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DISSERTATION

FUEL MODEL AND FIRE BEHAVIOR PREDICTION IN DRY DECIDUOUS DIPTEROCARP FOREST AT HUAI KHA KHAENG WILDLIFE SANCTUARY, UTHAI THANI PROVINCE

KRAISORN WIRIYA

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The objectives of the study were to determine fuel properties, fire behaviors and to construct fuel models for predicting fire behavior in the dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary, Uthai Thani Province. The nested sample plots of fuel data collection were laid in line plots systematic sampling for fuel properties and ecological data collection at the sample sites, where were divided into 3 sub-sites according to fuel bed characteristics namely: litter fuel, litter with short grass fuel and tall grass fuel. Totally twenty eight burning plots with 200m x 200m size of each were established in experimental burning site for fire behavior data collection. Rothermel's fire spread model was applied to predict rate of fire spread and Byram's model was applied to determine fireline intensity and flame length.

The results revealed that fuel types were classified into 2 categories: dead and live; dead fuels were litter, twig and dead herb; live fuels were live herb and undergrowth. Fuel model was classified into 3 models namely litter, litter with short grass and tall grass. Averages of rate of fire spread, fireline intensity and flame length for litter fuel model were 1.34 m min^{-1}, 184.71 kW m^{-1} and 0.86 m, respectively, averages of those for litter with short fuel model were 2.75 m min^{-1}, 414.76 kW m^{-1} and 1.27 m, respectively and averages of those for tall grass fuel model were 2.39 m min^{-1}, 408.61 kW m^{-1} and 1.24 m, respectively. Fire behavior predictions in conditions of wind velocities and slopes ranged from 0 to 12 km h^{-1} and from 0 to 40 per cent, respectively: for litter fuel model; rates of fire spread ranged from 0.79 to 6.25 m min^{-1}, fireline intensities ranged from 109 to 861 kWm^{-1}, flame lengths ranged from 0.69 to 1.79 m: for litter with short grass fuel model; rates of fire spread ranged from 0.86 to 10.72 m min^{-1}, fireline intensities ranged from 129 to 1,611 kWm^{-1}, flame lengths ranged from 0.75 to 2.39 m and for tall grass fuel model; rates of fire spread ranged from 0.88 to 12.41 m min^{-1}, fireline intensities ranged from 149 to 2,115 kWm^{-1}, flame lengths ranged from 0.80 to 2.71 m. Fire behaviors ranged from low to moderate fire severities, that could generally be attacked at the head, flanks and rear fires by firefighters using hand tools. Hand line with at least 4 m wide could hold the fire. Essentially, the study is firstly conducted in the area and it would be very useful information for forest fire control planning in the area.

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Student's signature Thesis Advisor's signature

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Finally, the dissertation would be useful for forest fire study and forest fire control planning in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary and in other sites with the same condition.

Kraisorn Wiriya

May, 2009

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FUEL MODEL AND FIRE BEHAVIOR PREDICTION IN DRY DECIDUOUS DIPTEROCARP FOREST AT HUAI KHA KHAENG WILDLIFE SANCTUARY, UTHAI THANI PROVINCE

INTRODUCTION

Forest fire in Thailand is occurred annually during dry period in deciduous forest. The daily fire or inappropriate fire is an important problem that damages and decreases richness and diversity of forest ecosystem such as decrease in forest health, tree quality, soil fertility and seedling. Consequently, the fire affects to surface run off, failed succession and danger to wildlife. In addition, forest fire does not cause only problem to forest but also to human and global such as smoke that are harmful to human health, cause of accident on high way, interrupt air traffic, global warming and climatic change. On the other hand, under the proper fire control is good for maintaining deciduous forest especially dry deciduous dipterocarp forest.

Huai Kha Khaeng Wildlife Sanctuary and Buffer Zone Forest, that located around the eastern border of Huai Kha Khaeng Wildlife Sanctuary have usually been burnt in dry period. Forest fire was occurred from mid December until late April and the peak fire season was in March. The fire has usually started in dry deciduous dipterocarp forest located in the Buffer Zone areas during the early fire season and spreads into mixed deciduous forest later. In addition, in the extreme drought year the fire would burn in dry evergreen forest at the core of Huai Kha Khaeng Wildlife Sanctuary as well. The fire mostly burns at the same place and time in every year.
As a result, the forest fire has been controlled annually in Huai Kha Khaeng Wildlife Sanctuary and Buffer Zone Forest, in order to conserve high diversity of forest tree species and wildlife resources.

Forest fire control has been conducted at Huai Kha Khaeng Wildlife Sanctuary since 1975. The main responsibility is to control and suppress fire in both of the core of the Wildlife Sanctuary and it's Buffer Zone area. The employed fire control and suppress techniques were based on the individual experience and skill of the staff. However, there is no any tool to be used for predicting fire behavior and assessing the hazard of the forest fire. Although there were many researches about fire and fuel were conducted in Huai Kha Khaeng Wildlife Sanctuary, but the prediction of forest fire behavior was still not documented. Therefore the research on fire behavior prediction in Huai Kha Khaeng Wildlife Sanctuary and Buffer Zone Forest is necessary. The results of the study could be applied for predicting fire behavior which included rate of spread, fire intensity, flame length, burning area and perimeter growths and for fire suppression planning. In addition, the fire behavior information was not only employed for formulating the fire control plan, but also for determining the benefit from early burning.

The main objective of this research is to predict fire behavior in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary, Uthai Thani Province. The study employed Rothermel's fire spread model for predicting rate of fire spread, and used Byram's model for predicting fireline intensity and flame length. Moreover, Van Wagner's fire growth model was also applied for predicting burning area and perimeter growths.

OBJECTIVES

The objectives of the study were as follows:

1. To determine fuel properties and fire behaviors in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary, Uthai Thani Province.

2. To construct fuel model and to predict fire behavior, burning area and perimeter growths of the fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary, Uthai Thani Province.

LITERATURE REVIEW

A forest fire is an unclosed and freely spreading combustion which consumes the natural fuels of a forest. i.e., duff, grass, weeds, brush, and tree (Brown and Davis, 1973). Forest fire occurred in three principle forms, the differences are depended essentially on their modes of spread and their positions in relation to the ground surface. Brown and Davis (1973) recognized three kinds of forest fire, based on the degree to which fuels from mineral soil upward to tree tops are involved in combustion; ground fire, surface fire and crown fires. Ground fire consumes the organic material beneath the surface litter of the forest floor such as duff, muck or peat. The fire spreading in and consuming such material is a ground fire. Surface fire is a fire that burns surface litter, other loose debris of the forest floor and small vegetation. Crown fire is a fire that advances from top to top of trees or shrubs more or less independently of the surface fire.

1. Fire behavior

Fire behavior is generally defined as the manner in which fuel ignites, flame develops, fire spreads and exhibits other related phenomena such as fire whirls (Countryman, 1964) as determined by the interaction of fuels, weather, and topography (Brown and Davis, 1973). This definition is like the National Wildfire Coordinating group as " the manner in which a fire reacts to the influences of fuel, weather and topography". From this definition, the primary factors that influence fire behaviors are fuel, weather and topography. The popular fire behavior phenomena are rate of spread, fire intensity and flame length.

Rate of spread is the horizontal distance that the flame zone moves per unit of time and usually refers to the head fire segment of the fire perimeter. It is the primary description of fire behavior and its prediction is crucial to achieve effectiveness in both wildfire control and application of prescribed burning (Mendes-Lopes, 1998). However, rate of spread can be measured from any point on the fire perimeter in a direction that is perpendicular to the perimeter. Because rate of spread can vary significantly over the area of fire, it is generally taken to be an average value over some given period of time. The fastest rate of spread is along the forward moving perimeter located at the head of the fire. The slowest rate of spread will be found on the back side of perimeter. The rates of spread along the flanks will be intermediate between the heading and backing rates of spread. Rate of spread can easily be estimated by timing the passage of the flaming front between two landmarks of known distance apart. It is most commonly expressed in meter per minute or kilometer per hour.

Fire intensity is a measurement of rate of energy which is released by a fire. It includes both radiant and conventional heat. There are several definitions and ways to measure fire intensity. The most common of these is fireline intensity also known as Byram's fireline intensity or frontal fire intensity is the rate of heat energy released per unit time per unit length of fire front, regardless of the depth of the flame zone (Byram, 1959). Other measures of fire intensity include reaction intensity, radiant intensity, convection intensity, total fire intensity.

Flame lengths were measured from ground level. Alexander (1982) advocates measuring flame lengths from the mid-point of the base of the flame to the tip of the flame. Flame length estimation may be needed to give an indication of suppression difficulty, or to formulate a fire danger index such as the Burning Index (BI) used by the US Forest Service (Bradshaw *et al*., 1983). Alternatively, flame length may be used to give a guide to fire intensity (Alexander, 1982) to determine the effects of the fire on flora and fauna. In either case, an equation relating flame length (L) to fire intensity (I_B) such as is given by Byram (1959): $L = 0.45I_B^{0.46}$.

Akaakara and Kittisatho (1992) studied fire behavior in dry deciduous dipterocarp forest at Doi Suthep-Pui National Park, Chiang Mai Province and found that rate of fire spread ranged from 0.28 to 6.41 m min^{-1} with the average value of 1.72 m min^{-1}. Fireline intensity ranged from 33.72 to 883.58 kWm^{-1} with the average value of 249.26 kWm^{-1}. The results of fire behavior studied in dry deciduous dipterocarp forest in Kanchanaburi Province showed that during fire season, the average rate of spread of head fire was 2.81 m min^{-1}, while flank fire and rear fire had the rates of spread of 0.59 and 0.40 m min^{-1}, respectively. The most severe fire took place in early March when rate of fire spread reached 6.96 m min^{-1} on a 45 per cent slope. Head fire advanced 4.9 times faster than rear fire. Shape or pattern of fire depended on degree of slope (Akaakara, 2000). Sompoh (1998) studied fuel complex in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary and found that the fireline intensity was 110.71 kWm^{-1}, the flame length was 70 cm. Fireline intensity, rate of fire spread and flame length from burning in February in dry deciduous dipterocarp forest, Sakaerat, Nakhon Ratchasima Province were 266.03 kWm^{-1}, 2 m min^{-1}. and 2.58 m, respectively (Sunyaarch, 1989).

2. Factors Affecting Fire Behavior

There are many causes and reasons for fire having as they do, the primary factors that influence fire behaviors are: fuel, weather and topography.

2.1 Fuel

Forest fuels are any thing in a forest that can be burned like; tree leaves, dead branches and grasses. More technically, fuel can be defined as live and dead biomass that either contributes to the advancement of the fire front or is consumed after the flaming front has passed (Keane *et al*., 2001). Given suitable conditions, both live fuel and dead fuel will be burned. Based on vertical distribution and general properties, fuels are classified into three groups that included ground fuel, surface fuel and aerial fuel (Brown and Davis, 1973). The properties of fuels that influence fire behavior compose of fuel particle property, fuel bed property and fuel moisture (Kaitpraneet, 1983).

2.1.1 Fuel Particle Properties

Fuel particles are the smallest elements considered in order to study the fuel structure. They are organs or pieces of the aerial parts of vegetation: branches, leaves, barks, cones, needles, etc. The physical, chemical and thermal properties of fuel particles or element of compounded particles belonging to the same biological entity e.g. the assemblage of leaves and small twigs of a given shrub species. Fuel particle properties have a direct effect on moisture relationships, heat transfer, ignition and combustion. Consequently, fuel particle contributes to the prediction of wildland fire intensity and severity with all its consequences on suppression difficulty and human safety (Allgöwer *et al.*, 2002). The important properties of fuel particle that are used to calculate rate of fire spread in Rothermel's fire spread model including; surface area to volume ratio, heat value, particle density or mass to volume ratio, total mineral content and effective mineral content.

a) Surface Area to Volume Ratio

The surface area to volume ratio for wildland fuel particle is the amount of surface area divided by the volume of the particle. A way to visualize the surface area to volume ratio is the number of square feet or meter of wrapping paper need to wrap a box divided by the volume in cubic feet or meter (Carlton, 2003). The higher of surface area to volume ratio is the finer the wildland fuel particle. On the contrary, the low surface area to volume ratio is large fuel particle. A weight average surface area to volume ratio for a fuel bed is called the characteristic of surface area to volume ratio. Fons (1946) gave emphasis to the ratio between the surface area and the volume occupied and found this significant in explaining the rate of spread of field fire. The fine fuel, which has high surface area to volume ratio can be received the heat from the adjacent fire more and rapidly for pre-heat itself. In addition the combustion reaction is occurred on the surface area of particle. As a result the fuel particle, which is high surface area to volume ratio is faster ignited than the low surface area to volume ratio fuel.

Based on the 13 fuel models, surface area to volume ratio were varied from 1,500 to 3,500 ft^{-1}. Surface area to volume ratios of 0.6 cm < Ø < 2.5 cm, 2.5 cm < Ø <7.5 cm, live herbaceous and live woody were 357, 98, 4,920 and 4,920 m^{-1}, respectively (Fischer, 1982). Surface area to volume ratios of Erica shrub, Pinus needles and moss were 6,698, 5,714 and 13,333 m^{-1}, respectively (Harvey, 1997). Sathirasilapin (1987) determined surface area to volume ratio in dry deciduous dipterocarp forest at Sakaerat, Nakhon Ratchasima Province was 3,585 ft^{-1} or 11,761.8 m^{-1}.

b) Heat Value

Heat value or caloric value was the heat of fuel particle, which released when it was burned. The heat value was varied to fuel composition (Philpot, 1969). The unit of heat value is Btu lb^{-1}, or cal g^{-1}, or kJ kg^{-1} and is used to estimate fire intensity and rate of fire spread. The heat values of the forest fuels were mostly between 7,500 and 10,000 Btu lb^{-1} or 4,167 and 5,556 cal g^{-1}. Some tree species, heat values of leaves were more than that of stems, but on the other hand some species, heat values of stems were more than that of leaves (Nord and Countryman, 1972). The heat values of parts of coniferous species such as stems, twigs, barks and leaves were more than those of hard wood species (Kelsey *et al*.,1979). Neenan and Steinbeck (1979) found that heat values of various hard wood species were not different, but heat values of various coniferous species and the parts of the coniferous species were significantly statistical differences.

