (a required calculation for day length), which facilitated the use of the program in the Southeast Asia region (R. Field, pers. com., 2003).

A starting date of June 23, 1980, was selected for both the codes. The KBDI requires that calculations begin after 150mm or greater rain have fallen in the previous seven days (cf., Fujioka, 1991; Weidemann et al., 2002).[120] In the seven-day period prior to June 23rd,

---

[119] Gesellschaft fur Technische Zusammenarbeit (GTZ), the German Development Agency

[120] KDBI calculations should be started at a point in time when the soil reservoir is saturated (Fujioka, 1991). In Indonesia, a field capacity of 200mm is assumed, and recommendations are made for starting the KBDI at 0 after a rainy period with 150-200mm rainfall within one week (Weidemann, 2002; Weidemann et al., 2002).

180mm fell at KNR station. DC does not specify a start date requirement, however it seemed reasonable to start the DC calculations on the same day as the KBDI.[121] The daily twenty-four-hour total rainfall, and maximum temperature were entered in both worksheets.[122] Maximum temperature values were used for both indices.[123] January 31st drought code values for 1981-2003 were calculated. Appendix 6-1 shows a sample of the KBDI and Appendix 6-2 shows a sample of the DC calculations.

Designated SEF 'fire' and 'non-fire' spread condition years were determined. First, a single numeric value representative of the $Rh_{min,SEF}$ for the period February 15th to March 15th for each year between 1981 and 2003 was established. This was done by averaging the $Rh_{min,SEF}$ for February 15th to February 28th values, then averaging $Rh_{min,SEF}$ values for March 1st to March 15th, and finally averaging the two averages. Second, the average 'threshold' level was calculated. The threshold was established by averaging the $Rh_{min,SEF}$ threshold for fire in grass, 73%, and the $Rh_{min,SEF}$ threshold for fire in SEF, 65%, giving a threshold value of 69%. Third, the $Rh_{min,SEF}$ value for each year was compared with the threshold value. Those fire season years (1981-2003) with average $Rh_{min,SEF}$ values of 69% or less were allocated as '1' (i.e., fire season years with the

---

[121] The water reservoir for the DC is smaller than that for the KBDI, so the DC can be started on the same date as the KBDI (Van Wagner, 1987).
[122] The limited hourly relative humidity data previously examined showed that the maximum temperature readings were actually close to the noon readings.
[123] Only a limited period of 1200-hour temperature data was available for the calculation.

conditions for fire in SEF), and those above the 69% threshold as ‘0’ (i.e., fire season years without the conditions for fire spread in SEF).

The logistic regressions were performed using an internet-based spreadsheet called Logistic Regression (version 05.07.20) (Pezzullo, 2005).[124] Table 6.1 shows the January 31st drought code value and the $Rh_{min,SEF}$ fire-season year designation for KBDI and DC, respectively.

6.3.3 Results

There is a significant relationship between the January 31st (pre-fire season) drought code value for both KBDI and DC and SEF ‘fire spread condition’ and ‘non-fire spread condition’ years. Specifically, the results showed that whether or not SEF had the potential to burn was reflected in the January 31st drought code value. Sustained low relative humidity fire season years were signaled in the January 31st KBDI value at a significance of (1, N21) = 18.76, p=0.0000, and confirmed in the January 31st DC value at a significance of (1, N21) = 13.69, p=0.0002. The fifty percent probability marker for differentiating sustained low $Rh_{min,SEF}$ years from other years was 1860 for KBDI and 430 for DC (Figs. 6.9a,b). However the selection of a working threshold for prediction should be adjusted down toward the base of the curve (Figs. 6.9a, b) so that all possible

[124] 1983 and 2002 were deleted due to lack of data.

Table 6.1 Logistic regressions for seasonal evergreen forest fire years and January 31st drought code values for both KBDI and DC

$KBDI_{Jan31}$	SEF fire conditions	Cumulative Probability		DC_{Jan31}	SEF fire conditions	Cumulative Probability
1253	0	0		193	0	0.0002
1388	0	0		234	0	0.0008
1448	0	0		263	0	0.0022
1504	0	0		289	0	0.0055
1554	0	0		295	0	0.0068
1555	0	0		299	0	0.0078
1654	0	0.0001		303	0	0.009
1664	0	0.0002		307	0	0.0104
1676	0	0.0003		314	0	0.0133
1691	0	0.0006		339	0	0.0318
1703	0	0.001		369	0	0.0875
1727	0	0.0027		381	0	0.1284
1832	1	0.206		396	0	0.2011
1843	0	0.2948		402	0	0.2377
1857	0	0.4343		415	1	0.3316
1861	0	0.4773		433	1	0.4856
1883	1	0.7035		470	1	0.7798
1925	1	0.9363		479	1	0.83
1933	1	0.9541		485	0	0.8582
1978	1	0.9932		543	1	0.9796
1988	1	0.9956		573	1	0.9929

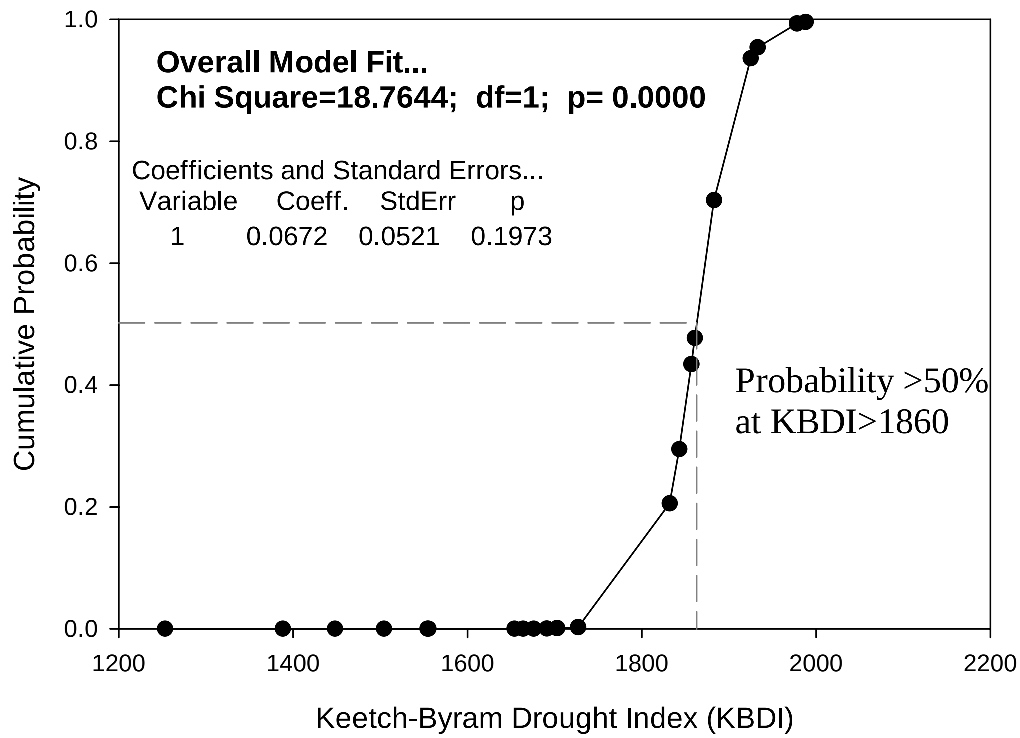


Fig 6.9a Probability of fire in seasonal evergreen forest using KBDI

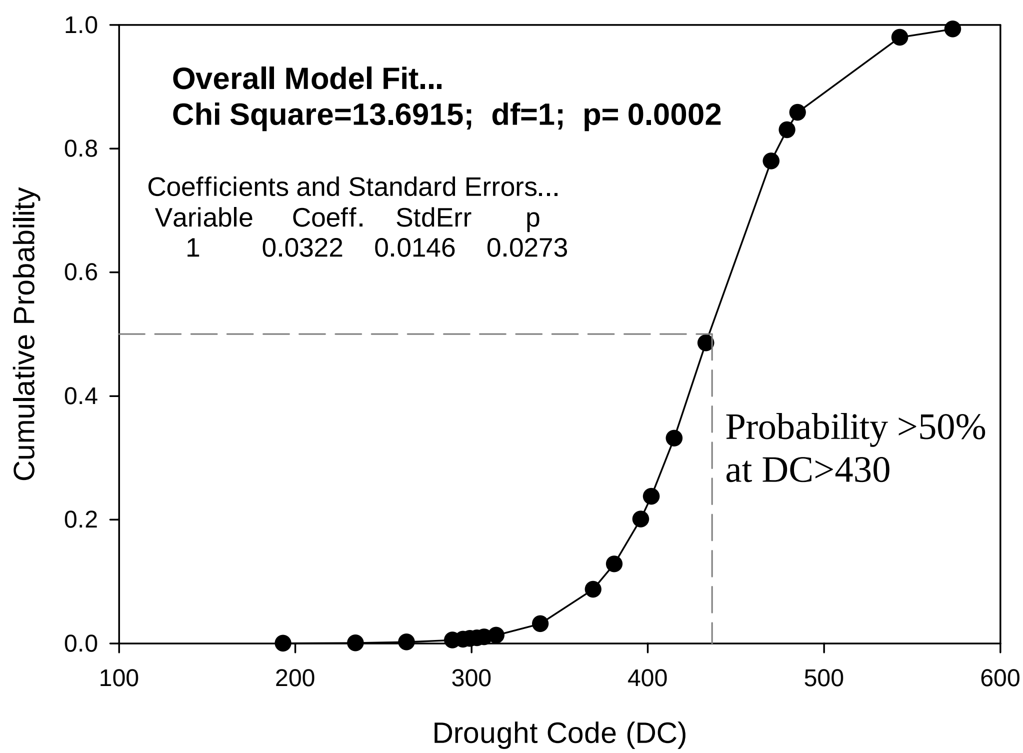


Fig 6.9b Probability of fire in seasonal evergreen forest using DC

SEF fire years are predicted. Working thresholds of 1800 and 340 for KBDI and DC, respectively, would be appropriate.

6.3.4 Discussion

The results show a significant relationship exists between the pre-fire season drought codes (KBDI and DC) and fire season years which have conditions for fire spread in SEF. This finding differs significantly from what is generally indicated in the literature (cf. Nepstad, 1996; Nepstad et al., 1998). First, there is little indication in the mainland Southeast Asia literature that prediction of fire is possible with available information and resources. Second, the research on SEF fire prediction in the Amazon indicates that drought codes cannot be used to predict fire, the drought code soil reservoirs being too shallow to reflect the plant soil water relationships that drive internal evergreen forest relative humidity. In comparison, the research findings reported here show that drought codes can be used to predict fire in SEF in HKK.

The reason that a significant relationship between the pre-fire-season drought code and fire probability exists is not clear. It may have to do with the fact that SEF in mainland Southeast Asia are not as deeply rooted as Amazon SEF. The literature indicates that seasonal evergreen species in mainland Southeast Asia have a rooting depth between 0.5 and 3m only (cf. Canadell et al., 1996; Weyerhaeuser, 1998; Tennigkeit, 2000). It could also be as Negreiros (2004) suggests that litter moisture contents are governed by the upper soil layer. The primary limitation of this research is that although a significant relationship was found in Huai Kha Khaeng, it might not necessarily be so for SEF in other parts of the region.

6.4 CONCLUSIONS

The purpose of the chapter was twofold. The first part of the chapter concerned determination of the fire frequency for SEF in HKK. This part of the research built an historic $Rh_{min,SEF}$ data set using values derived via linear regression to determine fire season years in SEF in HKK between 1984 and 2001 where fire was likely to be burning adjacent to SEF in March and SEF litter moisture contents of less than 15% at that time (i.e., $Rh_{min,SEF}$ less than 73% in February, and $Rh_{min,SEF}$ of less than 65 % in March). The second part of the chapter concerned whether drought code indices can be used to predict years with the conditions for fire spread in SEF. Two drought codes were generated, KBDI and DC, and a logistic regression performed between the January 31st drought code value for each drought code and the average relative humidity minimum for grass and for SEF ($Rh_{min,field\&SEF}$) in for the four-week period. Logistic regression showed there to be a highly significant relationship between pre-fire season drought codes (KBDI and DC) and years with the conditions for fire in SEF. Additional research is needed to replicate this work in order to determine whether the relationship holds for the region.

CHAPTER 7 CONCLUSIONS

In recent years large-scale fires have swept across the landscape including protected areas (PAs) in mainland Southeast Asia. Fire has historically been present in the region. Most fires were started by people to clear fields and maintain hunting grounds. Fires were generally limited to fields and smaller grassland areas. In this way successional aspects of the forest mosaic of seasonal evergreen forests (SEF), closed deciduous forest, and open deciduous forest and savanna (and fields) were maintained. However in recent years the situation has changed. There are more people lighting fires in remote areas of the region, and larger areas of flammable successional vegetation. In drought years the burning can be very extensive, and there have even been reports of fire in SEF – forests previously thought only very rarely to burn.

Fire is not a normal disturbance factor for SEF. There is concern that fire will degrade SEF to more open deciduous types, and that the result will be degradation of the landscape mosaic with a significant loss of biodiversity in the region. The primary management approach has been to try to eliminate all fire in order to prevent larger landscape-scale burns. However, this approach is not appropriate for PAs. Fire is needed in order to maintain successional elements in the landscape mosaic. Prescribed burning of open deciduous forests has also been suggested. However such an approach is impractical given the amount of open deciduous forest and savanna, which would need to be burned every two to three years.

Four research questions were posed as a way to address the problem of fire management in PAs in mainland Southeast Asia. First, information was sought on the extent of SEF burned in recent years, and in particular landscape-scale fire years. Gaining an understanding of the extent of burning in SEF is important in order to determine whether concerns about fire in SEF in PAs are warranted. Second, information was sought on why SEF have been burning. Gaining an understanding of why SEF have burned in recent years is important because it may help in forming a basis for a fire management policy in PAs. Third, information was sought on whether there has been a significant adverse effect to SEF as a result of fire. Understanding whether SEF has been adversely affected by the landscape fires of recent years is important because it informs on the necessity of management intervention, such as suppression, in PAs. Finally, information was sought on the frequency of conditions for fire in SEF as well as the ability to predict fire years with these conditions. Understanding how commonly the conditions for fire in SEF occur and the ability to predict SEF fire-probable years are important because they indicate whether the problem of fire in SEF might be managed by focusing the suppression effort on years that SEF is likely to burn.

To address these questions, Huai Kha Khaeng Wildlife Sanctuary was selected as the study area. This Sanctuary contains an extensive forest mosaic and has experienced landscape-scale fires intermittently over a number of years, three in the 1990s alone. The hope was that research on SEF would contribute to the development of a fire management approach that permits some fires but limits the risk of landscape-scale burns.

The first research objective was to determine the area of SEF burned in HKK between 1988 and 2002. This objective was achieved by first, building a fire history for the Sanctuary using satellite data, and then by querying each year for the SEF area burned. The results showed that significant areas of SEF had burned in the 14-year interval, and that some areas of SEF had burned more than once in the time period. Both intact SEF as well as the degraded edge areas of SEF were affected. Most burning of SEF occurred during major fire years. The research also found that Landsat TM, the satellite sensor most commonly used to detect fire in forests in mainland Southeast Asia, did not detect fire under the canopy in intact SEF.

The findings were important since until now it was believed that intact SEF did not burn, or at least rarely burned. Now it is established that significant areas of SEF in PAs have burned. However this stage of the research was limited in that it is not actually known how much SEF has burned in PA, a serious concern because SEF is an essential ecosystem component of the forest mosaic.

The second objective was to determine conditions for fire in SEF, specifically to identify ignition sources and to assess fuel conditions for fire spread. This was accomplished by first: performing a precursory reconnaissance during the fire season and by conducting interviews with Royal Forest Department (RFD) officials on when and how fires in SEF started; and second, by lighting test fires and measuring fuel load, fuel moisture content, litter continuity, and depth. Results of this preliminary research showed that the source of fire in SEF was primarily fires that were started by people in open deciduous forest and savanna during the first part of February which continued to burn through similar successional vegetation until adjacent to SEF. If fires are burning in and around SEF in March in years that the leaf litter moisture content is below 15%, the study indicates that fires will burn into SEF stands as well. It seems that SEF is more flammable towards the end of the dry season, in March and April. This phenomenon may be because of increased litter load by that time of year, but also by the potentially increased flammability of litter after a period of decomposition.

These research findings are important because it was previously thought that moisture content was believed to be the only major factor limiting fire in SEF. Another factor that also contributes to the definition of a specific ignition and spread seasonal window in SEF is the litter flammability. There were two limitations to the study results. First, the research findings on the litter flammability by season were not statistically proven because there were an insufficient number of test fires obtained during the field season year that ignited. Second, there were not enough test fire data to determine why leaf litter seemed to be more flammable later in the dry season (i.e., March and April). One explanation is increased flammability may be related to the degree of decomposition and the increased or decreased proportion of tannins and other phenolics.

The third study objective was to determine whether the area of SEF in HKK declined as a result of fire from 1989 to 2000. This was done first by classifying the spectral classes in two Landsat TM images, one from 1989 and one from 2000; and second by identifying the magnitude and direction of spectral class change for the SEF classes of interest; and finally by comparing the SEF change area to the SEF fire history. The results showed fire had a negative effect on the extent of SEF from 1989-2000. Between these two years, fifteen percent of the SEF in HKK was converted to deciduous forest types, or a more open SEF. The greatest amount of change occurred in the vicinity of the Sanctuary's permanent plot, an area of intact SEF known by local researchers to have burned twice during the 1990s.

These findings on the extent of the impact of fire on SEF are important because they suggest that landscape-scale fires have had a significant negative effect on the area of SEF in HKK. However, the study had limitations because only a ten-year period was examined, and therefore, it remains unknown whether the conversion in forest type is permanent. This study's research results, along with others from the tropics indicate that fire has had a net negative effect on SEF, but that longer-term study is needed to determine if the effect will be permanent.

The fourth study objective was to determine the number of years between 1984 and 2001 for which fires were likely to be burning adjacent to SEF in March and the litter moisture content at that time was less than 15%. This was done by: first, building a fifteen-day moving average of daily minimum relative humidity values for SEF ($Rh_{min,SEF}$) for the fire season each year; second, establishing the threshold $Rh_{min,SEF}$ values necessary for open deciduous forest and savanna fuels (grass) and SEF litter fuels to ignite and spread; and finally, identifying the fire season years where $Rh_{min,SEF}$ values were maintained below the threshold for fire spread in savanna for the last two weeks of February and below the threshold for fire spread in SEF for the first two weeks of March. The results showed that the conditions for ignition and spread of fire in SEF occurred four times in a seventeen-year period (1984 to 2001).

These research results are important because they help determine if it is practical to restrict open deciduous forest and savanna burning to occasional years when the fires will not spread into SEF. Since SEF is at risk of burning on average once in four years, it may be possible to consider increasing fire suppression resources and effectiveness only during specific fire-prone years. Knowing this fire frequency and the ability to predict severe fire seasons allows for a more flexible fire management organization. For example, if fire in SEF is only a concern in certain years, then early fire season open forest and savanna burning could be carried out in wetter years so that there is not a significant threat for fire entering the SEF. However, a limitation of the study result is that relative humidity was used as an indirect measure of fuel moisture content to determine fire frequency. The relationship between relative humidity and fuel moisture content was not established for mainland Southeast Asia directly, but had to be taken from published papers from other tropical forests like Brazil.

The fifth objective was to determine whether a significant relationship existed between the pre-fire season drought codes and years with the conditions for fire spread in SEF. A logistic regression of the January 31st (pre-fire season) Keetch-Byram Drought Code (KBDI) value and the January 31st Canadian Drought Code (DC) value, with the average of the mid February to mid March $Rh_{min,SEF}$ value, showed a significant relationship existed between both KBDI and DC and the years with the conditions for fire spread in SEF. The research results have limitations because the relationship between the January 31st drought code value and SEF fire spread years was only established for HKK and not the entire mainland Southeast Asia region.

The primary implication from the research results in SEF is that sufficient fire spread information exists to begin to manage the landscape-scale fire problem in HKK. There are six fire management implications that pertain to HKK. First, that SEF in HKK burned in major fire years and therefore concern is warranted. Second, that there is really only a narrow seasonal window of opportunity in which fire can enter SEF so fire management activities to protect SEF should focus on prevention and direct suppression of fire during this window (mid-February to mid-March). Third, if SEF is to be conserved in HKK, then the current frequency of burning must be significantly reduced. Fourth, conditions for fire in SEF can be expected once in every four years. Fifth, the years in which SEF is likely to burn can be predicted. Finally, historical burning of open deciduous forest and grasslands can be permitted in HKK, except in years when SEF is susceptible to burning from fires entering from adjacent open deciduous forest and savanna.