Although heat value is different among the parts of plants and species but the difference is only 4 to 10 per cent, because the main substances in wood are cellulose and lignin (Chomchan and Panyaatanya, 1981). The variation of heat values came from chemical compound in that plant (Countryman and Philpot, 1970). The heat values of the forest fuel was mostly about 8,000 Btu lb^{-1} except pitchy material such as Eucalyptus and some coniferous species. The heat value of 8,000 Btu lb^{-1} is used to represent for all the 13 fuel models for anticipating fire behavior. Generally, heat values of broad leaves species are 4,500 cal g^{-1} (Chomchan and Panyaatanya, 1981). Fuel model of Portugal Central Region the heat values were varied between 18,000 and 22,700 kJ kg^{-1} (Allgöwe *et al*., 2002).

c) Particle Density or Mass to Volume Ratio

The density of a fuel particle is the relation of its mass to its volume, symbolized by ρ_p or d and usually expressed in kg m^{-3} or g cm^{-3} (Allgöwer *et al*., 2002). The particle density is greatly varies between species and species, in same species or same part of tree. In forest fire used particle density 0.48 g cm^{-3} or 480 kg m^{-3} this number give ovendried particle density 30 pounds per cubic foot. The most particle density can be 32 pounds per cubic foot which the average density of wood. This maximum value would represent a solid cube of wood measuring one foot on side (Carlton, 2003).

Fons (1946) studied fuel bed of ponderosa pine needles and twigs and found that the ignition time for fuel particle of a given volume is directly proportional to the density. By the same token, fire spread is inversely proportional to particle density. Later, Fons *et al.* (1960) confirmed this results for larger fuels with experiments using wood crib fuel beds. They found that the rate of fire spread and the rate of combustion of the fuel in wood fuel cribs decrease as the density of the wood increase.

d) Total Mineral and Effective Mineral Contents

The almost of substances in plants are organic minerals or ash. The ash content of wood ranged from 0.1 per cent to 5 to 6 per cent, being mostly around 1 per cent. Bark usually contains considerably more than wood does, as much as 12 per cent being recorded for post oak. Wood ash consists principally of silica, lime, potash (potassium oxide) and phosphoric acid in combination (Koehler, 1924). The mineral or ash in natural fuels can be divided into two kinds: silica and silica free ash minerals. Deeming and Brown (1975) defined the silica free ash mineral content as that part of the total fuel comprised of inorganic material other than silica that should be accounted for separately because it actively suppresses the combustion process. Silica alone is benign. Mutch and Philpot (1970) also found that silica could be disregarded when relating inorganic content to pyrolysis. Steward (1974) noted that the rate of burning is reduced by an increase in the silica free mineral content.

There are two effects of ash to combustion; 1) decreasing the fuel loading because ash is not burned and 2) ash interrupt in combustion, if the fuel gave heat of combustion 8,000 Btu lb^{-1} and composed of 5 per cent ash, hence the fuel was burnt it would release heat yield 8,000 x (1.00 – 0.05) = 7,600 Btu lb^{-1}. For Rothemel's model the mineral content was subtracted from the ovendried of fuel loading, $w_o(1-s_t)$ because this mineral has not direct effect on combustion. The value of ash and silica free ash in total of 13 fuel models were 5.5 and 1 per cent, respectively. In Thailand, ash and silica free ash in dry deciduous dipterocarp forest at Sakaerat, Nakhon Ratchasima Province were 12 per cent and 4 per cent, respectively (Sathirasilapin, 1987).

2.1.2 Fuel Bed Properties

Fuel bed consist of a variety of fuel particle. It is the association of thoe fuel particles, each with individual characteristics, that to a major extent determines the burning behavior of the whole fuel bed. Attributes of fuel beds considered important to fire behavior are fuel loading, fuel bed depth, compactness, continuity and arrangement.

a) Fuel Loading

Fuel load or weight of fuel per unit area is one of the most important factor which affects the intensity and rate of spread. Fire intensity is directly proportional to fuel's heat of combustion, the amount of fuel consumed, and a rate of fire spread. Fuel loads are dependent on forest type, life stage of forest such as older, over mature forests may have an accumulation of large woody debris, and time since last fire (DeBano *et al.,* 1980). The proportion of this total fuel load that is consumed is influenced by fuel availability, which in turn is determined by moisture content, chemical characteristics, and size.

In Thailand, fuel load in dry deciduous dipterocarp forest was 3,868.68 kg ha^{-1}, which was composed of litter, twig, grass and undergrowth at amount of 1,703.54, 879.53, 457.38 and 828.24 kg ha^{-1}, respectively. (Wiriya, 2006).

b) Fuel Bed Depth

Fuel depth or fuel height has a few effect in fire behavior, but it has greater effect to fuel compactness, which affects to fire behavior. Brown (1974) gave the definition of fuel depth that was the vertical continuous of fuel from the lowest of litter to the maximum of fuel height in the fuel bed. Thus, Albini and Brown (1978) gave fuel bed depth that was the vertical perimeter of fuel, which connected to fire behavior. For the homogeneous natural fuel bed such as grass land the fuel depth was the height of vegetation, but in heterogeneous fuel bed, the fuel depth was the height of equivalent fuel bed or two third of vegetation height.

Fuel depth from the 13 fuel models: short grass, timber (grass and understory), tall grass, chaparral, brush, dormant brush, southern rough, closed timber litter, hardwood litter, timber (litter and understory), light logging slash, medium logging slash and heavy logging slash were 1.0, 1.0, 2.5, 6.0, 2.0, 2.5, 2.5, 0.2, 0.2, 1.0, 1.0, 2.3 and 3.0 ft, respectively (Pyne *et al.*, 1996). In dry deciduous dipterocarp forest, fuel heights of litter, twig, grass and undergrowth were 4.26, 3.05, 33.92 and 39.42 cm, respectively (Wiriya, 2006).

c) Fuel Bed Compactness

The spacing of individual fuel elements in the fuel bed, can refer to either as porosity or its converse, compactness. Fuel elements in a highly compact fuel bed are close together, whereas in a less compact fuel bed the individual fuel elements are far apart. A highly compact fuel bed has low porosity; a less compact bed is more porous.

Bulk density, fuel bed porosity and packing ratio are all used in describing the compactness of fuel beds. The bulk density of a fuel bed is the mass of fuel per unit volume (Anderson, 1969 ; Rothermel, 1972). It can be used as a measure of the oxygen availability and distance between particle across which heat must be transferred to ignite additional fuel (Fahnestock, 1960). The fuel bed porosity is a measure of the total volume of void space per unit volume of fuel (Brown, 1970 ; Steward, 1974).

Packing ratio is defined as the volume of fuel divided by the volume of the fuel bed (Rothermel, 1972). Fuel beds with low porosity burn slowly, since air flow into the fuel bed is restricted and the oxygen supply therefore deficient. The burning rate should increase rapidly as the porosity is increasing and reach a maximum at some optimum fuel element spacing. Beyond this point, further increases in porosity should lead to decreasing burning rate because of a reduction in the efficiency of heat transfer among the fuel elements as they become further and further apart. There is a range of porosities at which ventilation and heat transfer mechanisms are optimum; it is at this point that maximum rate of fire spread will occur. Anderson (1969) also noted that the tallest flames and highest burning rate occur at optimum porosity. A packing ratio of 1.0 would represent a solid fuel bed. Rate of fire spread would increase from this point to a maximum at the optimum packing ratio, and then decrease as the fuel particles become too sparse to carry the fire.

d) Continuity and Arrangement

Continuity is a term used to describe the gross distribution of fuel in the horizontal and vertical directions. Horizontally continuous fuel beds are those in which the fuel loading remains nearly the same over large area. Vertically continuous fuel beds consist of ladder fuels and surface fuels which extend more or less uniformly from the litter layer up into the lower parts of the overstory canopy. Vertical continuity may lead to crown fires under the right conditions. Thus, fuel continuity is important to the size and severity of wildfire. Fahnestock (1970) used horizontal continuity and particle position as two of the four variables necessary to estimate rate of spread and crowning potential.

Steward (1974) noted that arrangement of fuel within the bed can produce a substantial change in rate of fire spread. In his experiment, random fuel beds were prepared by spreading fuel particles evenly over a flat surface. Uniform beds were also constructed of the same type of fuel aligned in a vertical matrix. The fuel bed were burnt and in all cases the randomly packed beds exhibited a higher rate of fire spread. Steward (1971) suggested that increased rate of fire spread randomly packed beds was due to the propagation of fire along individual particle.

2.1.3 Moisture Content

Fuel moisture describes the condition of the fuel. Fuel moisture is a prime factor in judging the burning capability of fuel. The higher a fuel's water content or fuel moisture, the longer it will take for the fuel to ignite (Pyne *et al.*, 1996). Fuel moisture is product of past and present weather events, it obtains their moisture from: the atmosphere, precipitation, and the ground. Fuel moisture changes more rapidly in dead fuels than in live fuels. Moisture contents of live fuels are vary from 35 to 200 per cent and those of dead fuels vary from 1.5 to 30 per cent (Schroeder and Buck, 1970).

2.1.4 Moisture Content of Extinction

The dead fuel extinction moisture is the moisture content of the fuel at which the fire will not spread in the Rothermel model. This modeling parameter is generally associated with climate (humid versus dry), though fire science research has yet to explain the mechanism for the association. For litter fuels of ponderosa pine needles, moisture of extinction about 30 per cent; for other dead fuels it may vary between 10 per cent and 40 per cent (Rothermel, 1972). Brown (1972) indicated that moisture of extinction may be between 10 per cent and 15 per cent for logging slash, which is more porous than litter. Fuel models for dry climates tend to have lower dead fuel moistures of extinction, while fuel model for humid climate areas tend to have higher moisture of extinction (Scott and Burgan, 2005). Moisture content of extinction of the 13 fuel models varied from 12 to 40 per cent and those of fuel model of Portugal Central Region varied from 25 to 40 per cent (Allgöwer *et al*., 2002).

2.2 Environmental Variables

The variables associated with fuel particles and fuel beds do not change rapidly; however, environmental variables such as temperature, relative humidity and wind speed are constantly changing. These and others environmental variables are important in determining fire behavior.

2.2.1 Temperature

The temperatures of the air and the fuel are important variables affecting fire behavior. Fons (1946) showed that high fuel and air temperatures increase the combustion rate by reducing the temperature rise necessary for ignition. He also noted that when fuel temperature increased 28 º c, the rate of fire spread increased 30 per cent. Solar radiation also affects the temperature of the fuel. A bed exposed to strong sunlight can reach temperatures significantly above the temperature of the surrounding air (Steward, 1974). Perhaps the most important effect of temperature is on relative humidity. An increase in temperature of 11 º c will reduce the relative humidity of the air by approximately one-half. The combination of high temperature and low humidity means rapid loss of moisture from the dead fuels. It also means a high transpiration rate for living vegetation, which can lower live fuel moisture content if the available soil moisture is nearing depletion (Brown and Davis, 1973).

2.2.2 Relative Humidity

Although relative humidity has little direct effect on fire, it is important to fire behavior because it controls the moisture content of dead wildland fuel. Fire starts easily and spreads rapidly in dry fuels. But when the moisture of fuel is high, fire starts difficulty and spreads slowly (Countryman, 1971). The moisture content of fine dead fuels changes rapidly with change in relative humidity. Whenever relative humidity is 20 per cent or less, the moisture content of very fine dead fuels and outer surfaces of other fuels will also be low, and the probability of ignition from falling embers will be high (Brown and Davis, 1973).

Experimental studies have also demonstrated that the relative humidity of the air surrounding a fire affects the rate of fire spread (Steward, 1974; Konev and Sukhinin, 1977; Fang and Steward, 1969), and that the increasing the relative humidity proportionally reduces the rate of fire spread. Fahnestock (1953) studied the effect of relative humidity on the burning of logging slash and concluded that high humidities greatly reduced the rate of fire spread in light and medium concentrations of slash but it did not affect the rate of fire spread in heavy concentrations. These effects no doubt result from relative humidity’s effect on the moisture content of fine fuels

2.2.3 Wind

Wind acts as accelerator and enhances fire behavior (Rothermel and Anderson, 1966). Brown and Davis (1973) suggested that air movement is important for two reasons. First, it directly affects the rate of oxygen supply to the burning fuel;

and second, strong wind increases the rate of fire spread by tilting the flames closer to unburned fuel. This increases the heat flux to the unburned fuel by increasing effective flame radiation and heat convection. Wind also influences the moisture content of the fuel. If the wind speed is high, a forest fuel will dry out much faster than it would if the speed was low.

The effect of wind varies with the velocity of the wind and its direction with respect to the fire front. When wind speed increases the rate of heat fire spread increases (Rothermel and Anderson, 1966). Fire spreading into the wind is not greatly influenced by the wind velocity. Steward (1974) reported that fire intensity increases substantially with wind velocity in the forward direction but it is little influenced by a wind against the direction of spread.

However, the backing rate of spread may be increased with increasing wind spread, but it is more slowly than in head fire (Byram, 1959). The increase in the backing rate of spread might be due to an increased supply of oxygen. Wind velocity has little influence on backing rate of spread due to a lack of flame front radiation and preheating because the flames are being tilted away from the unburned fuel (Beaufait, 1965).

2.2.4 Slope

Slope is the steepness of the land in relation to the horizontal. The slope of the ground influences the rate of fire spread. The effect, similar to wind, is to reduce the angle between the flame and fuel, thus increasing the radiant and convective heating of fuels ahead of the fire. The rate of fire spread on a ten degree slope can be double the rate of spread on level ground. On a twenty degree slope rate of spread can be four times faster than on ground level. Winds blowing directly up-slope lower the angle of flames even more and exceptionally high rates of fire spread can occur. The effect of wind on a flame can override the effect of slope. Strong winds may blow directly down a slope reversing the normal pattern of fire spread. To a lesser extent breezes at night can make a fire move more rapidly down slope than normal.

Several researchers have investigated the relationships between slope and rate of fire spread. Curry and Fons (1938) reported that the rate of fire spread in pine needles increases curvilinearly with slope. Rate of spread of upslope fires increases sharply when the slope angle exceeds 20 degrees, but the rate of fire spread of upslope fires is nearly independent of the slope angle. Thus, the spread mechanism should be the same as for back fire in wind (Byram *et al.*, 1966). Steward (1974) also reported that slope affected the rate of spread up the slope but it did not affect the rate of spread for a fire backing down a slope. Countryman (1964) noted that rate of spread of wildland fire has been estimated to approximately double for each 15 degree increase in slope. Robertson (1980) showed that the rate of backing fire spread through crib fuel beds decreased with increasing slope. The reduction in backing fire down slope can be approximated by the cosine of the squared slope angle. Robertson (1980) further reported that flame depth and flame height were also reduced as the slope was increased.

3. Fuel and Fire Models

3.1 Fuel Model

Fuel model is a set of numerical values that describe some surface fuel characteristics that serve as inputs to mathematical fire spread model. The fuel model concept was developed in United States of America as a way to accommodate the detailed and complex fuel input requirement of Rothermel's fire spread model, there are 9 fuel characteristics following; fuel load, surface area to volume ratio, fuel bed depth, moisture content, moisture of extinction, heat content, mineral content, particle density and effective mineral content. These systems evolved from a simple conceptual classification of fuels into four groups including grasses, bush, timber, and logging slash to a 11 fuel models were initiated by Rothermel in 1972 and later expanded to the 13 fuel models. The 13 fuel models have used in fire behavior prediction system(FBPS) such as BEHAVE. In addition, there are many fuel models for Rothermel's fire spread model for used in each area such as fuel models of Portugal Central Region (Allgöwer *et al*., 2002). Recently, Scott and Burgan (2005) developed a comprehensive new set of standard fuel models for use with Rothermel's surface fire spread model for improving the accuracy of fire behavior prediction.

3.2 Fire Model

Fire model is a set of equations of fuel characterizations, which have been shaped a small number of dominant mathematical models developed to predict fire behavior. Existing models used for fire modeling are usually classified into 3 groups:

1) Empirical models which are based primary on statistics collected by observation of experimental or historical fire. There are two empirical models widely used in Australia and Canada. In Australia, the most widely used rate of spread models are McArthur's models for grassland fire and forest fire (McArthur, 1966; Noble *et al.*, 1980). Canadian Forest Fire Service has integrated 25 years of researching experimental and real scenario fire to develop Canadian Forest Fire Behavior Prediction System which is now available in book and electronic form. It consists of 89 formulae developed empirically and it is usually presented in tabular form (Bodrozic *et al.*, 2006).

2) Physical models are based on physical principles of fluid dynamics and laws of conservation of energy and mass.

3) Semi empirical models are based on global balance and on the assumption that the energy transferred to the unburned fuel is proportional to the energy released by the combustion of the fuel. Several terms of the model must be fitted from laboratory fire experimental results (Rothermel, 1972).

4. The Rothermel's Fire Spread Model

Rothermel's model is a semi-empirical model, that most widely used in United States of America is named after R.C. Rothermel who provided the equation (1) for calculating rate of fire spread (Bodrozic *et al.*, 2006). The model is comprised of set of equations of fuel characterizations, which have been shaped a small number of dominant mathematical models developed to predict fire behavior. Rothermel's model and modifications by Albini (Rothermel, 1972; Albini, 1976), which predicts surface fire spread and intensity based upon fairly complex surface fuel and environmental conditions. Rate of spread is then a ratio between the heat flux received from the source and the heat required for ignition by the potential fuel. The final form of the rate of spread equation as derived by Rothermel (1972) with minor adjustments by Albini (1976) is as follow:

$$R = \frac{I_R \xi (1+\phi_w+\phi_s)}{\rho_b \varepsilon Q_{ig}} \qquad (1)$$

where R = Rate of spread of the flaming front (m min^{-1}).

I_R = Reaction intensity, the energy release rate per unit area of fire front (kJ $m^{-2} \cdot min^{-1}$).

ξ = The propagating flux ratio, the proportion of the reaction intensity that heats adjacent fuel particles to ignition.

ϕ_w = A dimensionless multiplier that accounts for the effect of wind in increasing the propagating flux ratio.

ϕ_s = A dimensionless multiplier that accounts for the effect of slope in increasing the propagating flux ratio.

ρ_b = Bulk density, the amount of ovendry fuel per cubic meter of fuel bed (kg m^{-3}).

ε = The effective heating number, the proportion of a fuel particle that is heated to ignition temperature at the time flaming combustion starts.

Q_{ig} = The heat of preignition, the amount of heat required to ignite one kilogram of fuel (kJ kg^{-1}).

The defines of terms and inputs to terms for the Rothermel's fire spread model were shown in equation (1). With the understanding of the terms described above, each of the following terms of the spread were described as follows:

4.1 Reaction Intensity (I_R)

The reaction intensity is the rate of the energy release per area (square foot or square meter) within the flaming front. It is equal to the heat per unit area times the residence time. Residence time is the time that a given spot on the ground is in the flame front. The reaction intensity is not affected by wind, slope or direction of spread. The reaction intensity is calculated by using formula:

$$I_R = \Gamma' W_n H \eta_m \eta_s \qquad (2)$$

Where I_R = Reaction intensity (kW m^{-2})

Γ' = Optimum reaction velocity (s^{-1})

W_n = Net fuel loading (kg m^{-2})

H = Fuel heat of combustion (kJ kg^{-1})

η_m = Moisture damping coefficient

η_s = Mineral damping coefficient

4.2 Propagating Flux (ξ)

The total amount of quantified in the reaction intensity is available to preheat fuels. Not all of this energy though actually does preheat fuels. The proportion of this energy defined in the reaction intensity that actually goes to preheating fuel is the propagating flux. As such, the propagating flux is a volume between 0 and 1. The propagating flux is calculated by using formula:

$$\xi = \frac{\exp[(0.792+0.37597\sigma^{0.5})(\beta+0.1)]}{(192+0.0791\sigma)} \quad (3)$$

where ξ = Propagating flux

σ = Surface area to volume ratio (m^{-1})

β = Packing ratio

4.3 Wind Factor (ϕ_w) and Slope Factor (ϕ_s)

Wind tilts the flame angle increasing the amount of energy available for pre-heating of fuel. Flame may also come into direct contact with adjacent fuel. A fire burning on a slope has flames closer to adjacent fuel uphill. The wind and slope multipliers are 1 or greater that reflect the increase in the heat energy that will be available to pre-heat fuel. Wind and slope factors are calculated by using formulae:

$$\phi_w = CU^B(\beta/\beta_{op})^{-E} \quad (4)$$

$$\phi_s = 5.275\beta^{-0.3}(\tan\phi)^2 \quad (5)$$

where ϕ_w = Wind coefficient

ϕ_s = Slope coefficient

$C = 7.47 \exp(-0.133(0.3048\sigma)^{0.55})$

U = Wind velocity

$B = 0.02526(0.3048\sigma)^{0.54}$

$E = 0.715 \exp(-0.000359(0.3048\sigma))$

β = Packing ratio

β_{op} = Optimum packing ratio

$\tan\phi$ = Slope or vertical rise/horizontal distance

4.4 Bulk density (ρ_b)

As has been mentioned, the bulk density of fuel bed is the loading measured in weight per square meter divided by the depth of the fuel bed (meter). This ratio provided the amount as measured by weight of fuel in a cubic meter of fuel bed. The most is that can be 512.59 kg m.$^{-3}$ or 0.51 g cm^{-3}, which is the average density of wood. This maximum value would represent a solid cubic of wood measuring one meter on a side. Bulk density is calculated by using formula:

$$\rho_b = \frac{W_o}{\delta} \tag{6}$$

where ρ_b = Bulk density (kg m^{-3})

W_o = Ovendry fuel loading (kg m^{-2})

δ = Fuel bed depth (m)

4.5 Effective Heating Number (ε)

Not all of the fuel within a fuel bed needs to be heated to ignition temperature for the fuel bed to ignite. Only a proportion of the outside of a fuel particle needs to be heated to ignition. The effective heating number is a number between 0 and 1 that is the proportion of the loading in the fuel bed that needs to be heated to ignition temperature. The effective heating number is calculated by using formula:

$$\varepsilon = \exp(-452.76/\sigma) \tag{7}$$

where ε = Effective heating number

σ = Surface area to volume ratio (m^{-1})

4.6 Heat of Pre-ignition (Q_{ig})

The amount of heat required to rise a fuel to ignition temperature is defined as the heat of pre-ignition. The heat required for ignition is dependent upon (a) ignition temperature, (b) moisture content of the fuel, and (c) amount of fuel involved in the ignition process (Rothermel, 1972). The first major product of pre-ignition fuel heating is water vapor converted from liquid water contained within cells and loosely tied to cell wall structure. Fuel temperatures will not raise above 100°c until this water is volatilized. The heat of pre-ignition is associated with fuel moisture content in equation:

$$Q_{ig} = 581.5+25.957M_f \tag{8}$$

Where Q_{ig} = Heat of pre-ignition

M_f = Fuel moisture content (%)

4.7 Packing Ratio (β)

The packing ratio is a number between 0 and 1. It is calculated as the fuel bed bulk density divided by oven-dried particle density of fuel. It represents the proportion of a cubic meter of the fuel bed that is actual fuel. The remainder of the cubic meter is air. The packing ratio is found by formula:

$$\beta = \frac{\rho_b}{\rho_p} \tag{9}$$

where β = Packing ratio

ρ_b = Bulk density (kg m^{-3})

ρ_p = Ovendry particle density (kg m^{-3})

4.8 Optimum Packing Ratio (β_{op})

The packing ratio where the reaction velocity is at its maximum is called the optimum packing ratio for the fuel bed. The optimum packing ratio depends solely on the characteristic of surface area to volume ratio for the fuel bed in power equation, that is:

$$\beta_{op} = 8.8578\sigma^{-0.8189} \tag{10}$$

where β_{op} = Optimum packing ratio

σ = Surface area to volume ratio (m^{-1})

5. Byram's Fireline Intensity and Flame Length

The most useful and familiar measure of fire's energy output is the fire line intensity, define as the rate of heat release per unit length of fire front (Byram, 1959). It can be expressed as:

$$I_B = 0.007HW_aR \tag{11}$$

where I_B = Fireline intensity (kW m^{-1})

H = Heat yield (cal g^{-1})

W_a = Loading of available fuel (ton ha^{-1})

R = Rate of fire spread (m min^{-1})

The fireline intensity has proven very useful because it is proportional to the rate of fire front advance perpendicular to the fire front, and because the heat it produce has been used in describing the difficulty of controlling a fire (Hodgson, 1968). Byram (1959) related the flame length to the fireline intensity as the equation:

$$L = 0.08\, I_B^{0.46} \tag{12}$$

where L = Flame length (m)

I_B = Fireline intensity (kW m^{-1})

6. Burning Area and Perimeter

The expected area and perimeter of a fire starting from a point can be estimated from Van Wagner's fire growth model. The model assumes that, after an initial short period of adjustment, the fire's linear rate of spread at each point on the perimeter remains constant. This rate will vary continuously from a maximum at the head to a minimum at the rear. For simplicity, select values of this linear rate of spread for the head, flanks and rear of the fire, and assume a uniform fuel. Next assume that the fire's head burns a fan shaped area that widens as the head advances; flank spread then proceeds from the sides of the fan. Furthermore, it assume that the width of the fan is such that the fire's shape remains elliptical for any combination of head and flank rates. (Van Wagner, 1966). The burning area and perimeter are;

$$A = \frac{\pi(v + w)ut^2}{2} \tag{13}$$

$$P = \pi t \left[\frac{(v + w)}{2} + u\right] \left[1 + \left(\frac{M^2}{4}\right)\right] \tag{14}$$

where A = Burning area (m.^{2})

P = Perimeter (m.)

v = Rate of head fire spread (m min^{-1})

u = Rate of flank fire spread (m min^{-1})

w = Rate of rear fire spread (m min^{-1})

t = Burning time (min.)

$$M = \frac{(a-b)}{(a+b)}$$

$$a = \frac{(v + w)t}{2}$$

b = ut

7. Forest Fire at Huai Kha Khaeng Wildlife Sanctuary

Forest fire at Huai Kha Khaeng Wildlife Sanctuary is generally occurred in dry season, from December through to March or April. Toward the end of dry season, between February and April, forest fires become a major issue in the sanctuary. The fire has usually started in dry deciduous dipterocarp forest located in Buffer Zone areas during the early fire season and spread into mixed deciduous forest later. In addition, in the extreme drought year the fire would burn in dry evergreen forest at the core of Huai Kha Khaeng Wildlife Sanctuary as well. The burning areas within Huai Kha Khaeng Wildlife Sanctuary between 1997 and 2005 were presented in Table 1.

The causes of forest fire are human activities. Various factors have been identified as causes of forest fire in Huai Kha Khaeng Wildlife Sanctuary. People light the fires to remove litter, grass and undergrowth on the ground surface and to facilitate access to the forest for gathering non-timber forest products (e.g., mushrooms, edible vegetation). Local farmers often start fire to burn agricultural debris left over after residual harvesting, without taking adequate precautions. Fire is also used by rural people for hunting purposes. Other causes include encroachment on targeted land and arson provoked by confliction between local people and forestry staff.

Table 1 Burned areas in Huai Kha Khaeng Wildlife Sanctuary (HKKWS) from 1997 to 2005.

	Burned area (ha)		
Year	Inside HKKWS	Outside HKKWS	Total
1997	2,351	3,321	5,672
1998	9,466	2,660	12,126
1999	880	2,116	2,996
2000	217	2,414	2,631
2001	231	1,090	1,321
2002	4,170	882	5,052
2003	277	365	642
2004	6,718	1,097	7,815
2005	3,355	336	3,691

Source: Forest Fire Control Office (2006).

MATERIALS AND METHODS

Materials

The data were collected by using following materials and equipments,

1. Digital measuring weight
2. Oven drier
3. Anemometer
4. Wind direction meter
5. Thermometer
6. Psychrometer
7. Metric tape
8. Veneer caliper
9. Haga altimeter
10. Infrared Thermometer (Minolta Spot Thermometer; TA-0510)
11. Surveying Compass

Methods

1. Type of Fuel Model

Fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary could divided into 3 models; litter model, litter with short grass model and tall grass model.

Litter fuel model, the most of fuels are falling leaves and twigs of trees in dry period, this fuel model is appeared in the area where the crown covers are dense and close. The dominant trees are *Shorea obtusa* Wall. ex Blume and *Shorea. siamensis* Miq. Litter fuel model was shown in Figure 1.

Litter with short grass fuel model, the ground was more continuous with fallen leaves and dead short grasses such as *Themeda australis* Stapf and *Apluda nutica* L., the main fuels are tree leaves and short grass, dominant tree is *Dipterocarpus tuberculatus* Roxb. and *Dipterocarpus. obtusifolius* Teijsm. ex Miq. The canopy is much more open more than litter fuel model site. Litter with short grass fuel model was shown in Figure 2.