The recommendations for further research are as follows:

- Additional research is needed to investigate the capability of various satellite and aerial sensor systems to detect burn areas in SEF. Sensor systems should be evaluated using ground-truthed SEF burn area information. As part of this sensor evaluation, an extensive area (e.g. 10s of km^2) should be mapped on foot using a GPS. Mapping should occur after the fires have stopped burning (March or April) and before rainy season green-up (May).
- Additional research is needed on SEF litter flammability in mainland Southeast Asia. First, further test fire research is needed to determine the statistical importance of factors for the ignition and spread of fire in SEF. In order to use a logistic regression approach to determine whether an independent variable is important for ignition and spread of fires in SEF, there should be at least 10 test burns conducted that result in ignition and spread (Zhou, pers. com., 2005). This requirement necessitates the research be conducted in a year with the conditions for fire in SEF.[125] Second, controlled laboratory experiments are needed to

[125] The collection of several litter moisture content samples at each test fire site is recommended.

determine more specific information on SEF leaf litter chemistry and the effect of decomposition with respect to litter flammability such as the change in the proportions of cellulose, flammable tannins, phenols, and other volatiles.

- Additional change detection research of the evergreen and deciduous forest types is needed in HKK. Two studies are envisioned: the first, a circa 1970 to 2000 change detection analysis, using a Landsat MSS classification and Landsat TM classification, respectively; the second, a circa 1950 to 2000 change detection study using historic and recent aerial photos.[126] The primary objective of the change detection research would be to determine the proportion of the three major vegetation classes (i.e., SEF, closed deciduous forest, and open deciduous forest and savanna) which were historically present compared with the current landscape. Although some villages were present in HKK Sanctuary over the fifty-year period, there were no major landscape-scale disturbances (e.g., logging, wind throw) other than fire.[127] If the proportion of deciduous to evergreen forest has changed significantly, this might provide data to determine the long-term fire effects on SEF.
- Additional research is needed to determine the relationship between relative humidity and litter moisture content in SEF in mainland Southeast Asia. A multi-year experiment is required where leaf litter moisture content is monitored every day during the dry season. The recommended independent variable to predict leaf

---

[126] Both aerial photos and satellite sensor images are available for HKK.
[127] There was a small logging concession in the vicinity of the permanent plot in the mid-80s (Baker, 2001).

litter moisture content in SEF in mainland Southeast Asia should be $Rh_{min,SEF}$ Also, there is a need to establish a long-term program measuring the moisture content of the litter. While the standard approach for predicting moisture content in North America is using small diameter wooden sticks with a known oven weight (e.g. 100g), this approach may not be suitable to predict the moisture contents where the primary SEF fuel is leaf litter not sticks.

- Additional weather data analysis is needed to determine the relationship between the pre-fire season drought codes and sustained $Rh_{min,SEF}$ in protected areas (PAs) in other countries in Southeast Asia. One difficulty is locating weather stations in SEF with continuous records dating back 10 to 20 years. If this is the case, a short period of record may be available for several parts of the region, providing some capability to determine the relationships between drought codes and $Rh_{min,SEF}$ across the region.
- Improving the fire management program for HKK by implementing the following changes:
    - A need to better prioritize fires occurring in the SEF. Presently, the priority for fire suppression is in deciduous forest and savanna because of the belief of some local researchers that SEF is not being impacted by fire. There is also a need to change the emphasis of the fire prevention education program from encouraging local residents not to burn open forests and savanna, to allowing burning in December and January. The conditions for fire in open deciduous forests and savanna are commonly

present in December and January in HKK. Fires started by local residents in January are unlikely to continue burning through until mid-March when SEF may be flammable. Fire prevention staff need to stress the importance of not setting fires in or around HKK Sanctuary in February or March.

- Generate KBDI on a continuous and ongoing basis for KNR and Kapokapeang weather stations in HKK.[128] At present, the RFD Forest Fire Control Division monitors relative humidity and precipitation at the fire station in the lowlands adjacent to the HKK Sanctuary. However, daily dry season weather data including, temperature, relative humidity and precipitation are needed from weather stations in or near SEF. The fire fighting station should obtain the required weather data to calculate KBDI from KNR and Kapokapeang weather stations via daily 8AM radio communications. Additional budget allocations from the fire resource fund should be either allotted to Sanctuary management to maintain the existing weather stations or to set up additional fire weather stations in or near SEF.
- The current fire management staff and resources in the HKK Sanctuary are probably adequate but possible reallocation is needed. In years when the January 31st KBDI is above 1800, helicopter availability needs to be

[128] DC could be used as well, but KBDI uses a deeper soil reservoir, and seems to have a more significant relationship for predicting sustained low $Rh_{min,SEF}$ years.

maintained from February 1st until April or until the threat of fire in SEF has passed. During high fire risk conditions for SEF, additional fire suppression resources need to be put on standby. Additional effort is needed so that the community fire awareness prevention campaign is effective in reducing fires during years when SEF can burn. One consideration might be imposing significant fines for those who start fires in or near the Sanctuary in February and March. In years when the KBDI is below 1800 on January 31st, helicopters and ground-based fire suppression resources could be used to conduct prescribed burns to reduce fire hazard in open deciduous and savanna from November to January. The focus of the prescribed burn program would be to maintain the naturally high frequency of fire occurrence in the open deciduous forests, and savanna in HKK Sanctuary as was done historically by local peoples.

The research results contribute to two fields of study associated with Geography: Conservation and Protected Areas Management, and Fire Science and Management. From a Conservation and Protected Areas Management perspective, the research contributes in three ways. First, the research reveals that the satellite remote sensing technology commonly used for fire detection in the tropics is not capable of detecting fire in SEF; and that this important forest type has burned far more extensively in recent years than was currently thought. Second, the research presents a fire management approach for HKK that is appropriate in terms of the historic burning levels for vegetation types that require high fire frequency, open deciduous forests and savanna, while discouraging recurring landscape-scale fires that have been affecting low fire frequency vegetation such as closed deciduous forest and SEF. Third, in developing the contextual thinking the research offers a model for fire management with potential applicability for PAs throughout the larger mainland Southeast Asia region.

The research also contributes to the field of Fire Science and Fire Management in three ways. First, the research generated preliminary field data on fire environment in SEF, which until now were not available for mainland Southeast Asia. Second, the research extended the current thinking on tropical evergreen forest fire ecology and management of both the Amazon and Indo-Malayan regions to the more seasonally dry climate of the mainland Southeast Asia region. Finally, the research results contributed to the development of a fire management strategy that may serve to partially address the larger problem of effective fire management activities and programs at a national and even regional scale.

REFERENCES

Abdulhadi, R., Adhikerana, A. S., Ubaidillah, R., & Suharna, N. (2000). Preliminary study of the ecological impact of forest fires in G. Massigit, G. Gede-Pangrango National Park, West Java. *Korean Journal of Ecology, 23*(2), 125-129.

Agee, J. K. (1993). *Fire ecology of Pacific Northwest forests*. Washington, DC: Island Press.

Akaakara, S. (2001). Chief of Forest Fire Control Division, Royal Forest Department. Bangkok, Thailand.

Akaakara, S. (2002). *Thailand: Special Report*. Retrieved October 20, 2005, from http://www.fire.uni-freiburg.de/iffn/country/th/th_2.htm

Alencar, A., Solorzano, L., & Nepstad, D. C. (2004). Modeling forest understory fires in an eastern Amazonian landscape. *Ecological Applications*, *14*, S139-S149.

Anholt, B. (2001). Professor, Population and community ecology, Biology Department, University of Victoria. Victoria, BC, Canada.

Arbhabhirama, A. (1988). *Thailand Development Research Institute*. New York: Thailand Development Research Institute.

Ashton, P. S. (1989). Thailand: Biodiversity center for the tropics of Indo-Burma. In S. Wongsiri & S. Lorlohakarn (Eds.), *Biodiversity in Thailand* (pp. 51-58): Prachanchon Ltd. Co.

Baker, P. J. (2001). *Age structure and stand dynamics of a seasonal tropical forest in western Thailand.* Unpublished Dissertation, University of Washington, Seattle.

Baker, P. J. (2002). Ph.D. candidate, Faculty of Forestry, University of Washington. Seattle, USA.

Baker, P. J., & Bunyavejchewin, S. (In prep). *Fire and the landscape mosaic in the monsoon forests of Western Thailand.* Washington, Seattle.

Baker, P. J., Bunyavejchewin, S., Oliver, C. D., & Ashton, P. S. (2005). Disturbance history and historical stand dynamics of a seasonal tropical forest in western Thailand. *Ecological Monographs, 75*(3), 317-343.

Bangkok Post. (1998a, March 11). Forest fires rage at Sanctuary.

Bangkok Post. (1998b, March 19). Situation unstable at Sanctuary.

Bangkok Post. (1998c, March 19). Winds make forest fire hard to control.

Bangkok Post. (1998d, March 24). Forestry department admits defeat.

Bangkok Post. (1998e, March 27). Over 1m rai razed, say local groups.

Bangkok Post. (1998f, March 28). Obstacles to forest fire fighting cited.

Bangkok Post. (1998g, March 28). Much of the forest fire is now under control, officials claim.

Bangkok Post. (1998h, March 30). Month-long blazes doused.

Batchelder, R. B., & Hiri, H. F. (1966). *Fire in tropical forests and grasslands* (No. 67-41-ES): US Army Natick Lab.

Benton, R. A. (1990). *A comparative analysis of seven methods for the estimation of values for observations missing from temperature climate data series.* University of Victoria, Victoria, BC, Canada.

Biddulph, J., & Kellman, M. (1998). Fuels and fire at savanna-gallery forest boundaries in southeastern Venezuela. *Journal of Tropical Ecology, 14*, 445-461.

Blasco, F., Bellan, M. F., & Aizpuru, M. (1996). A vegetation map of tropical continental Asia at scale 1:5 million. *Journal of Vegetation Science, 7*, 623-634.

Briggs, J. C. (1996). Tropical diversity and conservation. *Conservation Biology, 10*(3), 713-718.

Bunyavejchewin, S. (1999). Structure and dynamics in seasonal dry evergreen forest in northeastern Thailand. *Journal of Vegetation Science, 10*, 787-792.

Bunyavejchewin, S. (2002). Senior ecologist, Silviculture Division, Royal Forest Department. Bangkok, Thailand.

Bunyavejchewin, S., & Baker, P. J. (1995). *Forest fire and the Huai Kha Khaeng Wildlife Sanctuary*. Retrieved September 15, 2002, from http://www.ctfs.si.edu/newletters/inside1995/bunya1995.htm

Bunyavejchewin, S., Baker, P. J., LaFrankie, J. V., & Ashton, P. S. (2001). Stand structure of a seasonal dry evergreen forest at Huai Kha Khaeng Wildlife Sanctuary, western Thailand. *Natural Historic Bulletin of the Siam Society, 49*, 89-106.

Bunyavejchewin, S., Baker, P. J., LaFrankie, J. V., & Ashton, P. S. (2002). *Stand structure of a seasonal dry evergreen forest at Huai Kha Khaeng Wildlife Sanctuary, western Thailand*. Retrieved November 3, 2005, from http://www.forest.go.th/silvic/WP_Publications/Paper_SVGPub_PDF/SilvicReport45/t1r45.pdf

Bunyavejchewin, S., Baker, P. J., LaFrankie, J. V., & Ashton, P. S. (2003). Floristic composition of a seasonal evergreen forest, Huai Kha Khaeng Wildlife Sanctuary, western Thailand. *Natural Historic Bulletin of the Siam Society, 50*, 125-134.

Bunyavejchewin, S., Baker, P. J., LaFrankie, J. V., & Ashton, P. S. (2004a). Huai Kha Khaeng Forest dynamics plot, Thiland. In E. C. Losos & E. G. J. Leigh (Eds.), *Tropical forest diversity and dynamism: Findings from a largescale plot network* (pp. 484-492). Chicago: University of Chicago Press.

Bunyavejchewin, S., Baker, P. J., LaFrankie, J. V., & Ashton, P. S. (2004b). Structure, history, and rarity in a seasonal evergreen forest in western Thailand. In E. C. Losos & E. G. J. Leigh (Eds.), *Tropical forest diversity and dynamism: Findings from a large-scale plot network* (pp. 145-158). Chicago: University of Chicago Press.

Bunyavejchewin, S., Baker, P. J., LaFrankie, J. V., & Ashton, P. S. (In Press). Structure, history, and rarity in a seasonal dry evergreen forest in western Thailand. *Journal of Tropical Ecology*.

Canadell, J., Ehleringer, J. R., Mooney, H. A., Sala, O. E., & Schulze, E. D. (1996). Maximum rooting depth of vegetation types at the global scale. *Oecologia, 108*, 583-595.

Carmona-Moreno, C., Malingreau, J. P., Antonovsky, M., Buchshtaber, V., & Pivovarov, V. (2003). *Hemispheric fire activity characterization from the analysis of global burned surfaces time series (1982-1993).* Paper presented at the Fourth international workshop on Remote Sensing and GIS Applications to Forest Fire

Management: Innovative concepts and methods in fire danger estimation, Ghent, Belgium.

Carvalho, J. A., Veras, C. A. G., Alvarado, E. C., Sandberg, D. V., Carvalho, E. R., Gielow, R., & Santos, J. C. (2003, Nov. 16-20). *Fire spread around a forest clearing site in the Brazilian Region.* Paper presented at the Proceedings of 5th Symposium on Fire and Forest Meteorology and 2nd International Wildland Fire Ecology and Fire Management Congress, Orlando, Florida.

Cochrane, M. A. (2001). Synergistic interactions between habitat fragmentation and fire in evergreen tropical forests. *Conservation Biology, 15*(6), 1515-1521.

Cochrane, M. A. (2003). Fire science for rainforests. *Nature, 421*, 913-919.

Cochrane, M. A., Alencar, A., Schulze, M. D., Souze, C. M. J., Nepstad, D. C., Lefebvre, P., & Davidson, E. A. (1999). Positive feedbacks in the fire dynamic of closed canopy tropical forests. *Science, 284*, 1832-1835.

Cochrane, M. A., & Laurance, W. F. (2002). Fire as a large-scale edge effect in Amazonian forests. *Journal of Tropical Ecology, 18*, 311-325.

Cochrane, M. A., & Schulze, M. D. (1999). Fire as a recurrent event in tropical forests of the Eastern Amazon: Effects on forest structure, biomass, and species composition. *Bioptropica, 31*(1), 2-16.

Collins, N. M., Sayer, J. A., & Whitmore, T. C. (1991). *The conservation atlas of tropical forests: Asia and the Pacific*. London: Macmillan Press Ltd.

Coppin, P., Jonckheere, I., Nackaerts, K., Muys, B., & Lambin, E. (2004). Review article digital change detection methods in ecosystem monitoring: A review. *International Journal of Remote Sensing, 25*(9), 1565-1596.

Davis, S. D. (1995). Identifying sites of global importance for conservation: The IUCN/WWF centres of plant diversity project. In R. B. Primack & T. E. Lovejoy (Eds.), *Ecology, conservation and management of Southeast Asian rainforests* (pp. 176-203). New Haven, Connecticut, USA: Yale University Press.

Dearden, P. (1996a). Biodiversity in the highlands of northern Thailand: Some research approaches. In J. A. McNeely & S. Samchevita (Eds.), *Biodiversity in Asia: Challenges and opportunities for the scientific community* (Vol. 22 &23, pp. 106-112). Bangkok: Office of Environmental Policy and Planning, Ministry of Science, Technology and Environment.

Dearden, P. (1996b). Development, the environment and social differentiation in northern Thailand. In J. Rigg (Ed.), *Counting the Costs: Environmental Growth and Economic Change* (pp. 111-130): ISEAS.

Dinerstein, E., Wikramanayake, E. D., & Forney, M. (1995). Conserving the reservoirs and remnants of the tropical moist forest in the Indo-Pacific Region. In R. B. Primack & T. E. Lovejoy (Eds.), *Ecology, conservation and management of Southeast Asian rainforests* (pp. 140-175). New Haven, Connecticut, USA: Yale University Press.

Elliott, S., Maxwell, J. H., & Beaver, O. P. (1989). A transect survey of monsoon forest in Doi Suthep-Pui National Park. *Natural History Bulletin of the Siam Society, 37*, 137-171.

FDRS. (2004). *Southeast Asia fire danger rating system project*. Retrieved May 21, 2004, from http://nofc.cfs.nrcan.gc.ca/seasia/en/index_e.html

Fearnside, P. M. (1990). Fire in the tropical rain forests of the Amazon basin. In J. G. Goldammer (Ed.), *Fire in the Tropical Biota* (Vol. Ecological Studies 84, pp. 106-115). New York: Springer-Verlag.

Fehr, C. (1998). *Pattern and ecology of regeneration in disturbed deciduous forests in central Southeast Asia - silvicultural implications.* Unpublished Dissertation, Florence University, Italy.

FFCD. (2005). *Historical Development: The development of forest fire control*. Retrieved December 17, 2005, from http://www.dnp.go.th/forestfire/Eng/historical3.htm

Field, R. (2003). Research Officer. Edmonton: Fire Research Group, Canadian Forest Service.

Fogden, S. C. L., & Proctor, J. (1985). Notes on the Feeding of Land Leeches (Haemadipsa zeylanica Moore and H. picta Moore) in Gunung Mulu National Park, Sarawak. *Biotropica*, *17*(2), 172-174.

Frazer, G. W., Canham, C. D., & Lertzman, K. P. (2000). Gap light analyzer (GPA), Version 2.0. *Bulletin of the Ecological Society of America, 81*(3), 191-197.

Frazer, G. W., Trofymow, J. A., & Lertzman, K. P. (1997). *A method for estimating canopy openness, effective leaf area index, and photosynthetically active photon flux density using hemispherical photography and computerized image analysis techniques* (No. BC-X-373). Victoria: Pacific Forestry Centre.

Fujioka, F. M. (1991). *Starting up the Keetch-Byram Drought Index.* Paper presented at the 11th Conference in fire and forest meteorology, Missoula, Montana.

Gerwing, J. J. (2002). Degradation of forests through logging and fire in the eastern Brazilian Amazon. *Forest Ecology and Management, 157*, 131-141.

Giri, C., & Shrestha, S. (2000). Forest fire mapping in Huai Kha Khaeng Wildlife Sanctuary, Thailand. *International Journal of Remote Sensing, 21*(10), 2023-2030.

GOFC. (2005, 2003). *GOFC/GOLD Fire Monitoring and Mapping Implementation Team*, 2005, from http://gofc-fire.umd.edu/index.asp

Goldammer, J. G. (1993). Historical biogeography of fire: Tropical and subtropical. In P. J. Crutzen & J. G. Goldammer (Eds.), *Fire in the Environment: The ecological, atmospheric, and climatic importance of vegetation fires* (pp. 297-314): John Wiley & Sons.

Goldammer, J. G. (1997a). Overview of fire and smoke management issues and options in tropical vegetation. In H. A. Hassan, D. Taha, M. P. Dahalan & A. Mahmud (Eds.), *Transboundary Pollution and the Sustainability of Tropical Forests: Towards wise forest fire management - The Proceedings of the AFM International Conference*. Kuala Lumpur: ASEAN Institute for Forest Management, Ampang Press.

Goldammer, J. G. (1997b). *The role of fire on greenhouse gases and aerosol emissions land use and cover change in Southeast Asia: Ecological background and research needs.* Paper presented at the the International Conference on Science and Technology for the Assessment of Global Environmental Change and Its Impacts on the Indonesian Maritime Continent, Jakarta, Indonesia.

Goldammer, J. G. (1999). Forests on fire. *Science, 284*, 1782-1783.

Goldammer, J. G., & Siebert, B. (1990). The impact of droughts and forest fires on tropical lowland rain forest of East Kalimantan. In J. G. Goldammer (Ed.), *Fire in the Tropical Biota, Ecological Processes and Global Challenges* (pp. 11–31). Berlin: Springer-Verlag.

Hawkes, B. (2002). Ph.D., Senior Researcher, Fire Science, Pacific Forestry Centre. Victoria, BC, Canada.

Hayes, D. J., & Sader, S. A. (2001). Comparison of change-detection techniques for monitoring tropical forest clearing and vegetation regrowth in a time series. *Photogrammetric Engineering & Remote Sensing, 67*(9), 1067-1075.

Hebda, R. (2006). Adjunct Professor, Environmental Studies, University of Victoria. BC, Canada.

Hoffmann, A. A. (2002). Ph.D. student (Germany), and consulting scientist for the Integrated Forest Fire Management Project (IFFM). Indonesia.

Holdsworth, A. R., & Uhl, C. (1997). Fire in Amazonian selectively logged rain forest and the potential for fire reduction. *Ecological Applications, 7*(2), 713-725.

Iisaka, J. (2004). Ph.D., Adjunct Professor, Geography Department, University of Victoria. Victoria, BC, Canada.