Tall grass fuel model is in opened crown cover, the ground cover was more continuous, with tall grasses and herbs. The main fuels are tall grass such as *Themeda trianda* Forssk. and *Imperata cylindrica* Beauv. A few *Cycas circinalis* L. were also presented. Dominant tree is *Shorea siamensis* Miq. and *Terminalia mucronata* Craib & Hutch. Tall grass fuel model was shown in Figure 3.

Figure 1 Litter fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Figure 2 Litter with short grass fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Figure 3 Tall grass fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

2. Fuel Types

The fuels were divided into 2 categories, dead fuel and live fuel and 5 types, litter, twig, dead herb, live herb and undergrowth as follow:

2.1 Dead Fuel.

The dead fuel is the fuel which has no living tissue. The moisture content of dead fuels is usually controlled by external factors as relative humidity, solar radiation etc. The dead fuel can be divided into 3 types as follows:

1) Litter is comprised of leaves, flower, fruit, bark, seed and the other parts of tree except twig and branch.

2) Twig is comprised of twig and branch of tree, its diameter does not exceed 7.6 cm.

3) Dead herb is composed of grasses and herbaceous plants, which are dead in dry period.

2.2 Live Fuel

The live fuel is the fuel which has living tissue. The fuel moisture is not controlled totally by external factors because tissues are able to maintain certain phase of moisture according to their life strategies. Thus, live fuel has big variety in moisture contents depending on their physiological abilities in e.g. tolerating drought. In this study the live fuel can be classified into 2 types as follows:

1) Live herb is composed of grasses and herbaceous plants, which are still alive in dry period.

2) Undergrowth is composed of seedling and shrub, its diameter does not exceed 0.6 cm.

3. Method of Fuel Data Collection

The line plot systematic sampling was employed for fuel data collection, in that the sample plots are distributed regularly in study area, to prevent the sampling bias. It is also convenient to work in the field (Spurr, 1952).

The sample sizes were calculated from Husch *et al.* (1982) equation.

$$n = \frac{t^2 (CV)^2}{AE^2} \tag{15}$$

Where n = Estimated sample size
t = Student's statistic for n degree of freedom, 95 per cent confidence level
CV = Coefficient of variation
AE = Allowable error of 20 per cent

The analysis showed that 50 plots of litter fuel model, 45 plots of litter with short grass fuel model and 45 plots of tall grass fuel model should give fuel properties estimate on each site within 20 per cent of the mean ($\alpha = 0.05$) for dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary. These limits were considered adequate for the purpose of the study.

3.1 Lay Out of Sample Plots

The sample plots using for the data collection comprise of 3 sizes namely: large, medium and small, they are 20 m x 20 m, 4 m x 4 m and 1 m x 1 m, respectively. The plot setting pattern was shown in Figure 4. The details of the sample plots were as follows:

1) 20 m x 20 m sample plot was used for collecting number, diameter at breast height (DBH), total height and canopy of tree.

2) 4 m x 4 m sample plot was laid at a corner within 20 m x 20 m plot and used for collecting number, diameter at breast height (DBH) and total height of saplings and shrubs.

3) 1 m x 1 m sample plot was laid at a corner within 4 m x 4 m plot, using for collecting species, fuel bed properties, fuel particle properties and fuel moisture content.

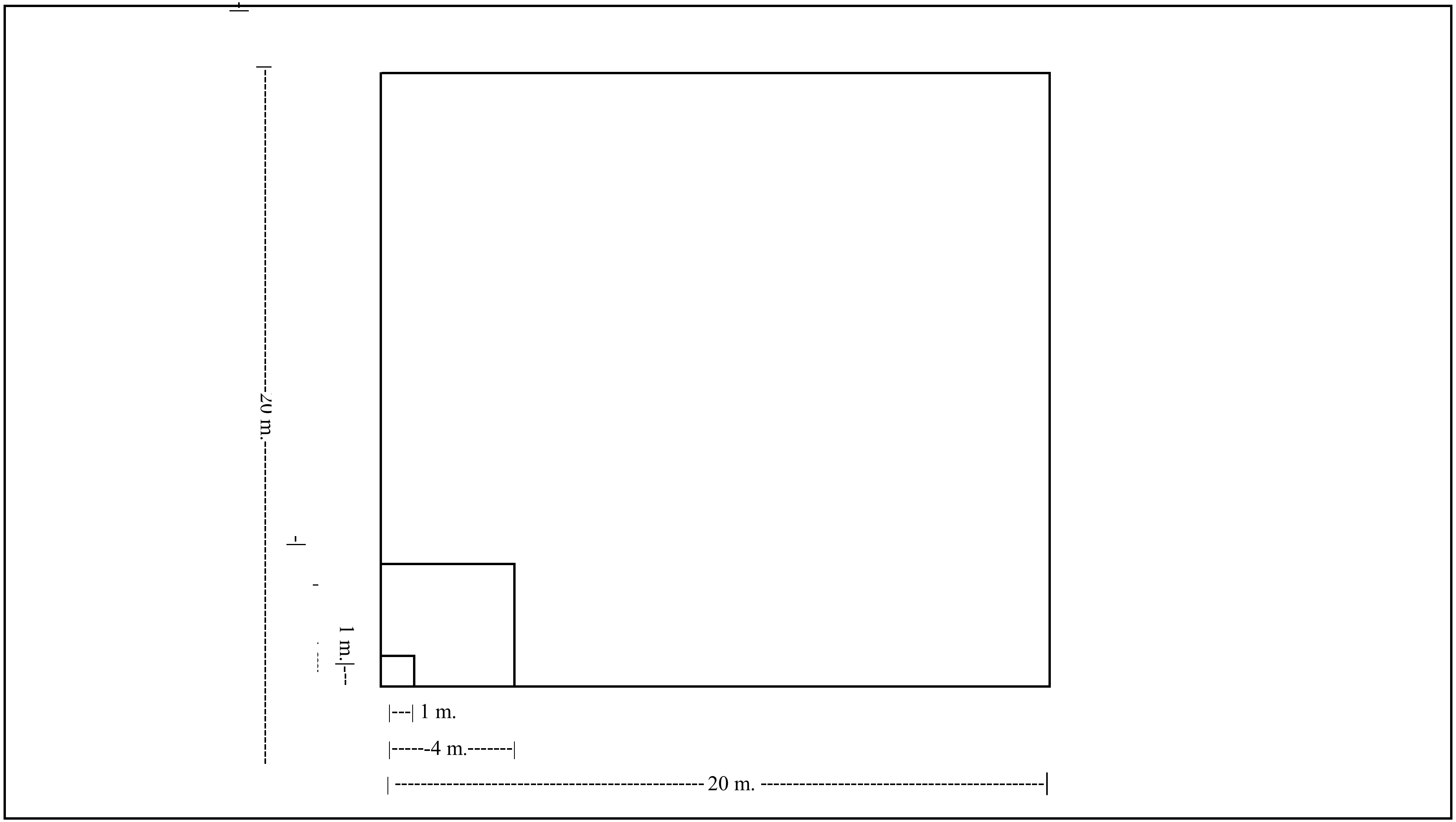


Figure 4 Diagram of sample plot for fuel data collection in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

4. Data Collection and Fuel Property Determination

Fuel property data included fuel loading, fuel bed depth or fuel height, surface area to volume ratio, fuel particle density, heat of combustion, total mineral content, effective mineral content and fuel moisture content were collected and were determined as follows:

4.1 Fuel Loading (Wo)

In 1 m x 1 m sample plots, each fuel type was sampled separately. Litter, twig and dead herb were counted to fuel categories of dead loading. Live herb and undergrowth belong to category of live fuel loading. Oven-dried fuel loading was determined as follows:

$$Wo = \frac{1{,}000{,}000\ Fw}{a\,(100+Mf)} \qquad (16)$$

where Wo = Oven-dried fuel loading (kg ha^{-1})

Fw = Sum of fresh weight fuel (kg)

Mf = Fuel moisture content (%)

a = Sum of sample plot area (m^2)

The oven-dried loadings of litter, twig, dead herb, live herb and undergrowth were added up to be gross fuel as follows:

$$Wo_{total} = \sum_{i=1}^{5} Wo_i \qquad (17)$$

where, Wo_{total} = Loading of gross fuel (kg ha^{-1})

Wo_1 = Loading of litter (kg ha^{-1})

Wo_2 = Loading of twig (kg ha^{-1})

Wo_3 = Loading of dead herb (kg ha^{-1})

Wo_4 = Loading of live herb (kg ha^{-1})

Wo_5 = Loading of undergrowth (kg ha^{-1})

4.2 Fuel Bed Depth (δ)

Height measurement of each fuel bed depth was made in each corner and in the middle of 1 m x 1 m sample plots. Litter fuel model, fuel bed depth was the accumulation of fallen leaves, and twig that were measured as fuel accumulation on the ground. Litter with short grass fuel model as a heterogeneous fuel bed, the fuel depth was the height of equivalent of litter and herbaceous plants. Tall grass fuel model, the fuel bed depth was the height of grasses and undergrowth were measured from the ground.

4.3 Surface Area to Volume Ratio (σ)

The surface area to volume ratio was separated thoroughly by species of fuel types, which can be calculated by following simple formula (Burgan and Rothermel, 1984).

Flat particles: surface area to volume ratio = 2/thickness (m.) (18)

Round particles: surface area to volume ratio = 4/diameter (m.)(19)

For measurement of surface area to volume ratio either particle thickness or diameter was measured. For dead herb and live herb with mixed particles proportions of round and flat particles were measured.

The average of surface area to volume ratio had to be weighted with the corresponding loading. Burgan and Rothermel (1984) defined the average of surface area to volume ratio as:

$$\sigma = \frac{\sum_{i=1}^{5} Wo_i Sv_i^2}{\sum_{i=1}^{5} Wo_i Sv_i} \qquad (20)$$

where, σ = Average of surface area to volume ratio (m^{-1})

Sv_1 = Surface area to volume ratio of litter (m^{-1})

Sv_2 = Surface area to volume ratio of twig (m^{-1})

Sv_3 = Surface area to volume ratio of dead herb (m^{-1})

Sv_4 = Surface area to volume ratio of live herb (m^{-1})

Sv_5 = Surface area to volume ratio of undergrowth (m^{-1})

Wo_1 = Loading of litter (kg ha^{-1})

Wo_2 = Loading of twig (kg ha^{-1})

Wo_3 = Loading of dead herb (kg ha^{-1})

Wo_4 = Loading of live herb (kg ha^{-1})

Wo_5 = Loading of undergrowth(kg ha^{-1})

4.4 Fuel Particle Density (ρ_p)

Fuel particles, which their volume were determined and their dry weights were found by placing in oven at 75 ^{0}c for 48 hours. Hence, fuel particle density was determined by typical formula as follow:

$$\rho_p = \frac{M}{V} \qquad (21)$$

Where ρ_p = Fuel particle density (kg m^{-3})

M = Fuel dry weight (kg)

V = Fuel volume (m^3)

Determining the volume of each fuel types;

Flat particles: the volume = surface area (m^2) x thickness(m) (22)

$$\text{Round particles: the volume} = \frac{\pi D^2 L}{4} \qquad (23)$$

Where D = Diameter (m)

L = Particle length (m)

The average of fuel particle density was weighted by loading as follows:

$$\rho p_{ave} = \frac{\sum_{i=1}^{5} Wo_i \rho p_i}{\sum_{i=1}^{5} Wo_i} \qquad (24)$$

where ρp_{ave} = Average particle density (kg m^{-3})

ρp_1 = Particle density of litter (kg m^{-3})

ρp_2 = Particle density of twig (kg m^{-3})

ρp_3 = Particle density of dead herb (kg m^{-3})

ρp_4 = Particle density of live herb (kg m^{-3})

ρp_5 = Particle density of undergrowth (kg m^{-3})

Wo_1 = Loading of litter (kg ha^{-1})

Wo_2 = Loading of twig (kg ha^{-1})

Wo_3 = Loading of dead herb (kg ha^{-1})

Wo_4 = Loading of live herb (kg ha^{-1})

Wo_5 = Loading of undergrowth(kg ha^{-1})

4.5 Heat of Combustion

Heat of combustion of fuel particle was determined by using adiabatic bomb calorimeter in laboratory at Royal Forest Department. Heat yield was determined by Brown and Davis's method (Brown and Davis, 1973).

4.6 Total Mineral Content

Total mineral content was determined by Standard Methods of Chemistry in laboratory at Science and Technology Research Institute of Thailand.

4.7 Effective Mineral Content

Effective mineral content was determined by Atomic Absorption Spectroscopy (AAS) in laboratory at Science and Technology Research Institute of Thailand.

4.8 Fuel Moisture Content

The samples were separated thoroughly by fuel types and classes, followed by weighting them to determine the fresh fuel weight. Then, the samples were oven-dried at 75 ^{0}c. for 48 hours. The fuel samples were then weighted again to determine dry fuel weight. Moisture content was calculated on a dry weight percentage basis. The fuel moisture contents were measured for each sample plot as follows:

$$Mf = \frac{100(Fw - Dw)}{Dw} \qquad (25)$$

Where Mf = Fuel moisture content (%)

Fw = Fresh weight (g)

Dw = Dry weight (g)

The average of fuel moisture content was weighted by loading as follows:

$$Mf_{av} = \frac{\sum_{i=1}^{5} Mf_i Wo_i}{\sum_{i=1}^{5} Wo_i} \qquad (26)$$

where Mf_{av} = The average of fuel moisture content (%)

Mf_1 = Moisture content of litter (%)

Mf_2 = Moisture content of twig (%)

Mf_3 = Moisture content of dead herb (%)

Mf_4 = Moisture content of live herb (%)

Mf_5 = Moisture content of undergrowth (%)

Wo_1 = Loading of litter (kg ha^{-1})

Wo_2 = Loading of twig (kg ha^{-1})

Wo_3 = Loading of dead herb (kg ha^{-1})

Wo_4 = Loading of live herb (kg ha^{-1})

Wo_5 = Loading of undergrowth (kg ha^{-1})

4.9 Ecological Data Analysis

Ecological data namely density, basal area and crown cover at the sample plots were determined by Kutintara's method (Kutintara, 1998).

5. Fuel Model

The set number of fuel properties of fuel models were come from fuel particle properties and fuel bed properties in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary. The set number of fuel properties included loading, surface area to volume ratio, fuel bed depth, moisture content, moisture of extinction, heat content, mineral content, particle density and effective mineral content.