Jipp, P. H., Nepstad, D. C., Cassel, D. K., & DeCarvalho, C. R. (1998). Deep soil moisture storage and transpiration in forests and pastures of seasonally-dry Amazonia. *Climatic Change, 39*, 395-412.

Johnson, L. A. (1998). *The common ground: Restoring degraded forest lands in Thailand's northern watershed.* Unpublished Masters, University of Calgary, Alberta, Canada.

Johnson, L. A., Johnson, E. G., Iisaka, J., & Easson, G. (2005, May, 16-18 2005). *Use of landsat tm to detect change in tropical forest types after fire, Huai Kha Khaeng Wildlife Sanctuary, Thailand.* Paper presented at the Third International Workshop on the Analysis of Multitemporal Remote Sensing Images, MultiTemp 2005, Biloxi, Mississippi.

Jones, S. H. (1997). *Vegetation fire in mainland Southeast Asia: Spatio-temporal analysis of AVHRR 1 km data for the 1992/93 dry season*. Luxembourg: Joint Research Centre, European Commission.

Jones, S. H. (1998). Vegetation fire and land use in southeast Asia: The interpretation of remotely sensed data for Cambodia. *Geocarto International, 13*(3, September), 63-73.

Jordan, C. F. (1985). *Nutrient Cycling in Tropical Forest Ecosystems*. New York: J.Wiley.

Jordan, C. F. (1991). Nutrient Cycling Processes and Tropical Forest Management. In A. Gomez-Pompa, T. Witmore & M. Hadley (Eds.), *Rain Forest Regeneration and Management* (Vol. 6, pp. 159-180). New Jersey: The Parthenon Publishing Group Inc.

Justice, C. O., Smith, R., Gill, A. M., & Csiszar, I. (2003). A review of current space-based fire monitoring in Australia and the GOFC/GOLD program for international coordination. *International Journal of Wildland Fire, 12*, 247-258.

Kanjanavanit, S. (1992). *Aspects of the temporal pattern of dry season fires in the dry dipterocarp forests of Thailand.* Unpublished Ph.D., University of London, London, England.

Kanzaki, M., Kagotani, Y., Kawasaki, T., Yoda, K., Sahunalu, P., Dhanmanonda, P., Prachaiyo, B., & Thoranisorn, S. (1985). Forest structure and composition of tropical seasonal forests of Sakaerat environmental research station and the effects of fire protection on a dry deciduous forest. In K. Yoda, P. Sahunalu & M. Kanzaki (Eds.), *Elucidation of the Missing Sink in the Global Carbon Cycling: Focusing on the dynamics of tropical seasonal forest* (pp. 1-20). Osaka: Department of Biology, Faculty of Science, Osaka City University.

Kauffman, J. B., & Uhl, C. (1990). Interactions of anthropogenic activities, fire, and rain forests in the Amazon basin. In J. G. Goldammer (Ed.), *Fire in the Tropical Biota: Ecosystem processes and global challenges* (pp. 117-133). New York: Springer-Verlag.

Kealhofer, L. (2002). Changing perceptions of risk: The development of Agro-ecosystems in Southeast Asia. *American Anthropologist, 104*(1), 178-194.

Kinnaird, M. F., & O'Brien, T. G. (1998). Ecological effects of wildfire on lowland rainforest in Sumatra. *Conservation Biology, 12*(5), 954-956.

Kohler, N. P. (2005). *Protected areas and landscape change in mainland Southeast Asia (Cambodia, Laos, Thailand, Vietnam).* Unpublished PhD Dissertation, University of Oregon, Eugene.

Köppen, W. (1931). *Klimakarte der Erde* (2nd ed.). Berlin and Leipzig: Grundriss der Klimakunde.

KUFF. (2000). *Reviewing fire management policy in the conservation of the Thung Yai and Huay Kha Kheng wildlife sanctuaries and world heritage areas of Thailand*. Bangkok: Kasetsart University.

Kunstadter, P., Chapman, E. C., & Sabhasri, S. (Eds.). (1978). *Farmers in the Forest: Economic development and marginal agriculture in northern Thailand*. Honolulu: East-West Center Press.

Lamotte, S., Gajaseni, J., & Malaisse, F. (1998). Structure diversity in three forest types of north-eastern Thailand (Sakaerat Reserve, Pak Tong Chai). *BASE Biotechnologie Agronomie Societe et Environnement, 2*(3), 192-202.

Laurance, W. F. (2003). Slow burn: The insidious effects of surface fires on tropical forests. *Trends in Ecology & Evolution, 18*(5), 209-212.

Laurance, W. F., Lovejoy, T. E., Vasconcelos, H. L., Bruna, E. M., Didham, R. K., Stouffer, P. C., Gascon, C., Bierregaard, R. O., Laurance, S. G., & Sampaio, E. (2001). Ecosystem decay of Amazonian forest fragments: a 22-year investigation. *Conservation Biology, 16*(3), 605-618.

Lekagul, B. (1988). *Mammals of Thailand*. Bangkok, Thailand: Association for the Conservation of Wildlife.

Liang, S., Fang, H., Morisette, J. T., Chen, M., Shuey, C. J., Walthall, C. L., & Daughtry, C. S. T. (2002). Atmospheric correction of Landsat ETM+ land surface imagery: II. Validation and Applications. *IEEE Transactions on Geoscience and Remote Sensing, 40*, 2736–2746.

Lillesand, T., & Kiefer, R. (1994). *Remote Sensing and Image Interpretation*. New York: John Wiley & Sons Inc.

Loranger, G., Ponge, J.-F., Imbert, D., & Lavelle, P. (2002). Leaf decomposition in two semi-evergreen tropical forests: Influence of litter quality. *Biology and Fertility of Soils, 35*, 247-252.

Lucas, R. M., Honzak, M., Foody, G. M., Curran, P. J., & Corves, C. (1993). Characterizing tropical secondary forests using multi-temporal Landsat sensor imagery. *International Journal of Remote Sensing, 14*(16), 3061-3067.

Lung, T., & Schaab, G. (2004). *Change-detection in Western Kenya – The documentation of fragmentation and disturbance for Kakamega Forest and associated forest areas by means of remotely-sensed imagery*. Paper presented at the Proceedings of the ISPRS XXth Congress.

Marod, D., Kutintara, U., Yarwudhi, C., Tanaka, H., & Nakashisuka, T. (1999). Structural dynamics of a natural mixed deciduous forest in western Thailand. *Journal of Vegetation Science, 10*(6), 777-786.

Mather, A. D. (1978). *Fire weather data*. Chiang Mai, Thailand: FAO and Royal Forest Department.

Maxwell, A. L. (2004). Fire regimes in north-eastern Cambodian monsoonal forests, with a 9300-year sediment charcoal record. *Journal of Biogeography, 31*(2), 225-239.

Mekong Travel. (2005). *Climate chart*. Retrieved November 3, 2005, from http://www.mekong-travel.com/climate.htm

Merrill, D. F., & Alexander, M. E. (1987). *Glossary of forest fire management terms* (No. 26516). Ottawa, Canada: National Research Council of Canada.

Mueller-Dombois, D. (1981). *Fire in tropical ecosystems.* Paper presented at the Fire Regimes and Ecosystem Properties conference, Honolulu, Hawaii.

Mutch, R. (1970). Wildland fires and ecosystems: A hypothesis. *Ecology, 51*, 1046-51.

Myers, N., Mittermeier, R. A., Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature, 403*, 853-858.

Nakhasathien, S., & Stewart-Cox, B. (1990). *Nomination of the Thung Yai - Huai Kha Khaeng Wildlife Sanctuary to be a UNESCO World Heritage Site*. Bangkok, Thailand: Royal Forest Department.

Negreiros, G. H. d. (2004). *Understanding and Modeling Ecological Processes Controlling Flammability in Seasonally Dry Evergreen Forests of the Brazilian Amazon.* Unpublished Dissertation, University of Washington, Seattle.

Nepstad, D. (1996). *Predicting fire susceptibility in the forests of Amazonia*. Retrieved November 6, 2001, from http://teco.ornl.gov/teco/nepstad2

Nepstad, D., LeFebvre, P., Da Silva, U. L., Tomasella, J., Schlesinger, P., Solorzano, L., Moutinho, P., Ray, D., & Benito, J. G. (2004). Amazon drought and its implications for forest flammability and tree growth: A basin-wide analysis. *Global Change Biology, 10*, 704-717.

Nepstad, D., Verissimo, A., Lefebvre, P., Schlesinger, P., Potter, C., Nobre, C., Setzer, A., Krug, T., Barros, A. C., Alencar, A., & Pereira, J. R. (1998). Forest fire prediction and prevention in the Brazilian Amazon. *Conservation Biology, 12*(5), 951-953.

Nepstad, D. C., DeCarvalho, C. J. R., Davidson, E. A., Jipp, P. H., Lefebvre, P. A., Negreiros, G. H., da Silva, E. D., Stone, T. A., Trumbore, S. E., & Vieira, S. (1994). The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. *Nature, 372*, 666-669.

Nepstad, D. C., Jipp, P. H., Moutinho, P., Negreiros, G. H., & Vieira, S. (1995). Forest recovery following pasture abandonment in Amazonia: Canopy seasonality, fire resistance and ants. In D. Rapport (Ed.), *Evaluating and monitoring the health of large-scale ecosystems* (pp. 333-349). New York: Springer-Verlag.

Nepstad, D. C., Klink, C., Uhl, C., Vieira, I. C., Lefebvre, P. A., Pedlowski, M., Matricardi, E., Negreiros, G., Brown, I. F., Amaral, E., Homma, A., & Walker, R. (1997). Land-use in Amazonia and the Cerrado of Brazil. *Ciencia e Cultura, 49*, 73-86.

Nepstad, D. C., Moreira, A. G., & Alencar, A. A. (1999a). *Flames in the Rain forest: Origins, impacts and alternatives to Amazonian fires*. Brasilia, Brazil.

Nepstad, D. C., Verissimo, A., Alencar, A., Nobre, C., Lima, E., Lefebvre, P., Schlesinger, P., Potter, C., Moutinho, P., Mendoza, E., Cochrane, M., & Brooks, V. (1999b). Large-scale impoverishment of Amazonian forests by logging and fire. *Nature, 398*(April), 505-508.

Neuner, J. A. (2002). *Detection of surficial failures in high plasticity, compacted clay slopes using remote sensing along the Mississippi River levee.* Unpublished Masters, University of Mississippi, Oxford.

Nopparat, N. (2001). Chief of Khao Nang Rum Wildlife Research Station, Royal Forest Department. Huai Kha Khaeng Wildlife Sanctuary, Thailand.

Noss, R. F., & Cooperrider, A. Y. (1994). *Saving Nature's Legacy: Protecting and restoring biodiversity*. Washington, DC: Island Press.

Ofren, R. S. (1999). *Spatial assessment and hazard modeling of tropical forest fires.* Unpublished Ph.D., University of Auckland, Auckland, New Zealand.

Ogino, K. (1976). Human influences on the occurrence of deciduous forest vegetation in Thailand. *Memoirs of the College of Agriculture, Kyoto University, 108*(4), 55-74.

Ongsomwang, S. (2000). *Appendix 5: Forest and forest fire assessment in Thailand.* Paper presented at the SEA Regional GOFC Planning Meeting, Bogor, Indonesia.

Paiboon. (2005). Manager, Nakhon Sawan Weather Station, Meteorological Department, Thailand. Nakhon Sawan, Thailand.

Panmon, M. (2004). Forest fire specialist. Bangkok, Thailand: Royal Forest Department.

Parr, C. L., & Brockett, B. H. (1999). Patch-mosaic burning: A new paradigm for savanna fire management in protected areas? *Koedoe, 42*(2), 117-129.

Pattanavibool, A. (1999). *Wildlife response to habitat fragmentation and other human influences in tropical montane evergreen forests, northern Thailand.* Unpublished Ph.D. dissertation, University of Victoria, BC, Canada.

Pattanavibool, A., & Dearden, P. (2002). Fragmentation and montane evergreen forests in northern Thailand. *Biological Conservation, 107*, 155-164.

Peres, C. A. (1999). Ground fires as agents of mortality in a Central Amazonian forest. *Journal of Tropical Ecology, 15*(4), 535-541.

Pezzullo, J. C. (2005). *Logistic Regression*. Retrieved November, 2005, from http://statpages.org/logistic.html

Potter, L. (1993). The onslaught on the forests in South-East Asia. In H. Brookfield & Y. Byron (Eds.), *South-East Asia's Environmental Future: The search for sustainability* (pp. 103-108). New York: United Nations University Press.

Preston, C. (2005). Research scientist, Soil Chemistry, Pacific Forestry Centre. Victoria, BC, Canada.

Pyne, S. J. (1982). *Fire in America: A cultural history of wildland and rural fire*. Princeton, New Jersey: Princeton University Press.

Pyne, S. J. (2004). *Tending Fire: Coping with America's wildland fires*. Washington, DC: Island Press.

Pyne, S. J., Andrews, P. L., & Laven, R. D. (1996). *Introduction to Wildland Fire* (Second ed.). New York: John Wiley & Sons, Inc.

Rabinowitz, A. (1990). Fire, dry dipterocarp forest, and the carnivore community in Huai Kha Khaeng Wildlife Sanctuary, Thailand. *Natural History Bulletin of the Siam Society, 38*, 99-115.

Rabinowitz, A. (2002). *Chasing the dragon's tail: The struggle to save Thailand's wild cats*. Washington DC: Island Press.

Ray, D., Nepstad, D., & Moutinho, P. (2005). Micrometeorological and canopy controls of fire susceptibility in a forested Amazon landscape. *Ecological Applications, 15*(5), 1664-1678.

RFD. (1999). *(In Thai)*. Bangkok, Thailand: Remote sensing subdivision, Royal Forest Department.

RFD. (2000). *(In Thai)*. Bangkok, Thailand: Remote sensing subdivision, Royal Forest Department.

RFD. (2002, November 4, 2005). *Special report of forest fire*. Retrieved November 6, 2005, from http://www.fire.uni-freiburg.de/iffn/country/th/th_2.htm

Richards, P. W. (1952). *The tropical rain forest: An ecological study*. London: Cambridge University Press.

Ropelewski, C. F., & Halpert, M. S. (1986). Global and regional scale precipitation patterns associated with the El Nino/southern oscillation. *Monthly Weather Review, 115*, 1606-1626.

Rowell, A., & Moore, P. F. (2000). *Global review of forest fires*. Gland, Switzerland: WWF/IUCN.

Roy, D. P., Jin, Y., Justice, C. O., Giglio, L., & Lewis, P. (2003). *Multi-year southern Africa MODIS burned area product generation and validation*.

Ruangpanit, N. (1995). Tropical seasonal forests in monsoon Asia: With emphasis on continental southeast Asia. *Vegetatio, 121*, 31-40.

Rundel, P. W., & Boonpragob, K. (1995). Dry forest ecosystems of Thailand. In S. H. Bullock, H. A. Mooney & E. Medina (Eds.), *Seasonally Dry Tropical Forests* (pp. 93-123). Cambridge: Cambridge University Press.

Russell-Smith, J., Ryan, P. G., & Durieu, R. (1997). A Landsat MSS-derived fire history of Kakadu National Park, monsoonal northern Australia, 1980-94: Seasonal extent, frequency and patchiness. *Journal of Applied Ecology, 34*, 748-766.

Sader, S. A., & Winne, J. C. (1992). RGB-NDVI colour composites for visualizing forest change dynamics. *International Journal of Remote Sensing, 13*(16), 3055-3067.

Santisuk, T. (1988). *An account of the vegetation of northern Thailand* (Vol. 5). Germany: Franz Steiner Verlag.

Satidporn. (2005). Manager, Kanchanaburi Weather Station, Meteorological Department. Kanchanaburi, Thailand.

Scheid, S., Barmettler, K., Christel, I., Kretzschmar, R., Nowack, B., & Schulin, R. (2003, June 15-19). *Influence of the leaf litter decomposition on the transport of heavy metals into soils.* Paper presented at the Proceedings of the 7th International Conference on the Biogeochemistry of Trace Elements (ICOBTE), Uppsala, Sweden.

Siegert, F., Ruecker, G., Hinrichs, A., & Hoffmann, A. A. (2001). Increased damage from fires in logged forests during droughts caused by El Nino. *Nature, 414*, 437-440.

Slik, J. W. F., Verburg, R. W., & Kebler, P. J. A. (2002). Effects of fire and selective logging on the tree species composition of lowland dipterocarp forest in East Kalimantan, Indonesia. *Biodiversity and Conservation, 11*, 85-98.

Smitinand, T. (1989). *Flora of the Thung Yai and Huai Kha Khaeng Wildlife Sanctuaries*. Bangkok, Thailand: Royal Forest Department, Forest Herbarium.

Smitinand, T. (1992). Thailand. In D. G. Campbell & H. D. Hammond (Eds.), *Floristic Inventory of Tropical Countries: The status of plant systematics, collections, and vegetation, plus recommendations for the future* (pp. 63-82). New York: New York Botanical Garden.

Sodhi, N. S., Koh, L. P., Brook, B. W., & Ng, P. K. L. (2004). Southeast Asian Biodiversity: An impending disaster. *Trends in Ecology & Evolution, 19*(12), 654-660.

Song, C., Woodcock, C. E., Seto, K. C., Lenney, M. P., & Macomber, S. A. (2001). Classification and change detection using Landsat TM data: When and how to correct atmospheric effects? *Remote Sensing of Environment, 75*, 230-244.

Stibig, H. J., & Beuchle, R. (2003). *Forest cover map of continental southeast Asia at 1:4 000 000* (No. EUR 20856 EN). Luxembourg: European Commission.

Stoms, D. M., & Hargrove, W. W. (2000). Potential NDVI as a baseline for monitoring ecosystem functioning. *International Journal of Remote Sensing, 21*(2), 401-407.

Stott, P. (1986). The spatial pattern of dry season fires in the savanna forests of Thailand. *Journal of Biogeography, 13*, 345-358.

Stott, P. (1988). The forest as Phoenix: Towards a biogeography of fire in mainland South East Asia. *Geographical Journal, 154*(3), 337-350.

Stott, P. (1990). Stability and stress in the savanna forests of mainland south-east Asia. *Journal of Biogeography, 17*, 373-383.

Stott, P. (2000). Combustion in tropical biomass fires: A critical review. *Progress in Physical Geography, 24*(3), 355-377.

Stott, P. A., Goldammer, J. G., & Werner, W. L. (1990). The role of fire in tropical lowland deciduous forest in Asia. In J. G. Goldammer (Ed.), *Fire in the Tropical Biota: Ecosystem processes and global challenges. Ecological Studies 84.* (pp. 21-44). Berlin-Heidelberg, Germany: Springer-Verlag.

Sukmasuang, R. (2004). Chief, Khao Nang Rum Wildlife Research Station, Huai Kha Khaeng. Thailand.

Swaine, M. D. (1992). Characteristics of dry forest in West Africa and the influence of fire. *Journal of Vegetation Science, 3*, 365-374.

Tangtham, N. (2001). Professor of Watershed Management, Department of Conservation, Faculty of Forestry, Kasetsart University. Bangkok, Thailand.

Tanpipat, V. (2002). Ph.D Candidate, Remote Sensing, Asian Institute of Technology. Bangkok, Thailand.

Tatian, P. A. (2000). *Indispensable Information: Data collection and information management for healthier communities*. Retrieved December 18, 2005, from http://www.communityhlth.org/communityhlth/files/files_resource/DataCollection&Mngt-Mod7.pdf

TDRI. (1986). *Thailand Natural Resource Profile*. Bangkok: Thailand Development Research Institute.

Tennigkeit, T. (2000). *Transformation of degraded forest into semi-natural production forests in northern Thailand.* Unpublished Ph.D., University of Freiburg, Germany.

Thawatchai, S. (1988). *An Account of the Vegetation of Northern Thailand* (Vol. 5). Germany: Franz Steiner Verlag.

Thompson, O. E., & Landsberg, H. E. (1975). Climatological conditions in the Sakaerat forest, Thailand. *Geografiska Annaler, 57*, 247-260.

Trisirisatayawong, I., & Samchimchom, W. (2002). *Large area change detection by differencing radiometrically-normallized images*. Retrieved June, 2002, from http://www.gisdevelopment.net/aars/acrs/2002/adp/adp004pf.htm

Tuller, S. (2005). Professor of Climatology, Department of Geography, University of Victoria. BC, Canada.

Tungittiplakorn, W., & Dearden, P. (2002a). Biodiversity conservation and cash crop development in northern Thailand. *Biodiversity and Conservation, 11*, 2007-2025.

Tungittiplakorn, W., & Dearden, P. (2002b). Hunting and wildlife use in some Hmong communities in northern Thailand. *Natural History Bulletin of the Siam Society, 50*, 57-73.

Turner, J. A., & Lawson, B. D. (1978). *Weather in the Canadian Forest Fire Danger Rating System: A user guide to national standards and practices* (No. BC-X177). Victoria, BC, Canada: Canadian Forest Service, Pacific Forestry Centre.

Uhl, C., & Kauffman, J. B. (1990). Deforestation, fire susceptibility, and potential tree responses to fire in the eastern Amazon. *Ecology, 71*(2), 437-449.

Uhl, C., Kauffman, J. B., & Cummings, D. L. (1988). Fire in the Venezuelan Amazon 2: Environmental conditions necessary for forest fires in the evergreen rainforest of Venezuela. *Oikos, 53*(2), 176-184.

UNEP. (unpub). *Cambodia*. Retrieved October 20, 2005, from http://www.rrcap.unep.org/lc/cd/html/countryrep/cambodia/report.pdf

UNESCO. (2003). Thailand National Periodic Report Section II: State of conservation of specific world heritage property. Bangkok, Thailand: Royal Forest Department.

Van Nieuwstadt, M. G. L., Shiel, D., & Kartawinata, K. (2001). The ecological consequence of logging in the burned forests of East Kalimantan, Indonesia. *Conservation Biology, 15*, 1183-1186.

Veblen, T. (2004). *Quantifying fire regimes based on tree-ring methods*. Retrieved November 18, 2005, from http://www.colorado.edu/geography/courses/geog_4371_f04/handouts/19FireMethods.html

Vibulsresth, S., Ratanasermpong, S., & Suwanweerakamtorn, R. (1994). *Forest fires monitoring and assessment by using TM images.* Paper presented at the Proceedings of the 15th Asian Conference on Remote Sensing, Bangalore, India.

WEFCOM. (1998). *WEFCOM Final Draft Report*. Bangkok, Thailand: Western Ecological Forest Complex.

Weidemann, D. (2002). *Development and extension of a fire danger rating system for the province of East Kalimantan, Indonesia*. Samarinda, East Kalimantan: GTZ - German development agency.

Weidemann, D., Buchholz, G., & Hoffmann, A. A. (2002). *A Fire Danger Rating for East Kalimantan, Indonesia*.

Werth, J. (2005). *Keetch-Byram Drought Index*. Retrieved October, 2005, from http://www.wrh.noaa.gov/sew/fire/olm/KEETCH.htm

Weyerhaeuser, H. (1998). *Perspectives of Semi-natural Silviculture of Deciduous Forests in Thailand.* Unpublished Ph D. Dissertation, Freiburg University, Freiburg, Germany.

Wharton, C. H. (1966). *Man, fire and wild cattle in North Cambodia.* Paper presented at the Tall Timbers Fire Ecology Conference 5.

Wikipedia. (2006). *Biodiversity hotspot*. Retrieved April 19, 2006, from http://en.wikipedia.org/wiki/Biodiveristy_hotspot

Wikramanayake, E., Dinerstein, E., Loucks, C., Olson, D., Morrison, J., Lamoreux, J., McKnight, M., & Hedao, P. (2001). *Terrestrial Ecoregions of the Indo-Pacific: A conservation assessment*. Washington, DC: Island Press.

Woodley, S. (2002). Planning and managing for ecological integrity. In P. Dearden & R. Rollins (Eds.), *Parks and Protected Areas in Canada: Planning and management* (Second ed., pp. 416). Oxford: Oxford University Press.

Woods, P. (1989). Effects of logging, drought, and fire on structure and composition of tropical forests in Sabah. *Biotropica, 21*, 290-298.

Woodward, P. (2000). Professor, Forest fire science, University of Alberta. Edmonton, AB, Canada.

Yah-tek-ho. (2001). Guard, Sai Ber station, Huai Kha Khaeng Wildlife Sanctuary. Uthai Thani, Thailand.

Zhou, J. (2005). Professor, Department of Mathematics and Statistics, University of Victoria. Victoria, BC, Canada.

Appendix 2-1 Forest classification*

II. Vegetation

A. TROPICAL RAIN FOREST

This and other forest types are illustrated in the accompanying map. In the Chanthaburi or Southeastern and Peninsular Regions where contact with the monsoons is direct, the precipitation is very high (2500 mm up), and thus nearly the whole region is covered with this type of forest. After a careful study of these forests, two zones can be recognized, i.e. the Lower Tropical Rain Forest, and the Upper Tropical Rain Forest.

The Lower Tropical Rain Forests occupy the peneplains and hillslopes up to 600m altitude. The forests are two storied, with the upper story composed of gigantic trees, mostly Dipterocarps (*Dipterocarpus*, *Hopea*, *Shorea*, *Balanocarpus*, *Parashorea*, and *Anisoptera*), and others such as *Dyera*, *Endospermum*, *Horsfieldia*, *Melanorrhoea*, *Palaquium*, *Planchonella*, *Mangifera*, *Swintonia*, *Ailanthus*, *Cedrela*, *Artocarpus*, *Bischofia*, *Sandoricum*, *Tetrameles*, *Pterocymbium*, *Scaphium*, *Sterculia*, *Intsia*, *Mesua*, *Pterospermum*, *Schima*, *Cinnamomum*, *Calophyllum*, *Litsea*, *Alstonia*, *Ficus*, *Adenanthera*, *Koompassia*, *Lagerstroemia*, *Nephelium*, *Manglietia*, and *Podocarpus*.

The lower story is constituted of trees of medium height and girth of the genera *Vatica*, *Talauma*, *Baccaurea*, *Alchornia*, *Macaranga*, *Mallotus*, *Drypetes*, *Cleistanthus*, *Gloghidion*, *Croton*, *Cleidion*, *Sumbavia*, *Antidesma*, *Aporosa*, *Dichapetalum*, *Streblus*, *Syzygium*, *Phoebe*, *Alseodaphne*, *Aglaia*, *Garcinia*, *Memecylon*, *Polyathia*, *Mitrephora*, *Goniothalamus*, *Pseuduvaria*, *Orophea*, *Gluta*, *Semecarpus*, etc. Palms, such as *Orania*, *Oncosperma*, *Calamus*, *Korthalsia*, *Daemonorops*, and *Licuala*, are abundant.

Vines are also abundant such as *Bauhinia*, *Dalbergia*, *Milletia*, *Tetrastigma*, *Willughbeia*, *Aganosma*, *Poikiolospermum*, *Trachyspermum*, *Epigynum*, *Derris*, and *Entada*.

Bamboos are common in disturbed areas, belonging to the genera *Gigantochloa*, *Bambusa*, *Dinochloa*, *Schizostachys*, and *Dendrocalamus*.

The Upper Tropical Rain Forests occupy the slopes of 600-900 m. altitude, and are also two-storied. The upper story is represented by a great proportion of oaks and chestnuts (*Quercus*, *Lithocarpus*, and *Castanopsis*), interspersed with *Magnolia*, *Michelia*, *Syzygium*, *Pentace*, *Dipterocarpus costatus*, *D. grandiflorus*, *Myristrica*, *Canarium* and *Podocarpus*. The lower story is composed of *Antidesma*, *Aglaia*, *Baccaurea*, *Glochidion*. Palms of the genera *Areca*, *Pinanga*, *Calamus*, and *Daemonorops* are abundant. A tree fern of the genus *Cyathea* is also present. Undergrowth is dense and mostly composed of Melastomataceae, Acanthaceae, and Zingiberaceae, with a great number of terrestrial ferns and orchids. Climbers are few and scattered, but epiphytes are abundant. Trees are heavily covered with mosses, ferns and orchids. This is a transitional area between the Hill Evergreen or Lower Montane Forest, which starts from the elevation of 1000 m upwards.

---

* Smitinand et al. 1978

B. DRY OR SEMI-EVERGREEN FOREST

This type of forest is scattered all over the country along the depressions on the peneplain, along the valleys of low hill ranges of about 500m. elevation, or forming galleries along streams and rivulets. The annual precipitation is between 1000-2000 mm.

Except the valleys of low hill ranges, the present dry evergreen forests are remnants of the once luxuriant and extensive forests covering the peneplains of the Central Region of the Chao Phraya Plain, and parts of the Korat Plateau or the Northeastern Region.

The forests are three-storied. The upper story consists of *Antisoptera costata*, *Dipterocarpus alatus*, *D. turbinatus*, *Hopea odorata*, *H. ferrea*, *Shorea thorelii*, *Alstonia scholaris*, *Pterocymbium tinctorium*, *Tetrameles nudiflora*, *Afzelia xylocarpa*, *Ailanthus triphysa*, *Ulums lanceifolius*, *Antiaris toxicaria*, *Lagerstroemia ovalifolia*, and *Acrocarpus fraxinifolius*. The middle story is composed of *Cratoxylum maingayi*, *Chaetocarpus castanicarpus*, *Castanopsis nepheloides*, *Euphoria longana*, *Lithocarpus harmandii*, *Spondias pinnata*, *Cinnamomum iners*, *Irvingia malayana*, *Vatica cinerea*, *Sapium insigne* and *Diospyros* spp. The lower story is represented by tree species of smaller stature of the genera *Memecylon*, *Cleistanthus*, *Aporusa*, *Alchornia*, *Baccaurea*, *Macaranga*, *Mallotus*, *Knema*, *Melodorum*, *Mitrephora*, *Tarenna*, *Dillenia*, *Crataeva*, and *Niebuhria*.

Palms of the genera *Calamus*, *Areca*, *Livistona*, *Corypha*, and *Raphis* are scattered. Bamboos (*Gigantochloa*, *Bambusa*, *Dendrocalamus*) are sparsely present. Lianes, however, are abundant, belonging to the genera *Bauhinia*, *Dalbergia*, *Derris*, *Entada*, *Strychnos*, *Securidaca*, *Toddalia*, *Acacia*, *Hymenopyramis*, *Congea*, *Sphenodesme*, *Uncaria*, *Ventilago*, *Tetrastigma*, *Artabotrys*, *Desmos*, *Uvaria*, and *Pisonia*. Strangling figs are also frequent. Epiphytes, mainly orchids and ferns, are sporadic.

The undergrowth is dense and composed of members of the family Zingiberaceae belonging to *Curcuma*, *Boesenbergia*, *Alpinia*, *Catimbium*, *Cenolophon* and *Amomum*; others are *Tacca*, *Strobilanthes*, *Micromelum*, *Clausena*, *Barleria*, *Flemingia*, *Desmodium*, *Lourea*, *Capparis*, and ferns of the genera *Helminthostachys*, *Lygodium*, and *Thelypteris*.

C. HILL EVERGREEN FOREST

Hill Evergreen Forest occurs in the upper elevations from 1000 m upwards, and appears discontinuously all over the country, with a larger percentage in the Northwestern Highland. This type of forest is also known as Temperate Evergreen Forest or Lower Montane Forest by some authors. The forest is two storied, and dominated by the oaks, chestnuts, laurels, magnolias, teas, and rhododendrons; gymnospermous elements are also present, such as *Podocarpus*, *Dacrydium*, *Cephalotaxus*, *Gnetum*, and *Cycas*. The soil is either red granitic, brown-black calcareous, or yellow-brown sandy. The humidity is very high, as explained by the mossclad trees; the precipitation is 1500-2000 mm annually.

The upper story is represented by *Schima wallichii*, *Cinnamomum* spp., *Fraxinus excelsa*, *Dacrydium elatum*, *Podocarpus imbricatus*, *Cephalotaxus griffithii*, *Betula* *alnoides*, *Ulmus lancifolia*, *Cedrela toona*, *Nyssa javanica*, *Quercus*, *Lithocarpus*, *Castanopsis*, and *Calophyllum*. The second layer is composed of small trees of medium height and girth, such as *Gordonia*, *Camellia*, *Pyrenaria*, *Acer*, *Carya*, *Carpinus*, *Tristania*, *Sladenia celastrifolia*, *Symingtonia populifera*, *Notophoebe*, *Alseodaphne*, *Lindera*, *Phoebe*, *Helicia*, *Macaranga*, *Mallotus*, *Rhododendron*, *Symplocos*, and *Aquilaria*.

Shrubs are also abundant, belonging to: *Daphne*, *Wikstroemia*, *Melastoma*, *Osbeckia*, *Embelia*, *Maesa*, *Rapanea*, *Rhamnus*, *Cornus*, and *Osyris*. Herbaceous species form a rich ground flora and are represented by *Catimbium*, *Boesenbergia*, *Curcuma*, *Globba*, *Hedychium*, *Strobilanthes*, *Rungia*, *Asystasia*, *Calanthe*, *Phajus*, *Malaxis*, *Liparis*, *Habenaria*, *Anoectochilus*, *Anthogonium*, *Pollia*, *Forrestia*, *Streptolirion*, and *Ophiorrhiza*. Bamboos are *Teinostachys*, *Dinochloa*, *Gigantochloa*, and *Schizostachys*. Palms are relatively few (*Trachyspermum speciosum* and members of *Pinanga* and *Phoenix*).

Ferns are richly represented, including species of *Athyrium*, *Asplenium*, *Leptochilus*, *Polypodium*, *Phymatodes*, *Thelypteris*, *Nephrolepis*, *Plagiogyria*, *Blechnum*, *Cyathea* and *Osmunda*. Sphagnums are found in the boggy areas of high altitude. Epiphytes are abundant and found festooning trees; besides mosses and lichens, there are ferns of the genera *Drynaria*, *Asplenium*, *Humata*, *Davallia*, *Davallodes*, *Pyrrhosia* and epiphytic orchids of the genera *Dendrobium*, *Eria*, *Porpax*, *Bulbophyllum*, *Drymoda*, *Pleione*, *Coelogyne*, *Neogyne*, *Oberonia*, *Cymbidium*, *Gastrochilus*, and *Vanda*.

In the region where the summits and ridges are open and exposed, the vegetation is sparse, recalling a subalpine nature. Here are found *Primula*, *Kalanchoe*, *Sedum*, *Saxifraga*, *Circaea*, *Spiraea*, *Pedicularis*, *Gentiana*, *Parnassia*, *Viola*, *Sophora*, *Bupleurum*, *Seseli*, *Selinum*, *Heracleum*, *Cotoneaster*, *Geranium*, *Rhododendron*, *Iris*, *Lilium* and *Asparagus*.

D. CONIFEROUS FOREST

This type of forest is scattered in small pockets in the Northwest Highland and the Khorat Plateau of about 200-1300 m elevation, where poor acid soil occurs. The soil is either grayish sandy, or brownish gravelly and sometimes lateritic. The annual rainfall is about 1000-1500 mm.

The forest is three storied and is rather open in nature; in certain localities where forest fire is concurrent, the forest grades into a savanna. The upper story is composed of *Pinus kesiya* and *P. merkusii*, in certain localities where lateritic soil is evident, *Dipterocarpus obtusifolius* and *D. tuberculatus* also come in, to form a *Pinus-Dipterocarpus* association.

The second story consists of saplings of upper story species, together with *Anneslea fragans*, *Quercus*, *Lithocarpus*, *Castanopsis*, *Styrax aprica*, *Myrica farquahariana* and *Tristania rufescens*; the lowest story is formed by small trees and tall shrubs such as *Adinandra*, *Embelia*, *Maesa*, *Phoenix humilis*, *Cycas pectinata*, *Vaccinium spregelii*, *V. bracteatum*, *Rhododendron moulmeinense*, *R. lyi*, *Baeckia frutescens* and *Styrax rugosus*.

E. SWAMP FOREST

Along the depressions in the low-lying land, the estuaries and the muddy shores, a unique type of vegetation is developed. This type of vegetation is more or less subjected to occasional inundation, and is scattered in the wet region of the country, where the annual precipitation is high (2000 mm up).

The forest can be physiographically classified into two kinds: 1) the Fresh Water Swamp forest and 2) the Mangrove Swamp forest.

1. Fresh Water Swamp forest

This type of forest is usually found along depressions inland, the soil is either alluvial or sandy. If it is on alluvial soil the ground floor is muddy and fen-like. Whenever peat deposits occur, the ground develops into a domed bog and a sub-type vegetation top story is composed of trees of large dimension such as *Dyera costulata*, *Palaquium gutta*, *Koompassia malaccensis*, *Calophyllum teysmannii* and *Scaphium lychnophorum*. The second story is composed of *Nephelium lappaceum*, *Hydnocarpus sumatranus*, *Walsura trijuga*, *Hopea latifolia*, *H. pierrei*, *Cratoxylon arborescens*, *Heritiera littoralis*, *Ploiarium alternifolium*, and *Xanthophyllum glaucum*. The lowest story consists of *Aglaia*, *Gluta*, *Casearia*, *Melaleuca leucadendra* and *Alstonia spathulata*. The ground flora is very poor and represented by *Apostasia*, *Boesenbergia*, *Hanguana*, *Hedychium*, *Hornstedtia*, *Costus*, *Dipodium*, *Bromheadia*, *Forrestia*, *Donax*, *Schumanianthus*, and *Nepenthes*.

Palms are very common, consisting of many species of thorny climing rattans of the genera *Calamus*, *Korthalsia*, *Plectocomia*, and *Daemonorops*, together with *Areca triandra*, *Licuala*, *Nenga*, *Pinanga*, *Cyrtostachys lacca* and *Oncosperma tigillaria*. Epiphytes are rich in ferns and orchids.

Where the soil is sandy, the composition of the forest is quite different, more open and the trees rather stunted. *Fagraea fragrans* forms a majority in this type of forest with the bushy *Baeckia frutescens* and *Licuala* palms as associates; in some localities, *Melaleuca leucadendra* occurs in a pure stand of one-story formation.

The much disturbed area in this type of forest forms a peculiar secondary growth, called in Malaysia "Belukar." This secondary growth is composed of stunted trees and shrubs such as *Melaleuca leucadendra*, *Syzygium grande*, *Flagellaria volubilis*, *Derris elliptica* and *Spirolobium cambodianum*.

2. Mangrove Swamp forest

Mangrove swamps are to be found along the estuaries of rivers and the muddy coastlines, where the soils are deep alluvial deposits with a high saline content. The forest is periodically tidally inundated. In Thailand this type of forest is very extensive on the West coast from Satun to Ranong, and within the Gulf of Thailand from Samut Sakhon in the Southwest to Trat in the Southeast.

Species inhabiting this type of forest are semi-xerophytic, even though they are occasionally submerged by sea water which they cannot use. These plants store fresh water in their characteristic thick leather-like leaves.

The stand is uniform and forms a one-storied profile. At a close study the forest will reveal zonal formations. The most outlying region facing the sea or ocean can be called the *Avicennia-Sonneratia* zone, composed of *Avicennia officinalis*, *A. marina*, *Sonneratia griffithii*, *S. alba*, and *S. caseolaris*. After this outlying formation, the *Rhizophora* zone appears, mainly constituted by *Rhizophora mucronata* and *R. apiculata*. The inner zone can be called *Bruguiera-Kandelia-Ceriops* and is composed of *Bruguiera parviflora*, *B. caryophylloides*, *B. hainesii*, *Kandelia rheedii*, *Ceriops* tagal and *C. roxburghiana*. The inner-most region is a mixed formation of *Lumnitzera-Xylocarpus-Bruguiera* consisting of *Lumnitzera coccinea*, *L. racemosa*, *Bruguiera gymnorrhiza*, *B. eriopetala*, *Xylocarpus obovatus* and *X. granatum*. *Rhizophora apiculata* also occasionally occurs in this zone. Along the creeks *Heritiera littoralis* is also frequent.

Along the estuaries where there is shelter from winds and waves, the outer-most zone is fringed by *Rhizophora mucronata* and *R. apiculata*. In all these zones the ground flora is very poor and is represented by *Acanthus ilicifolius*, *A. ebracteatus*, *Derris trifoliata*, *Acrostichum aureum* and *A. speciosum*, together with *Aegiceras corniculata* and *Scyphiphora hydrophyllacea*.

F. THE DECIDUOUS FORESTS

Along the dry belt of the country, where precipitation is low (under 1000 mm) the climate is more seasonal, and the soil is either sandy or gravelly loam and sometimes lateritic. The vegetation here is classified as deciduous and tree species shed their leaves during the dry season. Trees growing in this forest type tend to develop growth or annual rings. The height of predominant trees is comparatively lower (20-25 m) than that of the evergreen forest. This forest is more or less subject to ground fire during the dry season.

Deciduous forests can be sub-divided into three main categories: Mixed Deciduous Forest, Dry Deciduous Dipterocarp Forest, and Savanna Forest.

1. Mixed Deciduous Forest

This type of forest is composed of all deciduous species in a good proportion but in certain localities a species such as teak (*Tectona grandis*) may become predominant and the area would generally be called a Teak forest for convenience.