6. Methods of Fire Behaviors Data Collection

6.1 Burning Plot

Total 28 burning plots which were divided into 14 plots, 8 plots and 6 plots for litter, litter with short grass and tall grass fuel models, respectively were established in experimental burning site for fire behavior data collection. Each sample plot of 200 m x 200 m, size was located in study area and was surrounded by 4 m wide fire line. A metal post was staked at the center of the burning plot and other metal posts were staked along the 8 cardinal points of the compass, at 10 m of contour intervals. The burning plot was shown in Figure 5.

6.2 Preburn Fuel Sampling

Fuel loading was determined from 5 sampling plots of 1 m x1m size of each which located in the north, south, east, west and center of the burning plot. Fuel loading of each fuel type in each sample plot was sampled separately. Litter, twig and dead herb were recorded to fuel categories of dead fuel loading. Live herb and undergrowth which its diameter was less than 0.6 cm, belong to categories of live fuel loading.

Moisture content of each fuel type, samples of the vegetation were clipped immediately prior to each burning. The samples were put in plastic bags, sealed and brought to the laboratory. The sample of each fuel type in each sample plot was sampled separately. Litter, twig and dead herb were recorded to fuel categories of dead fuel moisture content. Live herb and the undergrowth belong to categories of live fuel moisture content. The average moisture content was mathematically weighted by the various oven-dried weight of fuel. Fuel bed depths were measured along the 8 radius lines of the burning plot.

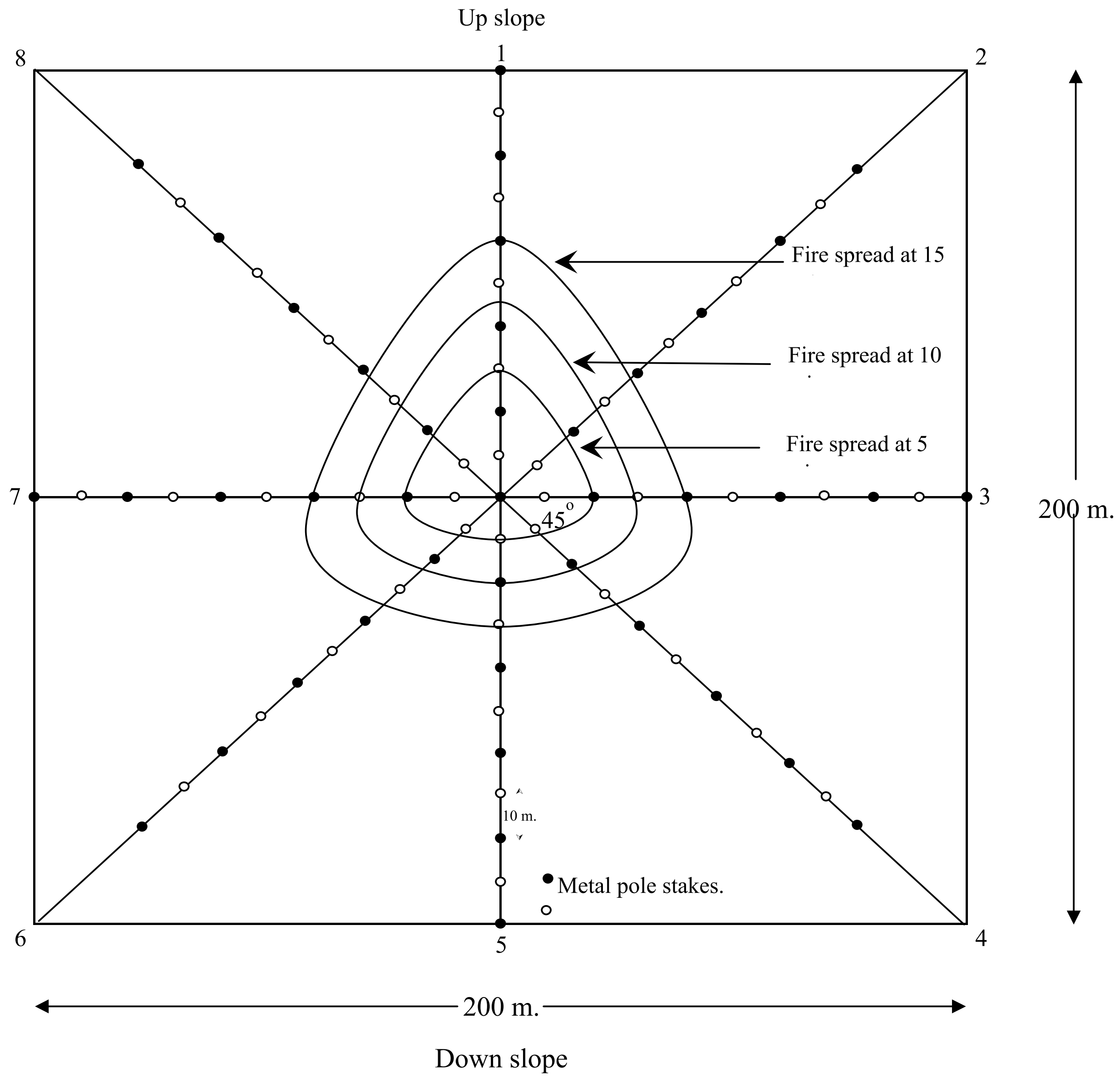


Figure 5 Fire behavior study plot in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

6.3 Burning

Fire was ignited at the center of the burning plot. During burning, the data was recorded every 5 minutes including: rate of fire spread was recorded every 5 minutes in every direction as shown in Figure 5. The spread maps were then sketched as fire growth. During burning, flame height was determined by the height level as marked on the stakes every 5 minutes in every spread direction until the burn is finished. Fire temperature, while fuel was being consumed, fire temperature was measured at head of fire by using Infrared Thermometer. In addition, wind velocity at midflame, air temperature and relative humidity were also recorded in every 5 minutes.

When the fire reached to edge of the burning plot, burning time was recorded, the distances of fire spread on the 8 radius lines of burning plots and perimeter of burning area were marked. Then, the fire was suppressed immediately.

6.4 Post Burning Sampling

Postburn fuel loading was estimated immediately after each fire to determine the amount of fuel consumed. Remaining fuel in each plot was estimated by clipping, oven drying and weighing all material from randomly located 5 sample plots of 1 m x 1 m size. Fuel consumption was then calculated based on the differences between the preburn and postburn fuel loadings. The slope of burning area between the ignition point and the head fire was measured. The burning area was determined by using surveying compass. Fire perimeter was determined by using measuring tape to measure along fire scorch around burning area.

7. Fire Behaviors Determination

7.1 Rate of Fire Spread

1) $$\text{Rate of head fire spread} = \frac{\text{Distance between ignition point and head fire.}}{\text{Total burning time}} \quad (27)$$

2) $$\text{Rate of rear fire spread} = \frac{\text{Distance between ignition point and rear fire}}{\text{Total burning time}} \quad (28)$$

3) $$\text{Rate of flank fire spread} = \frac{\text{The width between left flank and right flank of fire}}{\text{Total burning time x 2}} \quad (29)$$

7.2 Fire Intensity and Flame Length

Fireline intensity and flame length were determined by using Byram's formula (Byram, 1959) as equation (11) and (12), respectively.

7.3 Burning Area and Perimeter Growths

Burning area and perimeter growth were determined by using Van Wagner's fire growth model as equation (13) and (14), respectively.

8. Fire Prediction

Rate of fire spread was determined by using Rothermel's fire spread model as equation (1) that was applied by Bachmann (2001) as presented in Appendix.

9. Study Area

The study area was located in Huai Kha Khaeng Wildlife Sanctuary, that is located between latitudes $15^{\circ} 00^{\prime}$ to $15^{\circ} 50^{\prime}$ N and longitudes $99^{\circ} 00^{\prime}$ to $99^{\circ} 19^{\prime}$ E. The Wildlife Sanctuary covers an area of 2,780 km^2. The main of the area lies in Lan Sak, Huai Khot and Ban Rai districts, Uthai Thani Province, a few part of the area at the north is located in Umphang district, Tak Province. The northern boundary is with Nakhon Sawan and Tak Provinces, the eastern borders is in Uthai Thani Province, the western border is in Tak Province and the southern borders are with Kanchanaburi and Suphanburi Provinces (Giri and Shresta, 2000). Huai Kha Khaeng and Thung Yai Wildlife Sanctuaries were declared as a Natural World Heritage Site by UNESCO in December 1991.

The area is composed of complex mountains with heights ranging from 160 to 1,687 meters above mean sea level (MSL). The Huai Kha Khaeng River, the main permanent waterway, flows from the north to Srinakarin Reservoir in the south of the area. Most mountain chains run parallel in the north to south direction on both sides of the Huai Kha Khaeng River and have the narrow plains along the banks.

The climate in the study area is divided into three distinct seasons. Summer is from February to April, with the temperature ranging 24-38 ^{0}c. Rainy season is from May to October, with the temperature ranging 23-34 ^{0}c. Winter is from November to January, with the temperature ranging 18-20 ^{0}c. The annual rain intensity is about 1,500 millimeters in Huai Kha Khaeng Wildlife Sanctuary and between 800 and 1,200 millimeters in Buffer Zone Forest. The average relative humidity is 80 per cent. Climatic data of study site between 2001 and 2004 were presented in Table 2.

Faculty of Forestry (2000) reported that main vegetative covers within the area are dry deciduous dipterocarp forest, mixed deciduous forest, evergreen forest and bamboo forest. In addition, there are sub-forest vegetation types cover the area including rocky vegetation, pine forest, stream-sand dune vegetation and scrub forest. The key vegetation based on altitude gradients is as follows:

1) Dry deciduous dipterocarp forest: This type of forest is found at elevations ranging from 400 - 600 m above MSL. The major tree species include *Shorea obtusa* Wall. ex Blume, *Shorea siamensis* Miq., *Dipterocarpus tuberculatus* Roxb., *Dipterocarpus obtusifolius* Teijsm. ex Miq., and *Vitex peduncularis* Wall. ex schauer.

2) Mixed deciduous forest: This main forest type of the Sanctuary is distributed at elevations ranging from 400 - 950 m above MSL. The major tree species include *Largerstroemia tomentosa* C. Presl, *Afzelia xylocarpa* (Kurz) Craib, and *Tetrameles nudiflora* R. Br. etc. In addition, abundant bamboo groves are found such as *Bambusa bambos* (L.) Voss, and *Bambusa nutans* Wall., etc.

3) Dry evergreen forest: The distribution of this forest type ranges from 400 - 1,000 m above MSL. The major tree species include *Dipterocarpus alatus* Roxb. ex G. Don, *Hopea odorata* Roxb., and *Polyalthia viridis* Craib.

4) Hill evergreen forest: This forest type is found at elevations higher than 1,000 m above MSL. The major tree species include *Castanopsis acuminatissima* (Blume) A. DC., *Castanopsis indica* (Roxb.) A.DC., and *Castanopsis costata* (Blume) A. DC.

Huai Kha Khaeng Wildlife Sanctuary is the large home of wildlife, this is mainly due to a high diversity of habitats and other factors that are essential for wildlife. Based on the report of Faculty of Forestry (2000), there were 68 species of mammals, 355 species of birds, 77 species of reptiles, 29 species of amphibians and 55 species of fresh-water fishes.

Table 2 The climatic data at Huai Kha Khaeng Wildlife Sanctuary between 2001 and 2004.

Month	Rain fall (mm)	Temperatures (^{0}c)			Relative humidity (%)	Evaporation value (mm)
		Maximum	Minimum	Average		
January	10.85	31.59	16.88	24.24	92.41	4.14
February	37.48	33.61	18.62	26.12	86.45	5.32
March	53.08	34.13	21.28	27.71	82.68	5.64
April	80.08	38.02	24.33	31.18	77.82	7.65
May	221.03	33.09	24.13	29.02	88.53	6.09
June	123.70	32.81	23.81	28.31	90.26	5.03
July	152.73	32.99	23.55	28.27	88.28	5.39
August	125.48	32.21	23.26	27.74	89.50	4.63
September	279.30	31.85	22.47	27.16	93.35	4.80
October	191.00	31.65	21.16	26.41	96.26	4.46
November	40.83	31.58	18.97	25.28	93.60	4.53
December	6.50	30.62	16.23	23.43	90.44	4.30
Total	1,322.03	-	-	-	-	-
Average	-	32.91	21.22	27.07	89.14	5.17

Source: Huai Kha Khaeng Forest Fire Research Centre (2005).

10. Data Collection Period

The data were collected during dry period in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary, Uthai Thani Province from January to April, 2007.

11. Data Analysis and Expression

The sample mean, minimum, maximum of data, coefficient of variation were calculated for fuel properties. One way analysis of variance (ANOVA) and Duncan's multiple range test were applied to compare mean of fuel types for litter, litter with short grass and tall grass fuel models at 0.05 significant level ($\alpha = 0.05$). Pearson product-moment correlation was applied to determine relationships between fuel properties and ecological data and between fire behaviors and environmental factors. In addition, linear regression analysis was also applied to verify and adjust fire behavior predictions of fuel models.

RESULTS AND DISCUSSION

Results and discussion of the study on fuel model and fire behavior prediction in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary, Uthai Thani Province were presented as follows:

1. Fuel Properties

The fuels were divided into 2 categories, dead and live fuels and 5 types including; dead fuel was litter, twig and dead herb; live fuel was live herb and undergrowth. Based on the study, the fuel properties were composed of loading, moisture content, surface area to volume ratio, particle density, fuel bed depth, heat of combustion, mineral content, effective mineral content and moisture content of extinction were presented as follows:

1.1 Loading

Loading was the oven dried weight of fuel per a unit area or biomass. The results of study were expressed in kilogram (kg) per hectare (ha). Loading according to the fuel types and the fuel models were presented as follows:

1.1.1 Litter

Litter fuel was composed of leaves, flower, fruit, bark, seed and the other parts of tree except twig and branch, which fell to form heterogeneous fuel bed on the ground. Results of the study included values of mean, minimum, maximum and coefficient of variation of litter loads for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 3.

Table 3 Litter loads of various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	Litter loads of fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	kg ha^{-1}	2,137.89	1,973.72	233.05
Maximum	kg ha^{-1}	6,642.89	6,490.25	4,101.52
Mean	kg ha^{-1}	$3,858.27^{a}$	$3,605.25^{a}$	$1,926.90^{b}$
Coefficient of variation	%	26.41	26.24	43.52

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$ followed by Duncan's multiple range test) in litter loads for the fuel models.

Table 3 revealed that mean of litter load for litter fuel model presented the highest with value of 3,858.27 kg ha^{-1}, the nexts were litter with short grass fuel model and tall grass fuel model with values of 3,605.25 and 1,926.90 kg ha^{-1}, respectively. However, based on the ANOVA followed by Duncan's multiple range test indicated that the means of litter loads between litter fuel model and litter with short grass fuel model were not different at 0.05 significant level. But, there were the differences in the means of litter loads between litter fuel model and tall grass fuel model and between litter with short grass fuel model and tall grass fuel model at the same significant level. In addition, the minimum, maximum and coefficient of variation values of litter fuel model and litter with short grass fuel model were rather equivalent to each other. The values of those for litter fuel model were 2,137.89 kg ha^{-1}, 6,642.89 kg ha^{-1} and 26.41 per cent, respectively and the values of those for litter with short grass fuel model were 1,973.72 kg ha^{-1}, 6,490.25 kg ha^{-1} and 26.24 per cent, respectively. Moreover, the minimum, maximum and coefficient of variation values of tall grass fuel model were 233.05 kg ha^{-1}, 4,101.52 kg ha^{-1} and 43.52 per cent, respectively.

Litter load for litter fuel model showed the highest values, this was due to the litter fuel model which was found in the areas where were covered with dense trees. Results of study indicated that crown cover of tree for litter fuel model showed the highest with value of 10,258.80 m^2ha^{-1}. The nexts were litter with short grass fuel model and tall grass fuel model with the values of 9,111.38 and 3,199.76 m^2ha^{-1}, respectively. During dry period the leaves of tree were fallen to form heterogeneous fuel bed. Hence, the amount of litter fuel for litter fuel model was more than the other fuel models. In addition, the results of analysis showed that litter loads having positively correlated with density, basal area and crown cover of tree with the significant level of 0.01 as shown in Table 4.

Table 4 Correlations between litter load and ecological data in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

	Lit	Den	Ba	Cc
Lit	1			
Den	0.554**	1		
Ba	0.545**	0.700**	1	
Cc	0.607**	0.770**	0.804**	1

Abbreviations: Lit=Litter load, Den=Density, Ba=Basal area, Cc=Crown cover.
** Correlations (Pearson's correlation coefficients) significance level of 0.01

Samran *et al.* (2002) also found that litter loads in dry deciduous dipterocarp forest at Huai Kha Khaeng wildlife Sanctuary in January, February, March and April were 1,611.43, 3,165.84, 2,649.70 and 195.92 kg ha^{-1}, respectively. While, Akaakara *et al.* (2004) found that mean of litter loads in dry deciduous dipterocarp forest at Huai Kha Khaeng wildlife Sanctuary was 1,243.53 kg ha^{-1}. As for, litter loads in dry deciduous dipterocarp forest at Doi Sutep Pui National Park, Chiang Mai Province (Akaakara and Kittisatho, 1992) and at Salakphra Wildlife Sanctuary, Kanchanaburi Province (Akaakara, 2002) were 1,980 and 1,920 kg ha^{-1}, respectively.

Based on the study, litter loads of litter fuel model and litter with short grass fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng wildlife Sanctuary showed the higher values than other studies. For instance, litter load of tall grass fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng wildlife Sanctuary was rather similar to those in dry deciduous dipterocarp forest at Doi Sutep Pui National Park, Chiang Mai Province and at Salakphra Wildlife Sanctuary, Kanchanaburi Province.

1.1.2 Twig

Twig was composed of twigs and branches of trees, their diameters did not exceed 7.6 cm. Results of the study included values of mean, minimum, maximum and coefficient of variation of twig loads for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 5.

Table 5 Twig loads of various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	Twig loads of fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	kg ha^{-1}	184.05	238.28	221.01
Maximum	kg ha^{-1}	3,070.35	4,211.10	3,050.48
Mean	kg ha^{-1}	1,275.18^{a}	1,293.46^{a}	1,195.98^{a}
Coefficient of variation	%	62.64	71.08	69.77

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, p<0.05) in twig loads for the fuel models.

Table 5 revealed that means of twig loads for litter fuel model, litter with short grass fuel model and tall grass fuel model were rather similar to each other with values of 1,275.18, 1,293.46 and 1,195.98 kg ha^{-1}, respectively. In addition, the ANOVA indicated that the means of twig loads for litter fuel model, litter with short grass fuel model and tall grass fuel model were not different at 0.05 significant level. The minimum value of twig loads for those fuel models presented low with values of 184.05, 238.28 and 221.01 kg ha^{-1}, respectively. While the maximum value of twig loads for those fuel models presented high with values of 3,070.35, 4,211.10 and 3,050.48 kg ha^{-1}, respectively. As a result, coefficient of variation for those fuel models were high with values of 62.64, 71.08 and 69.77
per cent, respectively.

Samran *et al.* (2002) also found that twig loads in dry deciduous dipterocarp forest at Huai Kha Khaeng wildlife Sanctuary in January, February, March and April were 996.23, 1,731.83, 801.19 and 1,469.16 kg ha^{-1}, respectively. While, Akaakara *et al.* (2004) found that mean of twig loads in dry deciduous dipterocarp forest at Huai Kha Khaeng wildlife Sanctuary was 1,162.58 kg ha^{-1}. As for, twig loads in dry deciduous dipterocarp forest at Doi Sutep Pui National Park, Chiang Mai Province (Akaakara and Kittisatho, 1992) and at Salakphra Wildlife Sanctuary, Kanchanaburi Province (Akaakara, 2002) were 660 and 570 kg ha^{-1}, respectively.

Results of the study on twig loads were similar to the studies of Samran *et al.* (2002) and Akaakara *et al.* (2004) this mainly due to the studies were conducted at the same area. But, twig loads in dry deciduous dipterocarp forest at Huai Kha Khaeng wildlife Sanctuary was higher than those in dry deciduous dipterocarp forest at Doi Sutep Pui National Park, Chiang Mai Province and at Salakphra Wildlife Sanctuary, Kanchanaburi Province.

1.1.3 Dead Herb

Dead herb was composed of grasses and herbaceous plants, that were dead during dry period. Results of the study included values of mean, minimum, maximum and coefficient of variation of dead herb loads for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 6.

Table 6 Dead herb loads of various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	Dead herb loads of fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	kg ha^{-1}	10.84	123.89	237.67
Maximum	kg ha^{-1}	386.34	955.81	5,715.76
Mean	kg ha^{-1}	138.77^{a}	434.04^{b}	$2,625.30^{c}$
Coefficient of variation	%	57.56	56.00	47.17

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$ followed by Duncan's multiple range test) in dead herb loads for the fuel models.

Table 6 revealed that mean of dead herb load for tall grass fuel model presented the highest with value of 2,625.30 kg ha^{-1}. The nexts were litter with short grass fuel model and litter fuel model with values of 434.04 and 138.77 kg ha^{-1}, respectively. In addition, the ANOVA followed by Duncan's multiple range test indicated that means of dead herb loads of litter fuel model, litter with short grass fuel model and tall grass fuel model were significant differences. The dead herb fuels mostly were grasses and herbaceous plants, that were light demanding species. Because of dense canopy, that shaded the forest floor causing low herb loads such as the litter fuel model and litter with short grass fuel model, where the values of herb loads were low. Besides, the results of analysis were appeared that dead herb loads were significant correlated negatively with density, basal area and crown cover of tree with the significance level of 0.01 as shown in Table 7.

Table 7 Correlations between dead herb load and ecological data in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

	Dh	Den	Ba	Cc
Dh	1			
Den	-0.690**	1		
Ba	-0.549**	0.700**	1	
Cc	-0.645**	0.770**	0.804**	1

Abbreviations: Dh=Dead herb load, Den=Density, Ba=Basal area, Cc=Crown cover.
** Correlations (Pearson's correlation coefficients) significance level of 0.01

Samran *et al.* (2002) also found that dead herb loads in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary in January, February, March and April were 848.35, 459.98, 525.21 and 548.16 kg ha^{-1}, respectively. While, Akaakara *et al.* (2004) and Sompoh (1998) found that means of dead herb loads in dry deciduous dipterocarp forest at Huai Kha Khaeng wildlife Sanctuary were 803.78 and 1,179.42 kg ha^{-1}, respectively. As for, dead herb loads in dry deciduous dipterocarp forest at Doi Sutep Pui National Park, Chiang Mai Province (Akaakara and Kittisatho, 1992), Phu Phan National Park, Sakon Nakhon Province (Samran, 1992) and Salakphra Wildlife Sanctuary, Kanchanaburi Province (Akaakara, 2002) were 1,480, 1,016 and 1,470 kg ha^{-1}, respectively.

The mean of dead herb load for litter with short grass fuel model was similar to the studies of Samran *et al.* (2002) and Akaakara *et al.* (2004), this was due to the studies that were conducted at the same site. The mean of dead herb load for tall grass fuel model was higher than those sites. While, the means of dead herb loads for litter fuel model and litter with short grass fuel model were lower than those sites.

1.1.4 Live Herb

Live herb was composed of grasses and herbaceous plants, that are still alive during dry period. Results of the study included values of mean, minimum, maximum and coefficient of variation of live herb loads for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 8.

Table 8 Live herb loads of various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	Live herb loads of fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	kg ha^{-1}	17.85	76.17	159.20
Maximum	kg ha^{-1}	542.18	2,385.51	3,590.84
Mean	kg ha^{-1}	178.43^{a}	642.33^{b}	985.41^{c}
Coefficient of variation	%	80.77	68.33	73.30

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$ followed by Duncan's multiple range test) in live herb loads for the fuel models.

Table 8 revealed that results of the study on live herb loads were the same pattern as results of the study on dead herb loads that was due to they were the same fuel type. Mean of live herb load for tall grass fuel model presented the highest with value of 985.41 kg ha^{-1}. The nexts were the means of litter with short grass fuel model and litter fuel model with values of 642.33 and 178.43 kg ha^{-1}, respectively. The ANOVA followed by Duncan's multiple range test indicated that means of dead herb loads for litter fuel model, litter with short grass fuel model and tall grass fuel model were significant differences. The results of correlation analysis were appeared that live herb loads were significant correlated negatively with density, basal area and crown cover of tree with the significance level of 0.01 resembling dead herb that was due to it was the same fuel type as shown in Table 9.

Table 9 Correlations between live herb load and ecological data in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

	Lih	Den	Ba	Cc
Lih	1			
Den	-0.453**	1		
Ba	-0.325**	0.700**	1	
Cc	-0.417**	0.770**	0.804**	1

Abbreviations: Lih=Live herb load, Den=Density, Ba=Basal area, Cc=Crown cover.
** Correlations (Pearson's correlation coefficients) significance level of 0.01

1.1.5 Undergrowth

Undergrowth was composed of seedlings and shrubs, their diameters at middle point of length did not exceed 0.6 cm. Results of the study included values of mean, minimum, maximum and coefficient of variation of undergrowth loads for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 10.

Table 10 Undergrowth loads of various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	Undergrowth loads of fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	kg ha^{-1}	7.70	21.68	40.98
Maximum	kg ha^{-1}	1,094.44	1,080.40	1,167.33
Mean	kg ha^{-1}	338.58^{a}	378.64^{a}	451.00^{a}
Coefficient of variation	%	80.22	75.00	73.56

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$) in undergrowth loads for the fuel models.

Table 10 revealed that means of undergrowth load for litter fuel model, litter with short grass fuel model and tall grass fuel model were rather similar with values of 338.58, 378.64 and 451.00 kg ha^{-1}, respectively. In addition, the ANOVA indicated that means of undergrowth loads for litter fuel model, litter with short grass fuel model and tall grass fuel model were not significant differences. The minimum values of undergrowth loads of those fuel models were low with values of 7.70, 21.68 and 40.98 kg ha^{-1}, respectively. While, the maximum values of undergrowth loads of those fuel models were high with values of 1,094.44, 1,080.40 and 1,167.33 kg ha^{-1}, respectively.

Samran *et al.* (2002) also found that undergrowth loads in dry deciduous dipterocarp forest at Huai Kha Khaeng wildlife Sanctuary in January, February, March and April were 480.74, 409.12, 296.26 and 428.88 kg ha^{-1}, respectively. While, Akaakara *et al.* (2004) and Sompoh (1998) found that means of undergrowth loads in dry deciduous dipterocarp forest at Huai Kha Khaeng wildlife Sanctuary were 794.27 and 346.36 kg ha^{-1}, respectively. As for, undergrowth loads in dry deciduous dipterocarp forest at Doi Sutep Pui National Park, Chiang Mai Province (Akaakara and Kittisatho, 1992) and at Salakphra Wildlife Sanctuary, Kanchanaburi Province (Akaakara, 2002) were 1,070 and 1,050 kg ha^{-1}, respectively.

The results of this study were rather similar to the studies of Samran *et al.* (2002) and Sompoh (1998) that was due to such studies were conducted during the dry period. While, the study of Akaakara *et al.* (2004) and the studies at Doi Sutep Pui National Park, Chiang Mai Province and at Salakphra Wildlife Sanctuary, Kanchanaburi Province were conducted throughout a year including growing season. As a result, undergrowth loads of Akaakara *et al.* (2004), at Doi Sutep Pui National Park, Chiang Mai Province and at Salakphra Wildlife Sanctuary, Kanchanaburi Province were higher than those of the study and the studies of Samran *et al.* (2002) and Sompoh (1998).

1.1.6 Gross Fuel Loads

Gross fuel load was composed of litter, twig, dead herb, live herb and undergrowth. The amount of gross fuel loads expressed the total of fuel in the forest. Values of mean, minimum, maximum and coefficient of variation of gross fuel loads for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 11.

Table 11 Gross fuel loads of various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	Gross fuel loads of fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	kg ha^{-1}	3,194.35	4,252.67	3,261.48
Maximum	kg ha^{-1}	8,258.92	10,276.57	11,426.57
Mean	kg ha^{-1}	5,789.23	6,353.72	7,184.59
Coefficient of variation	%	20.46	25.05	28.78

Table 11 revealed that mean of gross fuel load for tall grass fuel model presented the highest with value of 7,184.59 kg ha^{-1}, the nexts were litter with short grass fuel model and litter fuel model with values of 6,353.72 and 5,789.23 kg ha^{-1}, respectively. Gross fuel load of tall grass fuel model showed the highest value this was mainly due to amounts of dead herb and live herb loads, were outstanding high values. While, gross fuel loads in dry deciduous forest at Doi Sutep Pui National Park, Chiang Mai Province (Akaakara and Kittisatho, 1992), at Phu Phan National Park, Sakon Nakhon Province (Samran, 1992) and at Salakphra Wildlife Sanctuary, Kanchanaburi Province (Akaakara, 2002) were 5,190, 4,133 and 5,010 kg ha^{-1}, respectively.