The mixed deciduous forest condition also can be classified into three kinds, based on the terrain and climate: Moist Upper Mixed Deciduous, Dry Upper Mixed Deciduous, and Lower Mixed Deciduous.

a. Moist Upper Mixed Deciduous Forest. This type of forest occurs between the elevations of 300-600 m altitude, and is 3-storied in profile. The soil in this forest is usually loamy, either calcareous or granitic. The upper story consists of *Tectona grandis*, *Lagerstroemia tomentosa*, *Terminalia alata*, *T. calamansanai*, *T. bellirica*, *Afzelia xylocarpa*, *Xylia kerrii*, *Bombax insigne*, *Pterocarpus macrocarpus*, *Dalbergia cultrata*, *D. oliveri*, *Adina cordifloia*, *Gmelina arborea*, *Anogeissus acuminata*, *Millettia leucantha*, *Albizia lebbeck*, *A. procera*, *A. lebbekiodes*, *A. chinensis*, *Acacia leucophloea*, *Adenanthera pavonina* and *Dillenia pentagyna*. The second story consists of *Combretum quadrangulare*, *Careya arborea*, *Barringtonia racemosa*, *Millettia brandisiana*, *Albizia lucida*, *Dalbergia ovata*, *D. nigrescens*, *Peltophorum dasyrachis*, *Lagerstroemia* *floribunda*, *L. speciosa*, *L. macrocarpa*, *L. villosa*, *L. undulata*, *Diospyros mollis*, *D. montana*, *Syzygium cumini*, *S. leptanthum*, *Vitex peduncularis*, *V. canescens*, *V. pinnata*, and *Dillenia aurea*.

The lowest story is composed of *Cratoxylon formosum*, *Mallotus philippinensis*, *Gardenia coronaria*, *G. obtusifolia*, *Casearia grewiaefolia*, *Bauhinia racemosa*, *B. malabarica*, *Croton oblongifolius* and *C. hutchinsonianum*.

A small number of palms such as *Phoenix humilis* and some species of *Calamus* may be found scattered in this type of forest. Shrubs are represented by species of *Croton*, *Mallotus*, *Premna*, and *Randia*, *Harrisonia perforata*, *Bauhinia acuminata*, and many others. Lianes such as *Hymenopyramis brachiata*, *Congea tomentosa*, *Artabotrys siamensis*, *Desmos chinensis*, *Bauhinia bracteata*, *B. scandens*, *Butea superba*, *Spatholobus parviflorus*, and *Dalbergia rimosa* are also scattered in this forest.

The ground flora is composed of herbaceous species such as grasses of the genera *Capillipedium*, *Sporobolus*, *Themeda*, *Thysanolaena*, *Andropogon*, *Bothriochloa*, *Saccharum*, *Oryza*, *Eragrostis* and *Hyparrhenia*; others are *Kaempferia*, *Curcuma*, *Boesenbergia*, *Fimbristylis*, *Carex*, *Cyperus*, *Ceropegia*, *Aristolochia*, *Habenaria*, *Peristylus*, *Pecteilis*, and *Brachycorythis*.

b. Dry Upper Mixed Deciduous Forest. Along the ridges at the elevations of 300-500 m altitude, the vegetation becomes more open due to the evaporation, exposure, surface erosion and the leaching of organic components from the soil. The forest is also three storied. Some species occurring also in the Moist Upper Mixed Deciduous Forest are present but here they are rather stunted and crooked. The more pronouncedly deciduous species such as *Shorea obtusa*, *S. siamensis*, *Dipterocarpus tuberculatus*, *D. obtusifolius* and *D. intrincatus* are only lightly represented. The soil is either sandy loam or lateritic. The ground flora is frequently destroyed by fire. This type of forest, especially when constantly disturbed by human beings, will degrade into a bamboo sward which sometimes covers quite an extensive area. The main bamboo species are *Bambusa arundinacea* and *Thyrsostachys siamensis*.

c. Lower Mixed Deciduous Forest. This forest type occurs on low-lying country at 50-300 m altitude in the dry zone where the soil is either sandy loam or lateritic. The forest is three-storied. The absence of teak (*Tectona grandis*) from the upper story is a distinct characteristic, differentiating the Lower from the Upper Mixed Deciduous Forest.

Hopea odorata, *H. ferrea* and *Shorea roxburghii* are sometimes found in the upper story. Along waterways, semievergreen species such as *Syzygium cumini*, *Hopea odorata*, *Sapium insigne*, *Afzelia xylocarpa* and *Dipterocarpus alatus* form a narrow strip on both banks and are generally known as Gallery forest.

Because of its accessibility and the number of commercially valuable species it contains, this type of forest is second only to teak forest in economic importance. Unfortunately, its natural assets and the fact that it is usually found in areas suitable for agriculture, brings it close to the verge of total destruction.

2. Dry Deciduous Dipterocarp Forest

On the undulating peneplain and ridges, where the soil is either sandy or lateritic, and subjected to extreme leaching, erosion and annual burning, the vegetation is markedly changed into a subclimax type. The predominant species belong to the

Dipterocarpaceae. The forest is rather open and can be considered as two-storied. The upper story consists of *Dipterocarpus obtusifolius*, *D. tuberculatus*, *Shorea obtusa*, *S. siamensis*, *Quercus kerrii*, and sometimes *Pterocarpus macrocarpus* and *Xylia kerrii*. Generally, the height of trees of the upper story is between 20-15 m but only 15-20 m in more arid areas. The second story is composed of low shrubby trees such as *Strychonos nux-vomica*, *S. nuxblanda*, *Dalbergia kerrii*, *Symplocos cochinchinensis*, *Diospyros ehretioides*, *Aporusa villosa*, *Phyllanthus emblica* and *Canarium subulatum*.

The ground flora consists of tuber and rootstock-bearing species, due to the effect of the fires, such as small bamboos of the species *Arundinaria pusilla*, *A. ciliata*, *Linostoma persimilis*, *Enkleia malaccensis*, *Phoenix acaulis*, *Pygmaeopremna herbacea* and numbers of the genera *Habenaria*, *Peteilis*, *Hibiscus*, *Decaschistia*, *Kaempferia*, and *Curcuma*. *Dillenia hookeri* is common, forming clumps of low bushes.

Epiphytes are relatively abundant and mostly consist of ferns belonging to the genera *Drynaria*, *Platycerium* and *Pyrrosia*, and orchids of the genera *Aerides*, *Eria*, *Dendrobium*, *Bullophyllum*, *Cleisostoma* and *Ascocentrum*. *Dischidia rafflesiana*, *Dischidia minor*, *Hoya pachyclada*, and *Hoya kerrii*, are also common.

G. SAVANNA FOREST

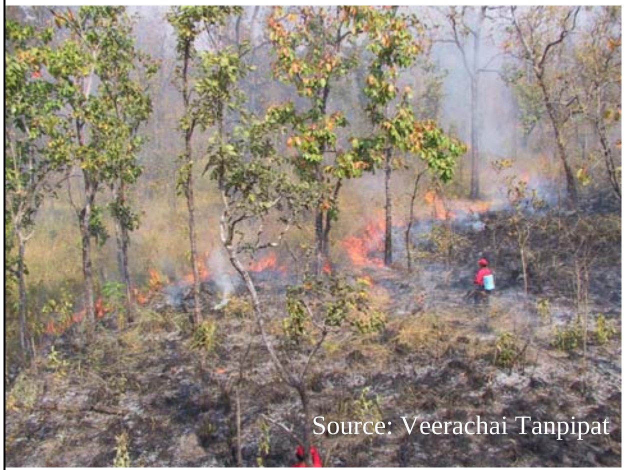
Savanna may be called the most extreme form of deciduous forest and is the result of fire. It is more frequent in the Northeastern region which has been cultivated from time immemorial. The soil is either sandy or lateritic. Precipitation is relatively low (50-500 mm). Small patches of savanna at different stages are scattered all over the region. The most extensive savanna, Thung Kula Rong Hai in Sakon Nakhon, has become a vast, desolate land.

Savanna forest is actually a grassland where trees of medium height grow, forming a very open stand. Besides trees, thorny shrubs such as *Feroniella lucida*, and *Carissa cochinchinensis* are interspersed with *Bambusa arundinacea*. In upper elevations, shrubs belonging to the genera *Aporusa*, *Ochna* and *Glochidion* are frequent. Tree species found in the savanna forest such as *Careya arborea*, *Mitragyna parvifolia*, *Acacia siamensis*, *A. catechu* and *Pterocarpus macrocarpus*, are fire resistant.

The grassland is composed of *Imperata* and *Vetiveria*, together with *Eulalia*, *Panicum*, *Sporobolus*, *Themeda*, *Eriochloa*, *Eremochloa* and *Sorghum*.

Appendix 2-2 Forest mosaic and fire in Huai Kha Khaeng

App. 2-2a Deciduous forest with pockets of SEF in the eastern part of HKK as seen from helicopter, February 2001



App. 2-2b Fire fighters in dry dipterocarp forest, HKK (2002).

App. 2-2c Winners of a children's poster contest for fire awareness in HKK (2001).

Appendix 3-1 RMS error for 1989 to 1994 burn area maps

	1989			1990			1991		
tic #	**x (m)**	**y (m)**	**RMS error**	**x (m)**	**y (m)**	**RMS error**	**x (m)**	**y (m)**	**RMS error**
1	64.167	-1067.663	1069.589	460.515	-903.634	1014.213	349.063	-317.647	471.958
2	469.988	889.634	1006.150	-960.207	1243.261	1570.890	-927.703	357.569	994.228
3	507.828	464.403	688.157	621.600	-283.813	683.327	693.642	-0.248	693.642
4	561.300	-285.818	629.881	1086.329	151.290	1096.813	624.812	226.710	664.671
5	-1256.412	-1022.571	1619.945	-1768.031	571.780	1858.189	-1327.117	-540.404	1432.926
6	490.841	534.564	725.730	588.704	136.791	604.387	500.391	116.019	513.665
7	105.264	487.451	498.687	-28.909	227.885	229.711	86.912	164.001	185.607
Overall RMS			**958.143**			**1136.233**			**800.512**

	1992			1993			1994		
tic #	**x (m)**	**y (m)**	**RMS error**	**x (m)**	**y**	**RMS error**	**x (m)**	**y (m)**	**RMS error**
1	285.122	58.653	291.092	64.105	-490.932	495.100	298.447	-540.405	617.340
2	-1087.531	2.435	1087.534	-615.732	30.283	616.476	-871.510	304.990	923.336
3	1069.829	-93.703	1073.925	673.194	678.291	955.651	684.405	406.943	796.249
4	305.861	411.624	512.821	169.412	78.157	186.572	553.907	121.887	567.159
5	-1435.382	-373.423	1483.161	-916.837	-1267.064	1563.983	-1248.312	-1061.070	1638.338
6	806.088	112.657	813.922	367.410	532.587	647.023	507.475	404.778	649.135
7	56.013	-118.242	130.838	258.448	438.679	509.151	75.588	362.877	370.666
Overall RMS			**891.477**			**891.160**			**880.930**

Overall RMS for entire data (1989 to 1994)	**921**	m

Appendix 3-2 Fieldwork in Huai Kha Khaeng

App. 3-2a Identification of areas of SEF burned in recent years, Yuyi station (2001)

App. 3-2b Observation of burned tree in the permanent plot, HKK (2001)

App. 3-2c End of a grueling four-day reconnaissance trek through the mountains between Sai Ber and Wang Pai (2001)

Appendix 4-1 Calculation of leaf moisture content in SEF for HKK

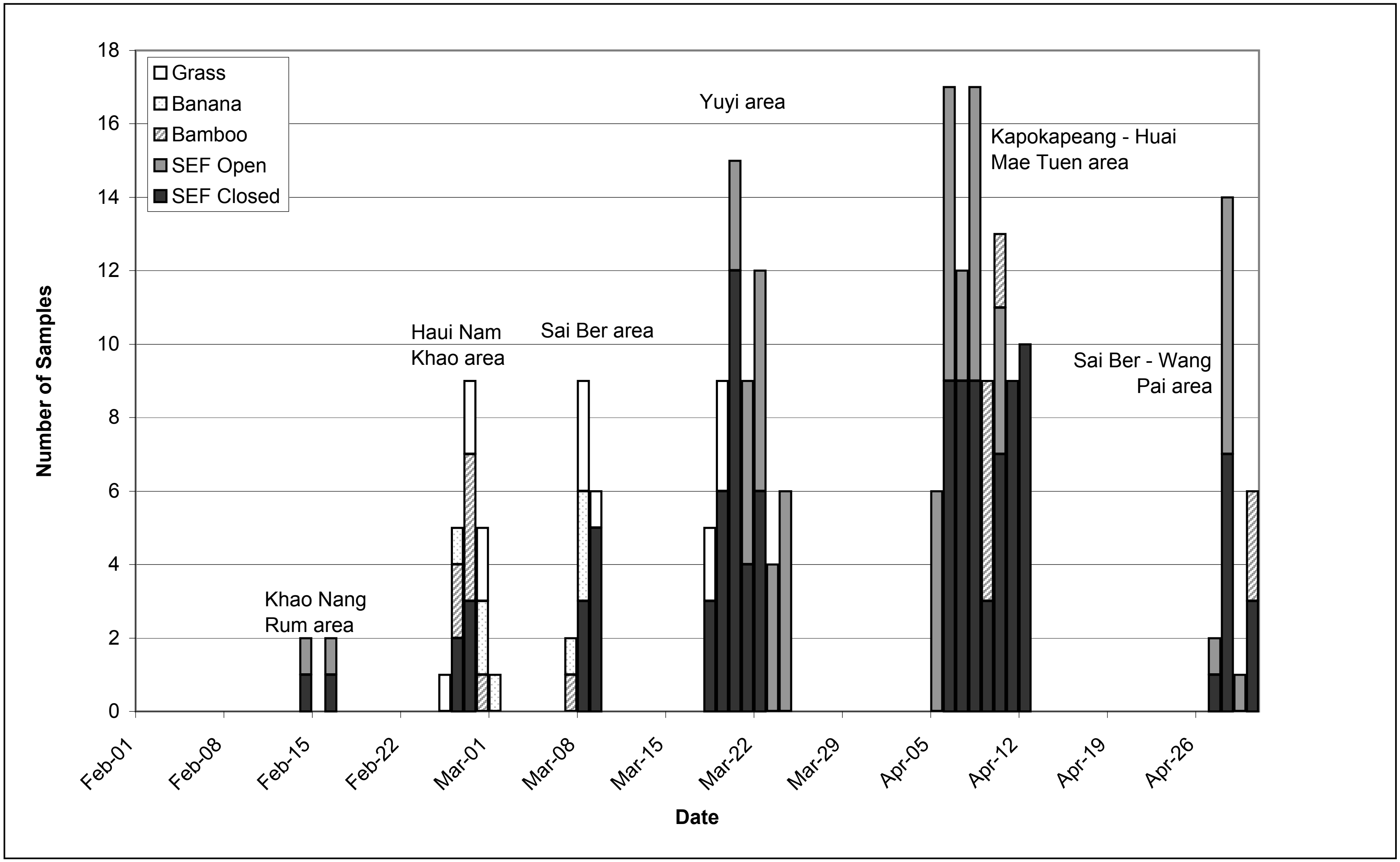
Plot ID	Date Sampled	Green weight (g/cm2)	Oven weight (g/cm2)	Fuel load (t/ha)	Moisture Content (%) (Ofren, 1995) *	Moisture Content (%) (Johnson, 2005) †	Difference
101	29/03/97	31.31	28.02	7.01	**10.51**	**11.74**	**1.23**
102	04/04/97	35.58	30.71	10.19	**13.69**	**15.86**	**2.17**
103	04/04/97	37.26	31.45	5.62	**15.59**	**18.47**	**2.88**
104	04/04/97	89.34	47.91	8.85	**46.37**	**86.47**	**40.10**
105	18/04/97	40.87	33.9	6.27	**17.05**	**20.56**	**3.51**
106	18/04/97	38.22	33.15	8.98	**13.27**	**15.29**	**2.03**
107	18/04/97	62.43	54.17	20.25	**13.23**	**15.25**	**2.02**
108	18/04/97	58.46	39.66	14.45	**32.16**	**47.40**	**15.24**
109	21/04/97	45.84	34.49	9.17	**24.76**	**32.91**	**8.15**
110	21/04/97	30.44	27.36	6.53	**10.12**	**11.26**	**1.14**
111	21/04/97	69.66	63.36	18.8	**9.04**	**9.94**	**0.90**
112	21/04/97	72.45	58.39	10.32	**19.41**	**24.08**	**4.67**

modified from Ofren (1999)

* $$MC = \frac{\text{green wt.} - \text{dry wt.}}{\text{green wt.}}$$

† $$MC = \frac{\text{green wt.} - \text{dry wt.}}{\text{dry wt.}}$$

Appendix 4-2 Plots per day for each vegetation type (2001)



Appendix 4-3 Field plot locations

Plot	Latitude (UTM)	Longitude (UTM)	Satel-lites	Fire Scar Tree	Tree Alive or Dead	Fire Year	Vegetation Type
2-01	1740027	506160	6	y	dead	1998	grass
2-02	1739669	506686	5	y	alive	1998	Banana
2-03	1739735	506918	5	y	dead	1998	SEF closed
2-04	1739724	507114	5	n			Bamboo
2-05	1739649	507275	3	n			SEF closed
2-06	1739193	507192	4	n			SEF closed
2-07	1740533	505821	7	y	dead	1998	Banana
2-08	1740559	505890	0	n	dead	1998	Bamboo
2-09	1740593	506080	3	n			SEF closed
2-10	1740711	506158	0				SEF open
2-11	1740713	506159	5				Bamboo
2-12	1740765	506204	3	n			SEF closed
2-13	1740414	505964	4	n			grass
2-14	1740037	505880	6				grass
2-15	1740101	505727	5	y	dead	1998	Banana
2-16	1740199	505723	6	n			Bamboo
2-17	1740455	505782	4	y	alive	1998	Banana
2-18	1740463	505742	5	y	dead	1998	grass
2-19	1740330	505758	8	y	dead	1998	Banana
2-20	1740600	505563	6	y	dead	1998	SEF open
3-01	1691515	545462	4	n			Bamboo
3-02	1691575	545414	3	y	dead	1994	Banana
3-03	1691204	545026	6	n			SEF closed
3-04	1690977	545230	3	y	dead		Banana
3-05	1690352	544774	4	y	alive		Banana
3-06	1688332	542482	5	y	dead		SEF closed
3-07	1687922	542686	4	y	alive	1994	SEF closed
4-01	1708158	507344	4	n			grass
4-02	1708409	507208	4	n			SEF closed
4-03	1709114	509358	0	y	alive	1998	SEF closed
4-04	1709609	510046	7	y	dead	1998	grass

Plot	Latitude (UTM)	Longitude (UTM)	Satel-lites	Fire Scar Tree	Tree Alive or Dead	Fire Year	Vegetation Type
4-05	1709666	510400	3	y	dead		SEF closed
4-06	1708513	507746	0	y	dead		SEF closed
4-07	1708513	507746	0	y	dead		SEF closed
4-08	1709737	508292	4	y	dead	1998	SEF closed
4-09	1710077	508757	5	y	alive	1998	SEF open
4-10	1710516	508580	4	y	dead	1998	SEF closed
4-11	1710139	509221	5	y	dead		SEF open
4-12	1710139	509414	0	y	alive		SEF closed
4-13	1710232	509496	5	y	dead		SEF open
4-14	1710287	509427	4	y	dead		SEF open
4-15	1710510	509530	3	y	alive		SEF closed
4-16	1711025	509583	4	y	dead		SEF closed
4-17	1712028	509988	0	y	dead		SEF closed
4-18	1712028	509988	7	y	dead		SEF open
4-19	1710841	509081	4	y	dead		SEF open
4-20	1708173	508718	4	y	alive		Banana
4-21	1708258	509631	5	y	dead		SEF closed
4-22	1707643	505424	3	y	dead		SEF closed
4-23	1707816	506166	4	y	alive		SEF closed
5-01	1729595	524173	4	y	dead		SEF open
5-02	1728407	523787	6	y			SEF open
5-03	1728207	523375	3	y	dead		SEF closed
5-04	1728053	522715	4	y			SEF open
5-05	1728031	522560	4	y	dead		SEF closed
5-06	1728032	522133	4	y	dead		SEF open
5-07	1727665	522120	6				SEF open
5-08	1727664	522530	5	y	dead		SEF closed
5-09	1727685	522582	4	y	dead		SEF open
5-10	1727832	523027	6	y	alive		SEF closed
5-11	1727536	523327	5	y	dead		SEF closed
5-12	1727700	523716	4	y	dead		SEF closed
5-13	1726786	523660	4	y	alive		SEF closed
5-14	1726276	523718	5	y	dead		SEF open
5-15	1726908	523993	5	y	dead		SEF open

Plot	Latitude (UTM)	Longitude (UTM)	Satel-lites	Fire Scar Tree	Tree Alive or Dead	Fire Year	Vegetation Type
5-16	1727537	523965	5	y			SEF open
5-17	1727584	523943	5	y	dead		SEF closed
5-18	1728311	523997	5	y	alive		SEF closed
5-19	1728903	523831	4				SEF open
5-20	1728980	523430	4	y			SEF closed
5-21	1728993	522733	4	y	dead		SEF closed
5-22	1735869	520756	4	y	alive		SEF closed
5-23	1736820	520477	5	y	dead	1998	SEF closed
5-24	1736783	519727	3	y	dead	1998	Bamboo
5-25	1736499	519118	5	y			SEF open
5-26	1736485	519104	4	y			SEF open
5-27	1736404	518608	4	n			SEF closed
5-28	1736382	518617	4	n			SEF open
5-29	1736398	518322	4	n			Bamboo
5-30	1736398	518320	4	n			SEF closed
5-31	1736304	517606	4	y	dead		Bamboo
5-32	1736468	519026	3	y	dead		SEF closed
5-33	1736181	519492	3	y	dead		SEF closed
5-34	1735916	519476	5	y	alive		SEF closed
5-35	1735570	519487	5	n			SEF closed
5-36	1729375	524225	3	n			SEF closed
5-37	1728252	523725	4	n			SEF closed
5-38	1727749	523525	4	y	dead		SEF closed
6-01	1696299	544109	4	n			SEF open
6-02	1696411	543750	7	n			SEF open
6-03	1696570	541662	3	y	dead		SEF closed
6-04	1696951	541369	0	y	dead		SEF closed
6-05	1696951	541369	4	y	dead		Banana
6-06	1696343	540190	5	y	dead		Banana
6-07	1699466	539123	4	y			Bamboo
6-08	1700217	539463	6	n			SEF closed

Appendix 4-4   Data collection in SEF in HKK from February to April, 2001

App. 4-4a Leaf litter from sampling square being weighed

App. 4-4b Forestry student taking hemispheric photo

App. 4-4c Test fire being timed in bamboo

App. 4-4d Hobo temperature and relative humidity sensor

Appendix 4-5 Sample plot card

LJ ver Jan31/01

Page ___ of ___

Plot ID:	Date:
Start time: AM / PM	End time: AM / PM

Site Description

Habitat: DEFcls DEFopen Grass Vine Banana Bamboo Other:			
Weather: Clear Cloud (light) Cloud Smoke (light) Smoke Rain			
Elev (m):	Slope (%):	lower mid upper	Aspect ( ):
Roll ID:	Photo #	no wind breeze wind (light) gusts wind	

Location

Map sheet:		Air photo:	# satellites
GPS:	North:	East:	
	North:	East:	
	North:	East:	
Avg:	North:	East:	

Canopy Description

Est. canopy ht to seal (m):	Species:
Notes:	

Fire History

Fire scar trees in the general area: Y N	Alive Dead
GPS (approx.) of fire scar tree: E	W
Fire history: Burned-1998 B-1994 unknown	Info: guard other
NB:	

% Canopy Cover (Densiometer (gap count)**)**

Subplot	*north*	*east*	*south*	*west*	*average*
A					
B					
C					

% Canopy Cover (Hemispheric photo)

LJ ver Jan31/01

Page ___ of ___

Subplot	Roll ID	Photo #	Aperature	Speed

% Ground Cover (50cm x 50cm plot)

	Leaf (green)	*Grass*		*Leaf litter*	*No litter*	*Other*
		Green	*Cured*			
A						
B						
C						

Fuel Load (50cmx50cm plot)

Subplot	*Live weight (g)*	*Dead weight (g)*
A		
B		
C		
Litter depth:	Grass Ht:	Seedling ht:

Fuel Moisture

Subplot	*Bag (g)*	*Live wt*	*Dead wt*	T_{dry}	T_{wet}	*RH%*
A						
B						
C						

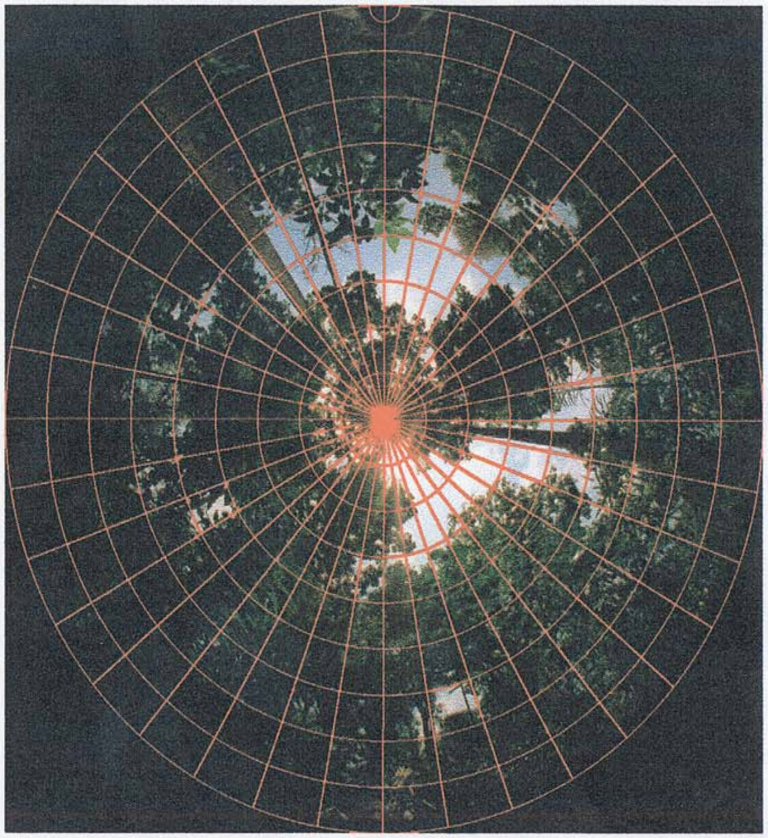
Fire Spread

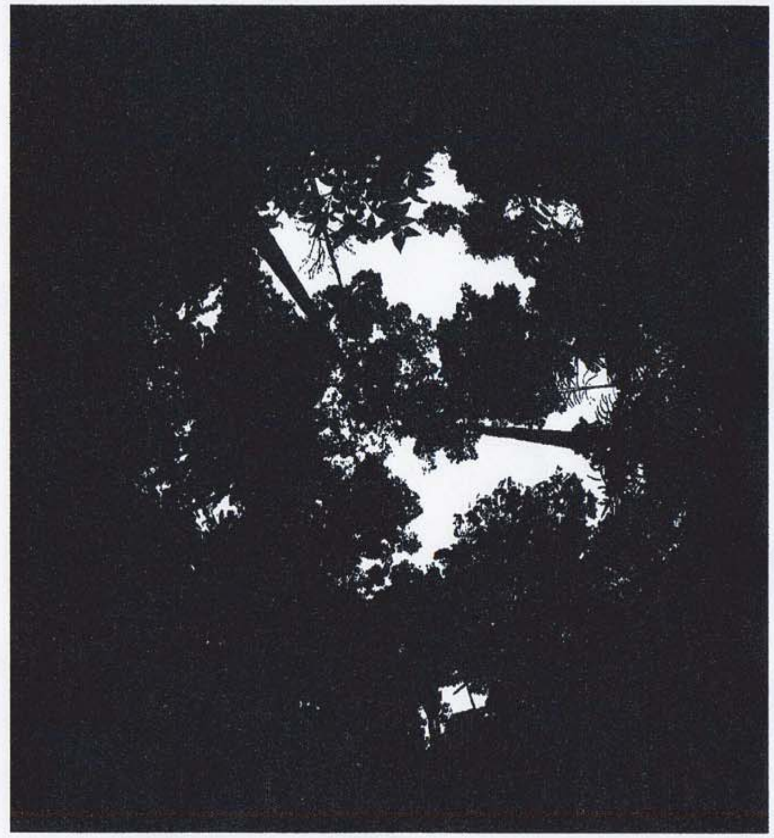
Subplot	Yes No	Rate to perimeter (r=50cm)	Roll ID	Photo#
A				
B				
C				

NB:

Appendix 4-6 Gap Light Analysis

GAP LIGHT ANALYSER





GLA software (Frazer and Canham, 1999)

Source: L. Johnson (2001)

% Sky Area:	100	% Canopy Openness:	10.46	LAI 4 Ring:	2.56
% Mask Area:	0	% Site Openness:	10.46	LAI 5 Ring:	2.68

Appendix 4-7 Grass fire and fuel in HKK

App. 4-7a Fire lit in HKK buffer zone by villagers at night (April, 2001)

App. 4-7b Grassland fuels adjacent to SEF at Huai Nam Khao guard station shown here cured in February (2001).

Appendix 4-8 Field plot data for Huai Kha Khaeng (2001)

Date	Plot	Sub-plot	Vegetation class	Litter MC** (dead, %)	Fuel Load (dead, t/ha)	Fuel Continuity %	Litter Depth (cm)	Canopy gap (%)	Fire Spread	Comment fire
2/26/2001	2-03	A	SEF closed	17.8	2.6	84	3	2.1	no	Burned for only 5sec
2/26/2001	2-03	B	SEF closed	16.4	6.6	88	3	5.7	…	
2/26/2001	2-03	C	SEF closed	12.4	4.7	85	3	2.1	…	
2/26/2001	2-05	A	SEF closed	7.4	11.1	89	3	1.8	yes	Spread for 5min 10sec to 45 cm, flame ht. 15 cm
2/26/2001	2-05	B	SEF closed	…	2.9	91	3	1.8	…	
2/26/2001	2-05	C	SEF closed	12.1	3.2	90	3	2.1	…	
2/26/2001	2-06	A	SEF closed	14.2	10.0	95	4	1.3	yes	No initial spread, after piling leaves a bit spread for 2min 3sec to 50cm
2/26/2001	2-06	B	SEF closed	12.7	10.1	94	4	2.9	…	
2/26/2001	2-06	C	SEF closed	9.8	5.5	94	4	2.3	…	
2/27/2001	2-09	A	SEF closed	13.7	6.1	85	3	2.1	no	Spread for 1min 8sec, but only to 10 cm, 20ml of gas used
2/27/2001	2-09	B	SEF closed	15.9	8.4	83	3	1.0	no	Spread for 4 min 2sec to 10 cm, 20 ml gas, lots of leaves
2/27/2001	2-09	C	SEF closed	…	7.3	74	…	1.3	…	
2/27/2001	2-12	A	SEF closed	11.6	7.1	95	5	1.3	no	Burned out quickly without spreading, 20ml of gas used
2/27/2001	2-12	B	SEF closed	11.7	5.5	98	5	7.5	…	
2/27/2001	2-12	C	SEF closed	5.8	6.7	100	5	9.4	…	
3/8/2001	3-03	A	SEF closed	12.1	3.9	97	5	5.7	no	Spread for 27 secs, not far

Date	Plot	Sub-plot	Vegetation class	Litter MC** (dead, %)	Fuel Load (dead, t/ha)	Fuel Continuity %	Litter Depth (cm)	Canopy gap (%)	Fire Spread	Comment fire
3/8/2001	3-03	B	SEF closed	8.4	4.9	86	5	1.8	…	
3/8/2001	3-03	C	SEF closed	9.3	10.2	99	5	5.5	yes	Spread well for 2min to 40 cm., some bamboo litter in plot
4/6/2001	5-03	A	SEF closed	38.9	8.4	100	3	1.6	no	
4/6/2001	5-03	B	SEF closed	36.1	9.6	100	3	4.9	no	
4/6/2001	5-03	C	SEF closed	28.9	11.8*	100	3	7.8	no	
4/6/2001	5-05	A	SEF closed	37.5	10.7	100	2	2.6	no	
4/6/2001	5-05	B	SEF closed	19.3	7.1	100	2	7.5	no	
4/6/2001	5-05	C	SEF closed	39.5	12.9	100	2	1.3	no	
4/6/2001	5-08	A	SEF closed	16.6	16.9*	100	3	4.2	no	
4/6/2001	5-08	B	SEF closed	18.6	9.1	100	3	4.2	no	
4/6/2001	5-10	A	SEF closed	24.2	9.3	100	3	1.8	no	
4/7/2001	5-12	A	SEF closed	20.7	5.6	98	3	1.8	no	
4/7/2001	5-12	B	SEF closed	17.2	5.9	100	3	3.4	no	
4/7/2001	5-12	C	SEF closed	43.6	7.0	96	3	13.8	no	Ignition, but spread only 3-4 cm
4/7/2001	5-13	A	SEF closed	25.9	6.9	98	3	1.8	no	Spread for 51 seconds to 10 cm, high wind in upper canopy
4/7/2001	5-13	B	SEF closed	17.1	8.8	100	3	3.9	no	Ignition but spread only 2-3 cm
4/7/2001	5-13	C	SEF closed	20.6	9.1	100	3	1.0	no	
4/8/2001	5-17	A	SEF closed	26.1	6.9	98	3	1.0	no	
4/8/2001	5-20	A	SEF closed	16.5	4.5	100	3	2.1	no	

Date	Plot	Sub-plot	Vegetation class	Litter MC** (dead, %)	Fuel Load (dead, t/ha)	Fuel Continuity %	Litter Depth (cm)	Canopy gap (%)	Fire Spread	Comment fire
4/8/2001	5-20	B	SEF closed	22.5	9.1	100	3	6.0	no	
4/8/2001	5-20	C	SEF closed	26.4	9.4*	100	3	0.5	no	
4/8/2001	5-21	A	SEF closed	17.0	9.2	92	3	6.8	no	
4/8/2001	5-21	B	SEF closed	27.1	8.5	…	3	2.3	no	
4/9/2001	5-23	A	SEF closed	34.7	10.7	100	3	3.4	no	
4/9/2001	5-23	B	SEF closed	20.1	17.8	98	3	0.8	no	
4/9/2001	5-23	C	SEF closed	27.9	8.4	100	3	0.8	no	
4/10/2001	5-27	A	SEF closed	12.8	7.7	96	3	1.6	no	
4/10/2001	5-27	B	SEF closed	40.4	10.7	100	3	2.3	no	
4/10/2001	5-30	A	SEF closed	9.0	10.1*	95	3	10.1	no	Some leaves ignite burn but no spread
4/10/2001	5-30	B	SEF closed	26.5	11.5*	96	3	9.6	no	Spread for 25sec to 15 cm
4/10/2001	5-30	C	SEF closed	26.5	15.1	100	3	0.3	no	
4/10/2001	5-32	A	SEF closed	13.9	5.7	100	3	2.6	no	Spread for 34sec to 5 cm
4/10/2001	5-32	B	SEF closed	26.3	16.1*	96	3	1.3	no	
4/11/2001	5-33	A	SEF closed	49.3	12.5	99	3	3.1	no	
4/11/2001	5-33	B	SEF closed	27.1	17.2	100	3	0.5	no	
4/11/2001	5-33	C	SEF closed	42.6	18.3	94	3	4.2	no	
4/11/2001	5-34	A	SEF closed	26.6	3.4	90	3	8.1	no	
4/11/2001	5-34	B	SEF closed	30.4	6.8	90	3	2.3	no	
4/11/2001	5-34	C	SEF closed	37.2	9.1	90	3	4.7	no	

Date	Plot	Sub-plot	Vegetation class	Litter MC** (dead, %)	Fuel Load (dead, t/ha)	Fuel Continuity %	Litter Depth (cm)	Canopy gap (%)	Fire Spread	Comment fire
4/11/2001	5-35	A	SEF closed	22.5	6.1	94	3	4.2	no	
4/11/2001	5-35	B	SEF closed	16.1	5.2	99	3	0.5	no	
4/11/2001	5-35	C	SEF closed	17.1	11.0	100	3	1.8	no	Spread for 20 sec to 10 cm (fed by light wind)
4/12/2001	5-36	A	SEF closed	24.4	7.0	97	3	6.8	no	
4/12/2001	5-36	B	SEF closed	51.3	24.2*	100	3	1.8	no	
4/12/2001	5-36	C	SEF closed	22.3	12.2	100	3	6.0	no	
4/12/2001	5-37	A	SEF closed	24.9	7.6	100	3	8.6	no	
4/12/2001	5-37	B	SEF closed	21.5	2.9	96	3	0.3	no	
4/12/2001	5-37	C	SEF closed	26.2	10.6	95	3	5.2	no	
4/12/2001	5-38	A	SEF closed	19.7	9.8	100	4	4.4	yes	Spread to perimeter in 4min 4sec
4/12/2001	5-38	B	SEF closed	14.6	5.3	92	4	4.2	no	No spread, no obvious reason
4/12/2001	5-38	C	SEF closed	14.9	7.1	100	4	4.4	no	No spread, no obvious reason
4/12/2001	5-38	D	SEF closed	14.5	13.3	100	4	4.7	yes	Spread and at a rate faster than subplot 5-38A, ie. 3 - 4 min
4/28/2001	6-03	A	SEF closed	38.7	8.9	…	4	0.0	no	
4/28/2001	6-03	D	SEF closed	25.5	7.9	…	3	1.0	no	
4/28/2001	6-04	A	SEF closed	37.8	7.5	98	3	0.3	no	
4/28/2001	6-04	B	SEF closed	40.7	7.5	100	3	1.6	no	
4/28/2001	6-04	C	SEF closed	30.2	15.1	95	3	0.9	no	
4/28/2001	6-05	A	SEF closed	18.7	3.5	100	6	1.8	no	

Date	Plot	Sub-plot	Vegetation class	Litter MC** (dead, %)	Fuel Load (dead, t/ha)	Fuel Continuity %	Litter Depth (cm)	Canopy gap (%)	Fire Spread	Comment fire
4/28/2001	6-05	C	SEF closed	33.2	7.6	100	6	3.9	no	
4/30/2001	6-08	A	SEF closed	22.8	11.0	100	5	0.0	no	
4/30/2001	6-08	C	SEF closed	17.4	12.6	100	5	1.6	no	
2/27/2001	2-10	A	SEF open	16.7	7.9	98	5	0.0	no	Spread only 10cm, 2ml gas used
2/27/2001	2-10	B	SEF open	13.8	8.0	96	5	1.6	…	
2/27/2001	2-10	C	SEF open	16.1	5.9	93	5	1.8	…	
3/1/2001	2-20	A	SEF open	23.6	8.5	96	4	24.7	no	
3/1/2001	2-20	B	SEF open	22.6	5.3	95	4	17.4	…	
4/5/2001	5-01	A	SEF open	21.2	10.1	99	2	3.6	no	Spread for 31sec but only moved 1cm from center
4/5/2001	5-01	B	SEF open	45.7	14.2	100	2	4.9	no	
4/5/2001	5-01	C	SEF open	36.1	13.6	100	2	6.2	no	
4/5/2001	5-02	A	SEF open	33.7	13.0*	100	3	6.2	no	
4/5/2001	5-02	B	SEF open	28.6	15.6	100	3	1.8	no	Spread 10 cm
4/5/2001	5-02	C	SEF open	22.1	2.7	100	3	12.0	no	
4/6/2001	5-04	A	SEF open	21.9	12.3	96	2	31.7	no	
4/6/2001	5-06	A	SEF open	20.3	5.2	100	3	16.6	no	
4/6/2001	5-06	B	SEF open	27.3	5.1	100	3	2.6	no	
4/6/2001	5-06	C	SEF open	49.6	13.1	100	3	7.5	no	
4/6/2001	5-07	A	SEF open	21.4	9.7	100	3	7.8	no	

Date	Plot	Sub-plot	Vegetation class	Litter MC** (dead, %)	Fuel Load (dead, t/ha)	Fuel Continuity %	Litter Depth (cm)	Canopy gap (%)	Fire Spread	Comment fire
4/6/2001	5-07	B	SEF open	16.8	7.8	100	3	14.8	no	Ignition but spread only 2 cm
4/6/2001	5-07	C	SEF open	20.3	10.5	100	3	11.2	no	
4/6/2001	5-09	A	SEF open	13.0	6.5	100	3	13.5	no	
4/7/2001	5-14	A	SEF open	13.5	7.9	100	3	6.5	no	Ignition but spead only 2-3 cm
4/7/2001	5-14	B	SEF open	11.3	3.3	95	3	3.1	no	
4/7/2001	5-14	C	SEF open	14.3	4.0	98	3	8.3	no	Some leaves ignite burn but no spread, high wind upper canopy
4/8/2001	5-15	A	SEF open	28.2	5.0*	100	3	7.5	no	
4/8/2001	5-15	B	SEF open	25.5	10.6	43	3	11.7	no	
4/8/2001	5-15	C	SEF open	22.1	8.9	100	3	5.7	no	
4/8/2001	5-16	A	SEF open	30.1	8.8	100	3	1.3	no	
4/8/2001	5-16	B	SEF open	20.7	7.9	96	3	5.7	no	
4/10/2001	5-25	A	SEF open	39.9	21.5*	81	2	2.3	no	
4/10/2001	5-25	B	SEF open	34.5	17.4*	97	2	2.6	no	
4/10/2001	5-26	A	SEF open	35.0	4.1	…	2	1.8	no	
4/10/2001	5-28	A	SEF open	14.7	5.0	87	3	0.5	no	
4/28/2001	6-02	A	SEF open	17.8	2.8	75	1	…	no	Ignites very well, but no spread. Not enough litter
4/28/2001	6-02	B	SEF open	49.4	16.2	70	1	10.7	no	Many leaves, but no spread
4/28/2001	6-02	C	SEF open	…	7.2	80	1	0.8	no	
4/28/2001	6-02	D	SEF open	28.3	5.9	…	1	0.0	no	