Based on the study, the gross fuel load in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary of every fuel model was higher than those at Doi Sutep Pui National Park, Phu Phan National Park and Salakphra Wildlife Sanctuary, that was due to Huai Kha Khaeng Wildlife Sanctuary was declared to world heritage site. There were extremely protected regulations especially forest fire control, hence the accumulation of fuels were higher than the other sites.

1.2 Fuel Moisture Content

Fuel moisture content could be divided into 2 categories: dead fuel and live fuel. Dead fuels were litter, twig and dead herb that were without living tissue. Live fuels were live herb and undergrowth that were with living tissue and were able to maintain moisture content according to their life strategies. Moisture content was determined by a dry weight percentage basis.

1.2.1 Litter

Results of the study on moisture content of litter fuel type included values of mean, minimum, maximum and coefficient of variation for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 12.

Table 12 Moisture contents of litter for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	Moisture contents of litter for various fuel models		
		Litter	Litter with short Grass	Tall grass
Minimum	%	2.81	3.67	4.43
Maximum	%	15.71	16.21	15.48
Mean	%	8.92[a]	8.45[a]	8.75[a]
Coefficient of variation	%	36.32	29.35	28.69

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$) in moisture contents of litter for the fuel models.

Table 12 revealed that values of mean, minimum and maximum of the moisture contents for litter fuel model, litter with short grass fuel model and tall grass fuel model were similar in values. The means of those were 8.92, 8.45 and 8.75 per cent, respectively. The minimum values of those were 2.81, 3.67 and 4.43 per cent, respectively. The maximum values of those were 15.71, 16.21 and 15.48 per cent, respectively. In addition, the ANOVA indicated that means of moisture contents of litter fuel type for litter fuel model, litter with short grass fuel model and tall grass fuel model were not significant differences. Results of the study were similar in values this was due to litter fuels were fallen dead fuel that comprised of no living tissue. The moisture content of dead fuels is usually controlled by external factors as relative humidity, solar radiation, temperature etc. As a result, the moisture contents of litter fuel for litter fuel model litter with short grass fuel model and tall grass fuel model were not different.

Samran *et al.* (2002) found that moisture content of litter in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary in January, February, March and April were 23.40, 15.96, 9.69 and 28.66 per cent, respectively. While, Akaakara *et al.* (2004) also found that moisture contents of litter in those months were 19.51, 12.97, 9.62 and 10.34 per cent, respectively. In addition, Samran (1992) found that average moisture content of litter in dry deciduous dipterocarp forest at Phu Phan National Park, Sakon Nakhon Province from November to June was 15.45 per cent with minimum and maximum values of 7.56 and 31.11 per cent, respectively.

Moisture contents of the study in every fuel models were lower than those of the study of Samran *et al.* (2002) and Akaakara *et al.* (2004). The differences might be due to the studies were conducted in different year. Then, there were the differences of environmental factors that controlled dead fuel moisture content as relative humidity, solar radiation, temperature etc.

1.2.2 Twig

Results of the study on moisture content of twig fuel type included values of mean, minimum, maximum and coefficient of variation for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 13.

Table 13 Moisture contents of twig for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	Moisture contents of twig for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	%	3.44	4.69	8.52
Maximum	%	19.83	18.58	36.45
Mean	%	9.50[a]	9.39[a]	9.10[a]
Coefficient of variation	%	38.00	31.20	35.07

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$) in moisture contents of twig for the fuel models.

Table 13 revealed that means of moisture contents of twig fuel type for litter fuel model, litter with short grass fuel model and tall grass fuel model were much similar with values of 9.50, 9.39 and 9.10 per cent, respectively. In addition, the ANOVA indicated that means of moisture contents of twig fuel type for litter fuel model, litter with short grass fuel model and tall grass fuel model were not significant differences. The minimum and maximum values of litter fuel model and tall grass fuel model were rather similar, the minimum values of those were 3.44 and 4.69 per cent, respectively and the maximum values of those were 19.83 and 18.58 per cent, respectively. While, the minimum and maximum values of tall grass fuel model were 8.52 and 36.45 per cent, respectively. The differences of minimum and maximum values of moisture contents for tall grass fuel model were mainly due to the study site which was quite far-away from the study sites of litter fuel model and litter with short grass fuel model.

Samran *et al.* (2002) also studied moisture contents of twig in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary in January, February, March and April were 21.83, 17.01, 10.36 and 15.83 per cent, respectively. While, Akaakara *et al.* (2004) found that moisture contents of twig in those months were 17.27, 11.13, 62.34 and 18.65 per cent, respectively.

Results of the study indicated that moisture contents of twig were similar to the study on moisture contents of litter that was due to they were fallen dead fuel. The moisture contents of twig in every fuel models were lower than those of the studied of Samran *et al.* (2002) and Akaakara *et al.* (2004). The differences might be due to the studies were conducted in different periods of times. Then, there were the differences of environmental factors that controlled dead fuel moisture content as relative humidity, solar radiation, temperature etc.

1.2.3 Dead Herb

Results of the study on moisture content of dead herb fuel type included values of mean, minimum, maximum and coefficient of variation for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 14.

Table 14 Moisture contents of dead herb for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	Moisture contents of dead herb for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	%	10.00	10.70	8.52
Maximum	%	46.94	43.41	36.45
Mean	%	25.23[a]	20.92[b]	15.34[c]
Coefficient of variation	%	37.73	34.03	35.07

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$ followed by Duncan's multiple range test) in moisture contents of dead herb for the fuel models.

Table 14 revealed that mean moisture content of dead herb fuel type for tall grass fuel model presented the lowest with value of 15.34 per cent. The nexts of that were litter with short grass fuel model and litter fuel model with values of 20.92 and 25.23 per cent, respectively. In addition, the minimum and maximum of moisture contents for tall grass fuel model also presented the lowest values of 8.52 and 36.45 per cent, respectively. Results of the ANOVA followed by Duncan's multiple range test indicated that means of moisture content of dead herb for litter fuel model, litter with short grass fuel model and tall grass fuel model were significant differences. The mean of dead herb moisture contents for tall grass fuel model showed the lowest value that it might be due to during dry period opened canopy allowed the light to the ground directly. On the other hand, the mean of dead herb moisture content for litter fuel model showed the highest value that it might be due to during dry period the dense of canopy shaded the light to ground, where reserved the high moisture content.

1.2.4 Live Herb

Results of the study on moisture content of live herb fuel type included values of mean, minimum, maximum and coefficient of variation for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 15.

Table 15 Moisture contents of live herb for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	Moisture contents of live herb for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	%	33.06	25.92	23.83
Maximum	%	293.62	268.34	151.85
Mean	%	137.99^{a}	99.87^{b}	52.01^{c}
Coefficient of variation	%	38.86	45.06	42.15

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$ followed by Duncan's multiple range test) in moisture contents of live herb for the fuel models.

Table 15 revealed that the moisture content of live herb fuel type was similar to results of the study on dead herb. The mean, minimum and maximum of live herb moisture contents for tall grass fuel model presented the lowest with values of 52.01, 23.83 and 151.85 per cent, respectively. The nexts were litter with short grass fuel model with those values of 99.87, 25.92 and 268.34 per cent, respectively and litter fuel model with those values of 137.99, 33.06 and 293.62 per cent, respectively. Results of the ANOVA followed by Duncan's multiple range test indicated that means of moisture content of dead herb for litter fuel model, litter with short grass fuel model and tall grass fuel model were significant differences.

1.2.5 Undergrowth

Results of the study on moisture content of undergrowth fuel type included values of mean, minimum, maximum and coefficient of variation for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 16.

Table 16 Moisture contents of undergrowth for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	Moisture contents of undergrowth for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	%	75.39	74.19	71.32
Maximum	%	362.50	312.16	200.91
Mean	%	145.82^{a}	128.06^{ab}	118.99^{b}
Coefficient of variation	%	35.40	45.06	26.83

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, p<0.05 followed by Duncan's multiple range test) in moisture contents of undergrowth for the fuel models.

Table 16 revealed that the moisture content of undergrowth fuel type was similar pattern to results of the study on dead herb and live herb fuel types. The mean moisture content of undergrowth for tall grass fuel model presented the lowest with value of 118.99 per cent. The nexts were litter with short grass fuel model and litter fuel model with values of 128.06 and 145.82 per cent, respectively. In addition, the maximum moisture content of undergrowth for tall grass fuel model also presented the lowest with value of 200.91 per cent. The nexts were litter with short grass fuel model and litter fuel model with values of 312.16 and 362.50 per cent, respectively. For instance, the minimum moisture contents for litter fuel model, litter with short grass fuel model and tall grass fuel model were closely similar with values of 75.39, 74.19 and 71.32 per cent, respectively. Results of the ANOVA followed by Duncan's multiple range test indicated that the means of undergrowth moisture contents between litter fuel model and litter with short grass fuel model were not different and the means of that between litter with short grass fuel model and tall grass fuel model were not different. But, the means of undergrowth moisture contents between litter fuel model and tall grass fuel model were significantly different.

Samran *et al.* (2002) studied on moisture contents of undergrowths in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary in January, February, March and April were 126.55, 100.42, 188.93 and 241.83 per cent, respectively. While, Akaakara *et al.* (2004) also found that moisture contents of litters in those months were 88.50, 73.45, 94.56 and 79.01 per cent, respectively.

Results of the study were similar to the study results of Samran *et al.* (2002) that was due to the studies were only conducted during dry period namely January, February, March and April. While, the study of Akaakara *et al.* (2004) was conducted throughout a year. In addition, undergrowths were live fuel and the moisture content was not controlled totally by external factors because tissues were able to maintain certain phase of moisture according to their life strategies. Moreover, live fuel has big variety in moisture contents depending on their physiological abilities in e.g. tolerating drought.

1.2.6 Moisture Content of Gross Fuel

Mean moisture content of gross fuel was weighted by biomass as shown in equation (26). During fire season, values of mean, minimum, maximum and coefficient of variation of moisture contents of gross fuel for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 17.

Table 17 Moisture contents of gross fuel for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	Moisture contents of gross fuel for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	%	4.92	10.38	8.72
Maximum	%	41.76	70.36	42.77
Mean	%	21.39[a]	25.04[a]	23.15[a]
Coefficient of variation	%	43.29	40.58	38.32

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$) in moisture contents of gross fuel for the fuel models.

Table 17 revealed that means of moisture contents of gross fuels for litter fuel model, litter with short grass fuel model and tall grass fuel model were rather similar to each other with values of 21.39, 25.04 and 23.15 per cent, respectively. Besides, results of the ANOVA indicated that the means of moisture content for litter fuel model, litter with short grass fuel model and tall grass fuel model were not significant differences. The minimum moisture contents of gross fuel for litter fuel model, litter with short grass fuel model and tall grass fuel model were 4.92, 10.38 and 8.72 per cent, respectively. For instance, the maximum values of those fuel models were 41.76, 70.36 and 42.77 per cent, respectively.

Akaakara *et al.* (2004) also found that moisture contents of gross fuels in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary in January, February, March and April were 56.55, 21.19, 33.96 and 33.41 per cent, respectively. Mean moisture content of fuel in dry deciduous dipterocarp forest during fire season at Doi Sutep Pui National Park, Chiang Mai Province was 19 per cent with minimum value of 9 per cent in April (Akaakara and Kittisatho, 1992) while, mean moisture content of fuel at Salakphra Wildlife Sanctuary, Kanchanaburi Province was 20 per cent with minimum value of 7 per cent in April (Akaakara, 2002).

Based on the study, means and minimum moisture contents of gross fuels for litter fuel model, litter with short grass fuel model and tall grass fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary were closely similar in values with fuel moisture contents of dry deciduous dipterocarp forest at Doi Sutep Pui National Park, Chiang Mai Province and at Salakphra Wildlife Sanctuary, Kanchanaburi Province.

1.3 Surface Area to Volume Ratio (σ)

Surface area to volume ratio of fuel particle is the whole of surface area around particle divided by its volume. It indicates the size of fuel, number value of fine fuel was higher than that of large fuel. The surface area to volume ratios of fuel particles which included litter, twig, herbs (dead and live) and undergrowth were determined. The unit of surface area to volume ratio was expressed in m^{-1} followed Bachmann (2001). Results of the study were presented as follows:

1.3.1 Litter

Results of the study on surface area to volume ratio of litter fuel type included values of mean, minimum, maximum and coefficient of variation for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 18.

Table 18 Surface area to volume ratios (σ) of litter for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	σ of litter for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	m^{-1}	6,789.51	6,786.42	6,312.38
Maximum	m^{-1}	11,055.86	10,635.24	9,723.95
Mean	m^{-1}	8,446.84^{a}	8,599.85^{a}	7,311.59^{b}
Coefficient of variation	%	12.14	10.12	11.56

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$ followed by Duncan's multiple range test) in surface area to volume ratios of litter for the fuel models.

Table 18 revealed that mean, minimum and maximum values of surface area to volume ratios for litter fuel model and litter with short grass fuel model were similar. The mean values of those were 8,446.84 and 8,599.85 m^{-1}, respectively, the minimum values of those were 6,789.51 and 6,786.42 m^{-1}, respectively and the maximum values of those were 11,055.86 and 10,635.24 m^{-1}, respectively. While, mean, minimum and maximum of surface area to volume ratio for tall grass fuel model were 7,311.59, 6,312.38 and 9,723.95 m^{-1}, respectively. In addition, results of the ANOVA followed by Duncan's multiple range test indicated that mean values of surface area to volume ratios for litter fuel model and for litter with short grass fuel model were not significant differences. There were significant differences between mean values of surface area to volume ratios for litter fuel model and for tall grass fuel model and between mean values of surface area to volume ratios for litter with short grass fuel model and for tall grass fuel model.

Hernando (2004) reported that surface area to volume ratios of leaves for broad leaves species ranged from 4,550 to 13,000 m^{-1} and for, needles of *Pinus spp.* ranged from 3,007 to 6,167 m^{-1}. Results of the study revealed that the values of surface area to volume ratios of litter for every fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary were within surface area to volume ratios of leaves for board leaves species. But, the values were higher than those for needles of *Pinus spp.*

1.3.2 Twig

Results of the study on surface area to volume ratio of twig fuel type included values of mean, minimum, maximum and coefficient of variation for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 19.