Date	Plot	Sub-plot	Vegetation class	Litter MC** (dead, %)	Fuel Load (dead, t/ha)	Fuel Continuity %	Litter Depth (cm)	Canopy gap (%)	Fire Spread	Comment fire
2/26/2001	2-04	A	Bamboo	7.0	1.9	98	4	2.4	yes	Spread for 1 min to 50 cm perimeter
2/26/2001	2-04	B	Bamboo	6.8	3.4	100	4	1.4	…	
2/26/2001	2-04	C	Bamboo	8.8	21.6	76	4	…	…	
2/27/2001	2-08	A	Bamboo	17.4	21.9*	100	10	3.1	no	Spread for 3 min 25 sec to 48 cm - 20 ml gas used
2/27/2001	2-08	B	Bamboo	13.6	9.5	99	10	16.6	yes	Spread quickly for 37sec to diameter limit*, 20 gas used, lots of litter
2/27/2001	2-08	C	Bamboo	12.0	3.1	91	10	9.1	…	
2/27/2001	2-11	A	Bamboo	7.3	7.8	100	6	20.0	yes	Spread in 44sec to perimeter
2/27/2001	2-11	B	Bamboo	8.7	4.8	100	6	13.5	yes	Spread for about 45sec to perimeter limit
2/27/2001	2-11	C	Bamboo	7.3	5.8	100	6	14.6	…	
2/28/2001	2-16	A	Bamboo	4.8	17.4*	100	6	6.5	yes	Spread for 1min 35sec to 50 cm perimeter limit
2/28/2001	2-16	B	Bamboo	12.2	4.0	96	6	0.5	…	
2/28/2001	2-16	C	Bamboo	8.4	7.2	100	6	6.0	…	
3/7/2001	3-01	A	Bamboo	10.1	4.3*	93	6	9.4	yes	Spread for 1min 19sec to perimeter, burned evenly out from source
3/7/2001	3-01	B	Bamboo	12.6	4.9*	95	6	4.2	…	
3/7/2001	3-01	C	Bamboo	12.2	11.8*	97	6	…	…	
4/9/2001	5-22	A	Bamboo	45.9	19.9*	100	5	0.5	yes	Spread for 2min 27sec to 50 cm diameter limit.
4/9/2001	5-22	B	Bamboo	13.9	4.5	95	5	0.3	no	
4/9/2001	5-22	C	Bamboo	12.9	7.3	96	5	3.1	no	Spread for 40 seconds to 35 cm

Date	Plot	Sub-plot	Vegetation class	Litter MC** (dead, %)	Fuel Load (dead, t/ha)	Fuel Continuity %	Litter Depth (cm)	Canopy gap (%)	Fire Spread	Comment fire
4/9/2001	5-24	A	Bamboo	21.8	12.6	95	6	2.6	no	Spread for 2 minutes to diameter of 42cm
4/9/2001	5-24	B	Bamboo	18.0	8.7	100	6	2.3	no	Spread for 1min 14 sec to 35 cm
4/9/2001	5-24	C	Bamboo	25.5	10.8	100	6	1.3	no	Spread for 10 seconds only, short distance
4/10/2001	5-29	A	Bamboo	1.5	3.0	95	3	34.6	yes	Spread for 30 sec to 50 perimeter
4/10/2001	5-31	A	Bamboo	7.7	4.9	98	3	3.1	no	Spread for 1min 31sec to 15 cm
4/30/2001	6-07	B	Bamboo	27.4	7.1	99	5	0.5	no	Spread for 1min 4sec to 25 cm
4/30/2001	6-07	C	Bamboo	28.1	7.8	93	5	4.9	no	Little spread
2/26/2001	2-02	A	Banana	16.2	7.5	97	8	4.2	no	Spread 3min and 12sec to 18 cm
2/26/2001	2-02	B	Banana	13.9	9.0	99	8	5.5	…	
2/26/2001	2-02	C	Banana	20.9	7.1	100	8	3.1	…	
2/28/2001	2-15	A	Banana	12.1	5.5	56	4	5.2	yes	Spread for 35 sec to 50 cm perimeter
2/28/2001	2-15	B	Banana	6.3	1.6	57	4	3.4	…	
2/28/2001	2-15	C	Banana	7.6	2.8	79	4	…	…	
2/28/2001	2-17	A	Banana	4.4	3.2	77	3	5.2	yes	Spread for 49 sec to perimenter on one banana leaf
2/28/2001	2-17	B	Banana	5.6	2.4	80	3	6.8	…	
2/28/2001	2-17	C	Banana	7.4	5.0	100	3	6.5	…	
3/1/2001	2-19	A	Banana	24.0	2.0	95	3	10.9	no	Spread for about 1min to 10 cm, 20 ml gas used
3/1/2001	2-19	B	Banana	25.3	3.4	100	3	32.5	…	
3/1/2001	2-19	C	Banana	18.5	5.1	93	3	25.0	…	

Date	Plot	Sub-plot	Vegetation class	Litter MC** (dead, %)	Fuel Load (dead, t/ha)	Fuel Continuity %	Litter Depth (cm)	Canopy gap (%)	Fire Spread	Comment fire
3/7/2001	3-02	A	Banana	9.2	4.8	93	3	4.7	no	
3/7/2001	3-02	B	Banana	10.0	4.8	92	3	12.7	…	
3/7/2001	3-02	C	Banana	9.1	4.2	89	3	12.0	…	
3/8/2001	3-05	A	Banana	9.8	3.2	52	5	10.9	yes	Spread for 2min 5sec, but more fuel in ring than in plot
3/8/2001	3-05	B	Banana	10.3	5.0	39	5	7.8	no	Spread for 2min 40 to 30 cm
2/25/2001	2-01	A	Grass	3.6	18.4	100	150	99.8	yes	Spread for 1min 9sec to 50 cm. Fire burned high (1m), full circle
2/25/2001	2-01	B	Grass	5.7	19.6	100	150	97.5	yes	
2/25/2001	2-01	C	Grass	20.1	17.4	100	150	99.8	yes	
2/27/2001	2-07	A	Grass	15.1	4.0	90	33	25.5	no	
2/27/2001	2-07	B	Grass	18.8	9.2	96	33	32.8	no	
2/27/2001	2-07	C	Grass	23.3	7.1	100	33	41.9	no	
2/27/2001	2-13	A	Grass	9.2	9.8	100	105	54.3	yes	Ignited on third try and spread fast, flame height 1 m
2/27/2001	2-13	B	Grass	9.6	18.4	100	105	95.4	…	
2/28/2001	2-14	A	Grass	18.9	14.7	96	805	76.2	yes	On second try, good fire for 1min 54 to perimeter
2/28/2001	2-14	B	Grass	6.6	17.9	100	805	96.2	…	
2/28/2001	2-14	C	Grass	…	17.0	100	805	88.4	…	
2/28/2001	2-18	A	Grass	14.1	24.6*	100	115	98.5	yes	Spread for 1min 1sec to 50 cm, flame height 1m, very hot!
2/28/2001	2-18	B	Grass	23.6	20.2*	100	115	92.0	…	

Date	Plot	Sub-plot	Vegetation class	Litter MC** (dead, %)	Fuel Load (dead, t/ha)	Fuel Continuity %	Litter Depth (cm)	Canopy gap (%)	Fire Spread	Comment fire
2/28/2001	2-18	C	Grass	8.6	22.4*	100	…	99.6	…	
3/8/2001	3-04	A	Grass	9.6	1.5	48	5	35.6	no	Spread for 1min 20sec, only spread 10cm, not enough fuel
3/8/2001	3-04	B	Grass	8.8	0.9	50	5	19.8	…	
3/8/2001	3-04	C	Grass	7.3	1.2	57	…	47.6	…	

* Litter load calculation includes the weight of part of a stick that was inside the plot.

** MC is moisture content

Appendix 5-1 Cloud removal process

Cloud Removal (1992 image)

The 1992 image was the only image in the data set with cloud present. The procedure adopted to remove clouds was as follows.

Step 1: Classification for clouds

Ran a cluster classification of the 1992 image for the purpose of removing clouds. Sixty classes were chosen for the isodata with eigenvector classification. A large number of classes were required in order to separate out the edges of the clouds where many spectral classes were apparent, as well as to try to differentiate as many clouds from shadow classes as possible; ii) identified the cluster classes relating to cloud (i.e., cluster numbers). In the case of the 1992 image of the 60 clusters, over 50 of the cluster classes were identified as being cloud.

Step 2: Creation of cloud Mask[1]

First, isolated out each cluster that has been classified as a cloud cluster. WIT software[2] and specifically the ‘threshold’ function was used to separate cluster classes associated with cloud from other spectral classes. Second, assembled the individual thresholded cluster classes in a new image. Cluster class values were divided by 255 to produce a binary image representing the area of clouds. Third, expanded the edge of the clouds to ensure the outer edge of the clouds which might not have been included in the threshold classes were included in the mask; Fourth, used WIT’s controsion tool to expand individual pixels and diminish the number of flecks in the image; Fifth, inverted the image so that the resultant mask represents an image where the clouds have a value of zero, and all other areas are one.

---

[1] A mask is a binary image (where the only values are either one or zero). The mask is used to remove clouds.

[2] WIT is a software which performs image arithmetic with the advantage of being able to view the image after each calculation so that the operator can monitor exactly what is happening to the image through a series of calculations or adjustments.

Step 3: Applied the mask by multiplying the 1992 image for classification with the newly created mask. Note that areas of the mask with the value of 1 will change to reflect the original DNs of the 1992 image, while areas of the mask with the value of zero will remain as zeros; that is, without a DN. Ultimately, if the 1992 image is subtracted from an image of another year, the areas which carried the zero DNs will simply reflect the DNs of the other image (as opposed to change).

Appendix 5-2 Change vector results

value	#pixels	%change	to or from back ground	pixels of import	Area that stayed the same (30x30m pixel)(km^2)	Area that changed class (30x 30m pixel)(km^2)	% Change	Change Type	Net Change
0	2597240	100.34%							
1	160004	6.18%	160004						
2	13108	0.51%	13108						
3	60512	2.34%	60512						
4	29036	1.12%	29036						
5	17716	0.68%	17716						
6	10696	0.41%	10696						
7	0	0.00%							
8	0	0.00%							
9	0	0.00%							
10	87084	3.36%	87084						
11	122952	4.75%		122952	110656.8		84%	same	
12	19072	0.74%		19072		17164.8	**13%**	**was mid elev dry w/ddf became sun high elev evergreen**	
13	3884	0.15%		3884		3495.6	***3%***	***was mid elev dry w/ddf became sun mid elev evergreen***	
14	336	0.01%		336		302.4	**0%**	**was mid elev dry w/ddf became mid elev evrgrn**	
15	36	0.00%		36		32.4	0%		
16	40	0.00%		40		36	0%		
17	0	0.00%					131688		
18	0	0.00%							
19	0	0.00%							
20	24072	0.93%	24072						

value	#pixels	%change	to or from back ground	pixels of import	Area that stayed the same (30x30m pixel)(km^2)	Area that changed class (30x 30m pixel)(km^2)	% Change	Change Type	Net Change
21	57956	2.24%		57956		52160.4	**20%**	**was sun high elev evrgrn became mid elev dry w/ddf**	**net shift 7% from sun high elev evrgrn to mid elev dry w/ddf**
22	132464	5.12%		132464	119217.6		46%	same	
23	78516	3.03%		78516		70664.4	27%	was sun high elev evrgrn became sun mid elev	net gain 9% was sun high elev evrgrn to sun mid elev evrgrn
24	14180	0.55%		14180		12762	5%	was sun high elev evrgrn became mid elev evrgrn	net 1% shift sun high elev evrgrn became mid elev evrgrn
25	244	0.01%		244		219.6	0%		
26	2320	0.09%		2320		2088	1%		
27	0	0.00%					285680		
28	0	0.00%							
29	0	0.00%							
30	130240	5.03%	130240						
31	38584	1.49%		38584		34725.6	***10%***	***was sun mid elev evrgrn became mid elev dry w/ddf***	***net shift 7% was sun mid elev became mid elev dry w/ddf***
32	63960	2.47%		63960		57564	16%	was sun mid elev became sun high elev	
33	206284	7.97%		206284	185655.6		53%	same	
34	72616	2.81%		72616		65354.4	19%	was sun mid elev became mid elev	
35	992	0.04%		992		892.8	0%		
36	8992	0.35%		8992		8092.8	2%	was sun mid elev evrgrn became shadow	
37	0	0.00%					391428		

value	#pixels	%change	to or from back ground	pixels of import	Area that stayed the same (30x30m pixel)(km²)	Area that changed class (30x 30m pixel)(km²)	% Change	Change Type	Net Change
38	0	0.00%							
39	0	0.00%							
40	114928	4.44%	114928						
41	3972	0.15%		3972		3574.8	***1%***	***was mid elev evrgrn became mid elev dry w/ddf***	
42	16920	0.65%		16920		15228	4%	was mid elev evrgrn became sun high elev evrgrn	
43	120160	4.64%		120160		108144	27%	was mid elev became sun mid elev	net shift 8% was mid elev evrgrn became sun mid elev evrgrn
44	233292	9.01%		233292	209962.8		53%	same	
45	6848	0.26%		6848		6163.2	2%	was mid elev evrgrn became shadow w/ deciduous	
46	61088	2.36%		61088		54979.2	14%	was mid elev became shadow	
47	0	0.00%					442280		
48	0	0.00%							
49	0	0.00%							
50	38540	1.49%	38540						
51	336	0.01%		336		302.4	0%		
52	1184	0.05%		1184		1065.6	1%		
53	4728	0.18%		4728		4255.2	2%		
54	18720	0.72%		18720		16848	8%	was shadow w/ deciduous became mid elev evrgrn	net shift 6% shadow w/ deciduous became mid elev evrgrn

value	#pixels	%change	to or from back ground	pixels of import	Area that stayed the same (30x30m pixel)(km^2)	Area that changed class (30x 30m pixel)(km^2)	% Change	Change Type	Net Change
55	125540	4.85%		125540	112986		54%	same	
56	80204	3.10%		80204		72183.6	35%	was shadow/deciduous became shadow	net gain 24% was shadow w/ deciduous became shadow
57	0	0.00%					230712		
58	0	0.00%							
59	0	0.00%							
60	69908	2.70%	69908						
61	908	0.04%		908		908	0%		
62	4184	0.16%		4184		4184	1%		
63	23472	0.91%		23472		23472	7%	was shadow became sun mid elev evrgrn	net shift 5% shadow became sun mid elev evrgrn
64	113760	4.40%		113760		113760	34%	was shadow became mid elev	net gain 20% was shadow became mid elev evergreen
65	36300	1.40%		36300		36300	11%	was shadow became shadow w/deciduous	
66	157492	6.08%		157492	141742.8		47%	same	
	2588380	**100.00%**	**755844**	**2E+06**	**978024**	**854512**			

The Table was produced to help interpret results from the change class analysis. The table was produced as follows:

Step 1: Exported histogram values (from the union) for each class (i.e., 0 – 66) to Excel spreadsheet.

Step 2: Removed pixels that were background and remained background (i.e., values 0 to 6), as well as removed the pixels that varied to and from the background class, approximately 29 % of the total pixels.

Step 3: Listed the remaining pixels of Importance.

Step 4: Listed the number of evergreen zone pixels that stayed the same for each class; for example code 10 + 1 = 11 (no change). Codes 11, 22, 33, 44, 55, 66 are all ‘no change’ categories.

Step 5: Calculated a percent change by dividing the number of evergreen pixels that changed class with total of pixels that stayed the same or changed class.

Step 6: Labeled the cluster classes so the direction of change could be identified; *i.e.*, from cluster class ‘mid elev dry w/ddf’ to cluster class ‘sun high elev evergreen’.

Step 7: Calculated net change between significant change classes. Omitted the change classes for which it was suspected that sun angle or shadow was the primary influence. For example, if from sun mid elevation to mid elevation then ignored the change pixels as a product of sun angle and time of day. The same with the shadow classes. In the final product, only evergreen to deciduous classes were counted and vice versa as long as sun and shadow were not considered the main cause of the change.

Step 8: Produced an output map showing the net shift of pixels (evergreen to deciduous as it turned out).

Appendix 6-1 Keetch-Byram Drought Index calculation sample

Date	Temp Max	RH 1:00 PM	Rain (mm) 24 Hrs	KBDI yesterday	Net Rain (mm) 24 Hrs	KBDI yesterday - 10x Net. Rain	Drought Factor	KBDI Today
								0
6/23/1980	28		12	0	7	-67	52	0
6/24/1980	34		0	0	0	0	90	90
6/25/1980	30		0	90	0	90	61	150
6/26/1980	32		0	150	0	150	68	218
6/27/1980	31		0	218	0	218	59	277
6/28/1980	27		0	277	0	277	38	315
6/29/1980	30		11	315	6	254	53	307
6/30/1980	30		1	307	0	307	54	361
6/1/1980	33		2	361	0	361	67	427
7/2/1980	32		0	427	0	427	61	488
7/3/1980	34		0	488	0	488	68	556
7/4/1980	34		0	556	0	556	68	624
7/5/1980	31		0	624	0	624	48	672
7/6/1980	33		23	672	18	493	54	547
7/7/1980	33		0	547	0	547	62	609
7/8/1980	35		2	609	0	609	69	678
7/9/1980	32		0	678	0	678	49	726
7/10/1980	32		0	726	0	726	49	775
7/11/1980	34		0	775	0	775	55	830
7/12/1980	33		0	830	0	830	50	880
7/13/1980	32		0	880	0	880	43	923
7/14/1980	30		7	923	2	902	34	936
7/15/1980	32		0	936	0	936	41	978
7/16/1980	30		3	978	0	978	32	1010
7/17/1980	33		11	1010	6	953	42	995
7/18/1980	34		2	995	0	995	45	1040
7/19/1980	31		1	1040	0	1040	32	1072
7/20/1980	29		0	1072	0	1072	27	1099
7/21/1980	32		25	1099	20	895	33	928
7/22/1980	30		21	928	16	772	34	806
7/23/1980	32		0	806	0	806	45	851
7/24/1980	32		0	851	0	851	43	894
7/25/1980	32		0	894	0	894	41	935
7/26/1980	32		0	935	0	935	40	975
7/27/1980	32		0	975	0	975	38	1013
7/28/1980	32		0	1013	0	1013	37	1050
7/29/1980	29		51	1050	46	592	27	619
7/30/1980	30		8	619	3	588	44	632
7/31/1980	31		1	632	0	632	48	680
7/1/1980	30		3	680	0	680	40	720
8/2/1980	30		13	720	8	643	39	681
8/3/1980	31		1	681	0	681	46	727
8/4/1980	32		0	727	0	727	49	777
8/5/1980	34		0	777	0	777	57	834
8/6/1980	32		0	834	0	834	45	879

Date	Temp Max	RH 1:00 PM	Rain (mm) 24 Hrs	KBDI yesterday	Net Rain (mm) 24 Hrs	KBDI yesterday - 10x Net. Rain	Drought Factor	KBDI Today
8/7/1980	34		0	879	0	879	50	929
8/8/1980	33		0	929	0	929	43	973
8/9/1980	31		0	973	0	973	34	1007
8/10/1980	33		0	1007	0	1007	40	1047
8/11/1980	32		0	1047	0	1047	37	1084
8/12/1980	32		0	1084	0	1084	35	1119
8/13/1980	33		0	1119	0	1119	36	1155
8/14/1980	33		0	1155	0	1155	34	1190
8/15/1980	33		4	1190	0	1190	33	1222
8/16/1980	32		7	1222	2	1199	30	1229
8/17/1980	32		10	1229	5	1177	28	1206
8/18/1980	33		0	1206	0	1206	34	1239
8/19/1980	33		8	1239	3	1208	32	1241
8/20/1980	33		26	1241	21	1026	31	1057
8/21/1980	30		0	1057	0	1057	28	1086
8/22/1980	30		2	1086	0	1086	28	1113
8/23/1980	31		0	1113	0	1113	31	1144
8/24/1980	31		0	1144	0	1144	30	1174
8/25/1980	33		13	1174	8	1097	34	1131
8/26/1980	31		10	1131	5	1079	29	1108
8/27/1980	32		0	1108	0	1108	33	1141
8/28/1980	32		0	1141	0	1141	32	1173
8/29/1980	32		0	1173	0	1173	30	1203
8/30/1980	33		0	1203	0	1203	32	1235
8/31/1980	26		7	1235	2	1219	15	1235
8/1/1980	30		17	1235	12	1119	23	1143
9/2/1980	28		1	1143	0	1143	22	1165
9/3/1980	34		0	1165	0	1165	39	1204
9/4/1980	34		9	1204	4	1165	37	1202
9/5/1980	33		1	1202	0	1202	34	1236
9/6/1980	25		11	1236	6	1172	14	1186
9/7/1980	30		8	1186	3	1160	26	1186
9/8/1980	25		8	1186	3	1160	15	1175
9/9/1980	26		34	1175	29	885	17	902
9/10/1980	31		3	902	0	902	37	939
9/11/1980	31		5	939	0	938	37	975
9/12/1980	30		0	975	0	975	31	1006
9/13/1980	31		0	1006	0	1006	35	1041
9/14/1980	31		0	1041	0	1041	34	1074
9/15/1980	31		0	1074	0	1074	32	1107
9/16/1980	32		0	1107	0	1107	33	1139
9/17/1980	32		0	1139	0	1139	33	1173
9/18/1980	31		2	1173	0	1173	28	1200
9/19/1980	30		3	1200	0	1200	25	1226
9/20/1980	30		30	1226	25	971	23	994
9/21/1980	30		1	994	0	994	30	1024
9/22/1980	29		1	1024	0	1024	28	1052
9/23/1980	27		0	1052	0	1052	22	1074

Date	Temp Max	RH 1:00 PM	Rain (mm) 24 Hrs	KBDI yesterday	Net Rain (mm) 24 Hrs	KBDI yesterday - 10x Net. Rain	Drought Factor	KBDI Today
9/24/1980	28		9	1074	4	1033	23	1056
9/25/1980	29		12	1056	7	981	27	1008
9/26/1980	29		2	1008	0	1008	27	1035
9/27/1980	30		0	1035	0	1035	31	1066
9/28/1980	30		13	1066	8	989	30	1018
9/29/1980	30		40	1018	35	670	31	701
9/30/1980	26		40	701	35	349	27	377
9/1/1980	26		53	377	48	-102	34	0
10/2/1980	26		13	0	8	-82	42	0
10/3/1980	28		11	0	6	-57	49	0
10/4/1980	29		13	0	8	-85	57	0
10/5/1980	24		20	0	15	-153	34	0
10/6/1980	34		26	0	21	-214	94	0
10/7/1980	38		35	0	30	-301	137	0
10/8/1980	30		0	0	0	0	64	64
10/9/1980	30		0	64	0	64	62	125
10/10/1980	30		0	125	0	125	60	185
10/11/1980	32		27	185	22	-39	67	28
10/12/1980	30		0	28	0	28	63	91
10/13/1980	30		0	91	0	91	61	151
10/14/1980	30		0	151	0	151	59	210
10/15/1980	38		8	210	3	176	123	299
10/16/1980	28		16	299	11	189	44	233
10/17/1980	30		0	233	0	233	56	290
10/18/1980	30		0	290	0	290	55	344
10/19/1980	30		23	344	18	160	53	213
10/20/1980	30		0	213	0	213	57	270
10/21/1980	30		0	270	0	270	55	325
10/22/1980	28		10	325	5	276	43	319
10/23/1980	28		0	319	0	319	43	363
10/24/1980	31		7	363	2	347	57	404
10/25/1980	31		5	404	0	404	56	460
10/26/1980	30		0	460	0	460	49	509
10/27/1980	30		3	509	0	509	47	556
10/28/1980	30		0	556	0	556	46	602
10/29/1980	29		0	602	0	602	40	642
10/30/1980	28		0	642	0	642	35	677
10/31/1980	30		0	677	0	677	42	719
10/1/1980	30		0	719	0	719	41	760
11/2/1980	18		145	760	140	-643	10	0
11/3/1980	18		0	0	0	0	17	17
11/4/1980	18		0	17	0	17	17	34
11/5/1980	18		0	34	0	34	17	50
11/6/1980	18		0	50	0	50	17	67
11/7/1980	18		0	67	0	67	16	83
11/8/1980	18		0	83	0	83	16	100
11/9/1980	18		0	100	0	100	16	116
11/10/1980	18		0	116	0	116	16	132

Date	Temp Max	RH 1:00 PM	Rain (mm) 24 Hrs	KBDI yesterday	Net Rain (mm) 24 Hrs	KBDI yesterday - 10x Net. Rain	Drought Factor	KBDI Today
11/11/1980	18		0	132	0	132	16	148
11/12/1980	18		0	148	0	148	16	163
11/13/1980	18		0	163	0	163	16	179
11/14/1980	18		0	179	0	179	15	194
11/15/1980	19		0	194	0	194	16	211
11/16/1980	18		0	211	0	211	14	225
11/17/1980	19		0	225	0	225	15	240
11/18/1980	19		0	240	0	240	16	256
11/19/1980	20		0	256	0	256	18	274
11/20/1980	20		0	274	0	274	17	291
11/21/1980	18		0	291	0	291	14	306
11/22/1980	18		0	306	0	306	14	320
11/23/1980	18		0	320	0	320	14	334
11/24/1980	18		0	334	0	334	14	348
11/25/1980	18		0	348	0	348	14	362
11/26/1980	18		0	362	0	362	14	376
11/27/1980	18		0	376	0	376	14	390
11/28/1980	17		0	390	0	390	11	401
11/29/1980	18		0	401	0	401	14	415
11/30/1980	16		0	415	0	415	9	423
11/1/1980	20		0	423	0	423	16	440
12/2/1980	27		0	440	0	440	34	474
12/3/1980	28		0	474	0	474	39	514
12/4/1980	27		0	514	0	514	35	548
12/5/1980	28		0	548	0	548	37	586
12/6/1980	29		0	586	0	586	40	626
12/7/1980	29		0	626	0	626	39	665
12/8/1980	30		0	665	0	665	42	708
12/9/1980	30		0	708	0	708	39	747
12/10/1980	28		0	747	0	747	32	779
12/11/1980	28		0	779	0	779	31	810
12/12/1980	28		0	810	0	810	30	840
12/13/1980	28		0	840	0	840	30	870
12/14/1980	28		0	870	0	870	29	898
12/15/1980	28		0	898	0	898	28	926
12/16/1980	28		0	926	0	926	27	954
12/17/1980	28		0	954	0	954	27	981
12/18/1980	29		0	981	0	981	28	1009
12/19/1980	28		0	1009	0	1009	25	1034
12/20/1980	28		0	1034	0	1034	25	1058
12/21/1980	28		0	1058	0	1058	24	1082
12/22/1980	28		0	1082	0	1082	23	1106
12/23/1980	28		0	1106	0	1106	23	1129
12/24/1980	28		0	1129	0	1129	22	1151
12/25/1980	28		0	1151	0	1151	21	1172
12/26/1980	28		0	1172	0	1172	21	1193
12/27/1980	27		0	1193	0	1193	19	1211
12/28/1980	27		0	1211	0	1211	17	1229

Date	Temp Max	RH 1:00 PM	Rain (mm) 24 Hrs	KBDI yesterday	Net Rain (mm) 24 Hrs	KBDI yesterday - 10x Net. Rain	Drought Factor	KBDI Today
12/29/1980	26		0	1229	0	1229	16	1245
12/30/1980	28		0	1245	0	1245	19	1263
12/31/1980	28		0	1263	0	1263	19	1282
12/1/1980	28		0	1282	0	1282	18	1301
1/2/1981	27		0	1301	0	1301	17	1318
1/3/1981	27		0	1318	0	1318	17	1334
1/4/1981	27		0	1334	0	1334	16	1350
1/5/1981	27		0	1350	0	1350	16	1366
1/6/1981	27		0	1366	0	1366	15	1382
1/7/1981	30		0	1382	0	1382	20	1401
1/8/1981	27		0	1401	0	1401	15	1416
1/9/1981	30		0	1416	0	1416	19	1434
1/10/1981	28		0	1434	0	1434	15	1449
1/11/1981	29		0	1449	0	1449	15	1464
1/12/1981	26		0	1464	0	1464	11	1474
1/13/1981	24		0	1474	0	1474	8	1483
1/14/1981	24		0	1483	0	1483	9	1492
1/15/1981	27		0	1492	0	1492	12	1504
1/16/1981	28		0	1504	0	1504	12	1516
1/17/1981	27		0	1516	0	1516	12	1528
1/18/1981	27		0	1528	0	1528	11	1539
1/19/1981	27		0	1539	0	1539	11	1551
1/20/1981	27		0	1551	0	1551	11	1561
1/21/1981	27		0	1561	0	1561	11	1572
1/22/1981	27		0	1572	0	1572	10	1583
1/23/1981	28		0	1583	0	1583	11	1593
1/24/1981	22		0	1593	0	1593	5	1599
1/25/1981	28		0	1599	0	1599	10	1609
1/26/1981	29		0	1609	0	1609	11	1619
1/27/1981	28		0	1619	0	1619	9	1629
1/28/1981	28		0	1629	0	1629	10	1638
1/29/1981	30		0	1638	0	1638	11	1649
1/30/1981	30		0	1649	0	1649	11	1660
1/31/1981	27		0	1660	0	1660	8	1668
1/1/1981	27		0	1668	0	1668	8	1676
2/2/1981	32		0	1676	0	1676	13	1689
2/3/1981	32		0	1689	0	1689	12	1701
2/4/1981	32		0	1701	0	1701	12	1713
2/5/1981	32		0	1713	0	1713	11	1724
2/6/1981	32		0	1724	0	1724	11	1735
2/7/1981	32		0	1735	0	1735	10	1746
2/8/1981	32		0	1746	0	1746	10	1756
2/9/1981	32		0	1756	0	1756	10	1765
2/10/1981	30		0	1765	0	1765	7	1772
2/11/1981	32		0	1772	0	1772	9	1781
2/12/1981	30		0	1781	0	1781	7	1788
2/13/1981	31		0	1788	0	1788	7	1795
2/14/1981	32		0	1795	0	1795	8	1803

Date	Temp Max	RH 1:00 PM	Rain (mm) 24 Hrs	KBDI yesterday	Net Rain (mm) 24 Hrs	KBDI yesterday - 10x Net. Rain	Drought Factor	KBDI Today
2/15/1981	31		0	1803	0	1803	7	1810
2/16/1981	32		0	1810	0	1810	7	1817
2/17/1981	32		0	1817	0	1817	7	1824
2/18/1981	32		0	1824	0	1824	7	1831
2/19/1981	34		0	1831	0	1831	8	1839
2/20/1981	33		0	1839	0	1839	7	1846
2/21/1981	32		0	1846	0	1846	6	1852
2/22/1981	35		0	1852	0	1852	7	1859
2/23/1981	33		0	1859	0	1859	6	1865
2/24/1981	34		0	1865	0	1865	6	1871
2/25/1981	35		0	1871	0	1871	7	1878
2/26/1981	32		0	1878	0	1878	5	1882
2/27/1981	32		0	1882	0	1882	5	1887
2/28/1981	32		20	1887	15	1736	4	1741
2/1/1981	32		23	1741	18	1560	10	1570
3/2/1981	32		0	1570	0	1570	17	1587
3/3/1981	32		0	1587	0	1587	16	1603
3/4/1981	32		0	1603	0	1603	15	1618
3/5/1981	32		0	1618	0	1618	15	1633
3/6/1981	32		0	1633	0	1633	14	1646
3/7/1981	32		0	1646	0	1646	14	1660
3/8/1981	30		0	1660	0	1660	10	1670
3/9/1981	33		4	1670	0	1670	14	1684
3/10/1981	32		0	1684	0	1684	12	1696
3/11/1981	30		12	1696	7	1624	9	1633
3/12/1981	32		0	1633	0	1633	14	1647
3/13/1981	19		0	1647	0	1647	3	1651
3/14/1981	32		49	1651	44	1210	14	1224
3/15/1981	32		0	1224	0	1224	30	1254
3/16/1981	35		20	1254	15	1101	37	1138
3/17/1981	32		0	1138	0	1138	33	1171
3/18/1981	32		0	1171	0	1171	32	1203
3/19/1981	36		0	1203	0	1203	45	1249
3/20/1981	32		0	1249	0	1249	29	1278
3/21/1981	32		0	1278	0	1278	28	1306
3/22/1981	32		0	1306	0	1306	27	1333
3/23/1981	32		0	1333	0	1333	26	1359
3/24/1981	34		0	1359	0	1359	29	1387
3/25/1981	36		0	1387	0	1387	33	1421
3/26/1981	36		0	1421	0	1421	33	1454
3/27/1981	35		0	1454	0	1454	28	1482
3/28/1981	32		0	1482	0	1482	20	1502
3/29/1981	32		0	1502	0	1502	19	1521
3/30/1981	32		0	1521	0	1521	19	1540
3/31/1981	32		0	1540	0	1540	18	1558
3/1/1981	32		23	1558	18	1379	17	1396
4/2/1981	33		20	1396	15	1243	26	1269
4/3/1981	35		0	1269	0	1269	38	1307

Appendix 6-2 Drought Code (Canadian Fire Weather Index) calculation sample

Date	Temp max KNR	Rain KNR	CDC
			0
6/22/1980	28.0	12	8
6/23/1980	33.5	0	18
6/24/1980	30.0	0	27
6/25/1980	31.5	0	36
6/26/1980	30.5	0	45
6/27/1980	26.5	0	53
6/28/1980	30.0	11	44
6/29/1980	30.0	1	53
6/30/1980	32.5	2	62
7/1/1980	32.0	0	72
7/2/1980	33.5	0	81
7/3/1980	34.0	0	91
7/4/1980	31.0	0	100
7/5/1980	32.5	23	67
7/6/1980	33.0	0	77
7/7/1980	34.5	2	87
7/8/1980	31.5	0	96
7/9/1980	32.0	0	106
7/10/1980	33.5	0	116
7/11/1980	33.0	0	125
7/12/1980	32.0	0	135
7/13/1980	30.0	7	131
7/14/1980	32.0	0	141
7/15/1980	30.0	3	150
7/16/1980	33.0	11	138
7/17/1980	33.5	2	148
7/18/1980	30.5	1	157
7/19/1980	29.0	0	166
7/20/1980	31.5	25	120
7/21/1980	30.0	21	90
7/22/1980	31.7	0	99

Date	Temp max KNR	Rain KNR	CDC
7/23/1980	31.7	0	108
7/24/1980	31.7	0	118
7/25/1980	31.7	0	127
7/26/1980	31.7	0	137
7/27/1980	31.7	0	146
7/28/1980	29.0	51	53
7/29/1980	30.0	8	50
7/30/1980	31.0	1	59
7/31/1980	29.5	3	68
8/1/1980	29.5	13	56
8/2/1980	31.0	1	64
8/3/1980	32.0	0	73
8/4/1980	34.0	0	82
8/5/1980	32.0	0	91
8/6/1980	33.5	0	100
8/7/1980	32.5	0	109
8/8/1980	30.5	0	117
8/9/1980	32.5	0	126
8/10/1980	32.0	0	135
8/11/1980	32.0	0	144
8/12/1980	32.5	0	152
8/13/1980	32.5	0	161
8/14/1980	32.5	4	163
8/15/1980	32.0	7	158
8/16/1980	31.5	10	146
8/17/1980	33.0	0	155
8/18/1980	33.0	8	149
8/19/1980	32.5	26	102
8/20/1980	29.5	0	111
8/21/1980	29.5	2	119
8/22/1980	31.0	0	128
8/23/1980	31.0	0	136
8/24/1980	32.5	13	120
8/25/1980	30.5	10	110
8/26/1980	31.5	0	119

Date	Temp max KNR	Rain KNR	CDC
8/27/1980	31.5	0	128
8/28/1980	31.5	0	136
8/29/1980	32.5	0	145
8/30/1980	25.5	7	141
8/31/1980	29.5	17	116
9/1/1980	28.0	1	123
9/2/1980	34.0	0	130
9/3/1980	34.0	9	122
9/4/1980	33.0	1	130
9/5/1980	25.0	11	114
9/6/1980	30.0	8	108
9/7/1980	25.0	8	101
9/8/1980	26.0	34	45
9/9/1980	30.5	3	49
9/10/1980	31.0	5	49
9/11/1980	29.5	0	56
9/12/1980	31.0	0	64
9/13/1980	31.0	0	71
9/14/1980	31.0	0	78
9/15/1980	31.5	0	86
9/16/1980	32.0	0	93
9/17/1980	30.5	2	100
9/18/1980	30.0	3	107
9/19/1980	29.5	30	57
9/20/1980	29.5	1	64
9/21/1980	29.0	1	71
9/22/1980	27.0	0	77
9/23/1980	27.5	9	69
9/24/1980	29.0	12	56
9/25/1980	28.5	2	62
9/26/1980	30.0	0	69
9/27/1980	30.0	13	55
9/28/1980	30.0	40	7
9/29/1980	26.0	40	6
9/30/1980	26.0	53	6

Date	Temp max KNR	Rain KNR	CDC
10/1/1980	26.0	13	5
10/2/1980	27.5	11	6
10/3/1980	29.0	13	6
10/4/1980	24.0	20	5
10/5/1980	34.0	26	7
10/6/1980	38.0	35	8
10/7/1980	30.1	0	14
10/8/1980	30.1	0	20
10/9/1980	30.1	0	26
10/10/1980	31.5	27	6
10/11/1980	30.1	0	12
10/12/1980	30.1	0	19
10/13/1980	30.1	0	25
10/14/1980	38.0	8	21
10/15/1980	28.0	16	6
10/16/1980	30.1	0	12
10/17/1980	30.1	0	18
10/18/1980	30.1	23	6
10/19/1980	30.1	0	12
10/20/1980	30.0	0	18
10/21/1980	28.0	10	10
10/22/1980	28.0	0	16
10/23/1980	31.0	7	13
10/24/1980	31.0	5	15
10/25/1980	30.0	0	21
10/26/1980	30.0	3	24
10/27/1980	30.1	0	30
10/28/1980	29.0	0	36
10/29/1980	28.0	0	42
10/30/1980	30.1	0	48
10/31/1980	30.1	0	54
11/1/1980	18.0	145	3
11/2/1980	18.5	0	6
11/3/1980	18.5	0	9
11/4/1980	18.5	0	12

Date	Temp max KNR	Rain KNR	CDC
11/5/1980	18.5	0	15
11/6/1980	18.5	0	18
11/7/1980	18.5	0	21
11/8/1980	18.5	0	24
11/9/1980	18.5	0	27
11/10/1980	18.5	0	30
11/11/1980	18.5	0	33
11/12/1980	18.5	0	36
11/13/1980	18.5	0	39
11/14/1980	19.0	0	42
11/15/1980	18.0	0	45
11/16/1980	18.5	0	48
11/17/1980	19.0	0	51
11/18/1980	20.0	0	55
11/19/1980	19.5	0	58
11/20/1980	18.5	0	61
11/21/1980	18.5	0	64
11/22/1980	18.5	0	67
11/23/1980	18.5	0	70
11/24/1980	18.5	0	73
11/25/1980	18.5	0	76
11/26/1980	18.5	0	79
11/27/1980	17.0	0	82
11/28/1980	18.5	0	85
11/29/1980	15.5	0	87
11/30/1980	20.0	0	91
12/1/1980	26.5	0	95
12/2/1980	28.0	0	100
12/3/1980	27.0	0	105
12/4/1980	28.0	0	109
12/5/1980	29.0	0	114
12/6/1980	29.0	0	119
12/7/1980	30.0	0	124
12/8/1980	29.5	0	129
12/9/1980	27.9	0	134

Date	Temp max KNR	Rain KNR	CDC
12/10/1980	27.9	0	139
12/11/1980	27.9	0	143
12/12/1980	27.9	0	148
12/13/1980	27.9	0	153
12/14/1980	27.9	0	158
12/15/1980	27.9	0	162
12/16/1980	28.0	0	167
12/17/1980	28.5	0	172
12/18/1980	27.9	0	177
12/19/1980	27.9	0	181
12/20/1980	27.9	0	186
12/21/1980	27.9	0	191
12/22/1980	27.9	0	195
12/23/1980	27.9	0	200
12/24/1980	27.5	0	205
12/25/1980	27.9	0	210
12/26/1980	27.0	0	214
12/27/1980	26.5	0	219
12/28/1980	26.0	0	223
12/29/1980	27.5	0	228
12/30/1980	27.9	0	232
12/31/1980	27.9	0	237
1/1/1981	27.4	0	242
1/2/1981	27.4	0	246
1/3/1981	27.4	0	251
1/4/1981	27.4	0	256
1/5/1981	27.4	0	260
1/6/1981	30.0	0	265
1/7/1981	27.4	0	270
1/8/1981	30.0	0	275
1/9/1981	28.0	0	280
1/10/1981	28.5	0	285
1/11/1981	25.5	0	289
1/12/1981	23.5	0	293
1/13/1981	24.0	0	297