Table 19 Surface area to volume ratios (σ) of twig for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	σ of twig for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	m^{-1}	775.01	705.38	712.49
Maximum	m^{-1}	2,031.98	2,013.82	2,047.69
Mean	m^{-1}	1,275.64^{a}	1,160.61^{a}	1,282.73^{a}
Coefficient of variation	%	22.99	25.75	26.15

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$) in surface area to volume ratios of twig for the fuel models.

Table 19 revealed that mean, minimum and maximum values of surface area to volume ratios of twig for litter fuel model, litter with short grass fuel model and tall grass fuel model were rather similar to each other. The mean values of the surface area to volume ratios of those for fuel models were 1,275.64, 1,160.61 and 1,282.73 m^{-1}, respectively, the minimum values of the surface area to volume ratios of those for fuel models were 775.01, 705.38 and 712.49 m^{-1}, respectively and the maximum values of the surface area to volume ratios of those for fuel models were 2,031.98, 2,013.82 and 2,047.69 m^{-1}, respectively. In addition, results of the ANOVA indicated that the mean values of the surface area to volume ratios of twig for those fuel models were not significant differences. The mean, minimum and maximum values of surface area to volume ratios of twigs for those fuel models were similar, that might be due to most twigs were fallen branch of tree, their diameters did not exceed 7.6 cm.

Hernando (2004) reported that surface area to volume ratios of twig for broad leaves species as following; 0-2 mm diameter ranged from 2,450 to 2,780 m^{-1}, 0-6 mm diameter ranged from 1,865 to 4,500 m^{-1}, 2-6 mm diameter ranged from 959 to 9,600 m^{-1} and 6-25 mm diameter ranged from 307 to 412 m^{-1}. Based on results of the study, the means of surface area to volume ratios of twig for every fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary were within the surface area to volume ratios of twig for broad leaves species 2-6 mm diameter.

1.3.3 Herbs

Results of the study on surface area to volume ratio of herbs (dead and live) fuel type included values of mean, minimum, maximum and coefficient of variation for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 20.

Table 20 Surface area to volume ratio (σ) of herbs for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	σ of herbs for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	m^{-1}	3,433.71	3,464.96	3,020.15
Maximum	m^{-1}	10,579.15	10,304.56	8,731.74
Mean	m^{-1}	6,421.55[a]	6,367.10 [a]	5,394.73 [b]
Coefficient of variation	%	24.77	24.06	26.08

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$ followe by Duncan's multiple range test) in surface area to volume ratios of herbs for the fuel models.

Table 20 revealed that the surface area to volume ratios of herbs were similar pattern to the litter. Mean, minimum and maximum values of surface area to volume ratio for litter fuel model and litter with short grass fuel model were rather equivalence to each other. The mean values of surface area to volume ratios for those fuel models were 6,421.55 and 6,367.10 m^{-1}, respectively, the minimum values of surface area to volume ratios for those fuel models were 3,433.71 and 3,464.96 m^{-1}, respectively and the maximum values of surface area to volume ratios for those fuel models were 10,579.15 and 10,304.56 m^{-1}, respectively. While, mean, minimum and maximum of surface area to volume ratio for tall grass fuel model were 5,394.73, 3,020.15 and 8,731.74 m^{-1}, respectively. In addition, results of the ANOVA followed by Duncan's multiple range test indicated that mean values of surface area to volume ratios for litter fuel model and for litter with short grass fuel model were not significant differences. There were significant differences between mean values of the surface area to volume ratios for litter fuel model and for tall grass fuel model and between mean values of the surface area to volume ratios for litter with short grass fuel model and for tall grass fuel model.

Surface area to volume ratio of live herb for NFFL model was 4,920 m^{-1} (Fischer, 1982). While, surface area to volume ratios of live herb for the BehavePlus program were set between 358 and 13,123 m^{-1} (USDA Forest Service, 2000). Surface area to volume ratios of herbs for every fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary were rather similar to the surface area to volume ratio of live herb for the NFFL model and within the values of live herb for the BehavePlus program.

1.3.4 Undergrowth

Results of the study on surface area to volume ratio of undergrowth fuel type included values of mean, minimum, maximum and coefficient of variation for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 21.

Table 21 Surface area to volume ratios (σ) of undergrowth for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	σ of undergrowth for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	m^{-1}	645.44	795.45	713.02
Maximum	m^{-1}	2,960.61	2,290.99	2,378.97
Mean	m^{-1}	1,469.01[a]	1,357.55[a]	1,562.88[a]
Coefficient of variation	%	30.29	28.63	23.89

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$) in surface area to volume ratios of undergrowth for the fuel models.

Table 21 revealed that the surface area to volume ratios of undergrowth were similar pattern to the twig. Mean, minimum and maximum values of surface area to volume ratios of undergrowths for litter fuel model, litter with short grass fuel model and tall grass fuel model were rather similar in values. The mean surface area to volume ratios of those fuel models were 1,469.01, 1,357.55 and 1,562.88 m^{-1}, respectively, the minimum surface area to volume ratios of those fuel models were 645.44, 795.45 and 713.02 m^{-1}, respectively and the maximum surface area to volume ratios of those fuel models were 2,960.61, 2,290.99 and 2,378.97 m^{-1}, respectively. In addition, results of the ANOVA indicated that the mean surface area to volume ratios of undergrowths for litter fuel model, litter with short grass fuel model and tall grass fuel model were not significant differences. The mean, minimum and maximum surface area to volume ratios of undergrowths for litter fuel model, for litter with short grass fuel model and for tall grass fuel model were similar, that might be due to most undergrowths were seedling and shrub, their diameters do not exceed 0.6 cm.

The study showed that, surface area to volume ratio of litter fuel type was the highest in values. The nexts were herbs, twig and undergrowth, respectively. Hence, the fuel sizes in dry deciduous forest at Huai Kha Khaeng Wildlife Sanctuary from small to large were litter, herb, twig and undergrowth, respectively. In addition, surface area to volume ratios were applied to classify forest fuel into 3 classes following; 6,310 - 13,000 m^{-1} were fine fuels, 1,570 - 6,300 m^{-1} were medium fuels and 520 - 1,560 m^{-1} were coarse fuels (Kaitpraneet, 1983). According to the classification litter was fine fuel, twigs were medium to coarse fuels, herbs were fine to medium fuels and undergrowths were medium to coarse fuels. Consequently, litter and herbs were strongly affected to fire behaviors more than twig and undergrowth in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

1.3.5 Gross Fuel

Mean of surface area to volume ratio of gross fuel had to be weighted with the corresponding loading. Burgan and Rothermel (1984) defined the mean of surface area to volume ratio as shown in equation (20). Values of mean, minimum, maximum and coefficient of variation of surface area to volume ratio of gross fuel for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 22.

Table 22 Surface area to volume ratios (σ) of gross fuel for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	σ of gross fuel for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	m^{-1}	6,435.72	6,121.03	4,297.04
Maximum	m^{-1}	10,617.52	9,841.92	8,041.02
Mean	m^{-1}	7,937.95[a]	7,853.29[a]	5,998.82[b]
Coefficient of variation	%	12.68	9.51	15.00

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$ followed by Duncan's multiple range test) in surface area to volume ratios of gross fuel for the fuel models.

Table 22 revealed that values of mean, minimum and maximum values of surface area to volume ratios of gross fuel for litter fuel model and litter with short grass fuel model were rather similar to each other. The mean surface area to volume ratios of those fuel models were 7,937.95 and 7,853.29 m^{-1}, respectively, the minimum surface area to volume ratios of those fuel models were 6,435.72 and 6,121.03 m^{-1}, respectively and the maximum surface area to volume ratios of those fuel models were 10,617.52 and 9,841.92 m^{-1}, respectively. While, mean, minimum and maximum values of surface area to volume ratios of gross fuel for tall grass fuel model were 5,998.82, 4,297.04 and 8,041.02 m^{-1}, respectively. In addition, results of the ANOVA followed by Duncan's multiple range test indicated that mean of surface area to volume ratios of gross fuel for litter fuel model and for litter with short grass fuel model were not significant differences. There were significant differences between mean surface area to volume ratios of gross fuel for litter fuel model and for tall grass fuel model and between mean surface area to volume ratios of gross fuel for litter with short grass fuel model and for tall grass fuel model.

Sathirasilapin (1987) found that surface area to volume ratio of fuel in dry deciduous dipterocarp forest at Sakaerat, Nakhon Ratchasima Province was 11,761.80 m^{-1}, this value was similar to the maximum surface area to volume ratios of litter fuel type for litter fuel model and for litter with short grass fuel model.

1.4 Fuel Particle Density (ρ_p)

Particle density or mass per volume ratio affected to ignition time, Fons (1946) found that the ignition time for fuel particles were directly proportional to their densities. The density of fuel particles which included litter, twig, herbs (dead and live) and undergrowth were determined. Results of the study were presented as follows:

1.4.1 Litter

Results of the study on fuel particle density of litter fuel type included values of mean, minimum, maximum and coefficient of variation of the particle densities of litter for litter fuel model, for litter with short grass fuel model and for tall grass fuel model were presented in Table 23.

Table 23 Particle density (ρ_p) of litter for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	ρ_p of litter for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	kg m^{-3}	321.50	321.11	220.00
Maximum	kg m^{-3}	476.00	485.00	460.00
Mean	kg m^{-3}	392.03^{a}	407.69^{a}	343.09^{b}
Coefficient of variation	%	9.28	9.35	12.61

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$ followed by Duncan's multiple range test) in particle density of litter fuel for the fuel models.

Table 23 revealed that mean, minimum and maximum values of particle densities of litter for litter fuel model and litter with short grass fuel model were rather similar to each other. The mean particle densities of litter for those fuel models were 392.03 and 407.69 kg m^{-3}, respectively, the minimum particle densities of litter for those fuel models were 321.50 and 321.11 kg m^{-3}, respectively and the maximum particle densities of litter for those fuel models were 476 and 485 kg m^{-3}, respectively. While, mean, minimum and maximum values of particle densities of litter for tall grass fuel model were 343.09, 220 and 460 kg m^{-3}, respectively. In addition, results of the ANOVA followed by Duncan's multiple range test indicated that mean values of particle densities of litter for litter fuel model and for litter with short grass fuel model were not significant differences. There were significant differences between mean particle densities of litter for litter fuel model and for tall grass fuel model and between mean particle densities of litter for litter with short grass fuel model and for tall grass fuel model.

Hernando (2004) reported that particle densities of leaves for broad leaves species ranged from 571 to 810 kg m^{-3} as for, needles of *Pinus spp.* ranged from 490 to 847 kg m^{-3}. Based on the study, particle densities of litter fuel type for every fuel models were lower than particle densities of leaves for broad leaves species and needles of *Pinus spp.*

1.4.2 Twig

Results of the study on fuel particle density of twig fuel type included values of mean, minimum, maximum and coefficient of variation for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 24.

Table 24 Particle density (ρ_p) of twig for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	ρ_p of twig for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	kg m^{-3}	399.24	400.57	414.11
Maximum	kg m^{-3}	935.11	900.82	840.95
Mean	kg m^{-3}	646.30^{a}	623.50^{a}	598.52^{a}
Coefficient of variation	%	18.07	17.15	13.77

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$) in particle density of twig fuel type for the fuel models.

Table 24 revealed that mean, minimum and maximum values of particle densities of twig for litter fuel model, litter with short grass fuel model and tall grass fuel model were rather similar to each other. The mean particle densities of twig for those fuel models were 646.30, 623.50 and 598.52 kg m^{-3}, respectively, the minimum particle densities of twig for those fuel models were 399.24, 400.57 and 414.11 kg m^{-3}, respectively and the maximum particle densities of twig for those fuel models were 935.11, 900.82 and 840.95 kg m^{-3}, respectively. In addition, results of the ANOVA indicated that the mean values of particle densities of twig for litter fuel model, for litter with short grass fuel model and for tall grass fuel model were not significant differences. The mean, minimum and maximum values of particle densities of twig for those fuel models were similar pattern, that it might be due to most twigs were woody branch of tree.

Hernando (2004) reported that particle densities of twig for broad leaves species as following; 0-2 mm diameter ranged from 680 to 935 kg m^{-3}, 2-6 mm diameter ranged from 227 to 970 kg m^{-3} and 6-25 mm diameter ranged from 924 to 962 kg m^{-3}. The ranges of particle densities values of twig in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary were closely to the particle densities of twig for broad leaves species.

1.4.3 Herbs

Results of the study on fuel particle density of herbs fuel type included values of mean, minimum, maximum and coefficient of variation for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 25.

Table 25 Particle density (ρ_p) of herbs for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	ρ_p of herbs for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	kg m^{-3}	227.78	242.28	229.21
Maximum	kg m^{-3}	549.85	736.74	491.33
Mean	kg m^{-3}	368.26^{a}	378.27^{a}	350.26^{a}
Coefficient of variation	%	20.71	23.91	20.35

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$) in particle densities of herbs for the fuel models.

Table 25 revealed that mean, minimum and maximum values of particle densities of herbs for litter fuel model, for litter with short grass fuel model and for tall grass fuel model were rather similar to each other. The mean particle densities of herbs for those fuel models were 368.26, 378.27 and 350.26 kg m^{-3}, respectively. While, Hernando (2004) reported that particle density of live grass was 442 kg m^{-3}. The minimum particle densities of herbs for those fuel models were 227.78, 242.28 and 229.21 kg m^{-3}, respectively and the maximum particle densities of herbs for those fuel models were 549.85, 736.74 and 491.33 kg m^{-3}, respectively. In addition, results of the ANOVA indicated that the mean values of particle densities of herbs for litter fuel model, for litter with short grass fuel model and for tall grass fuel model were not significant differences. The mean, minimum and maximum values of particle densities of herbs for those fuel models were similar, that it might be due to herbs in all fuel models were composed of grasses and herbaceous plants that were the same type and species.

1.4.4 Undergrowth

Results of the study on fuel particle density of undergrowth fuel type included values of mean, minimum, maximum and coefficient of variation for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 26.

Table 26 Particle density (ρ_p) of undergrowth for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	ρ_p of undergrowths for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	kg m^{-3}	585.48	490.83	611.75
Maximum	kg m^{-3}	1,129.49	1,005.69	1,603.56
Mean	kg m^{-3}	789.53[a]	763.34[a]	862.96[b]
Coefficient of variation	%	18.17	16.72	20.54

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$ followed by Duncan's multiple range test) in particle densities of undergrowth for the fuel models.

Table 26 revealed that mean, minimum and maximum values of particle densities of undergrowths for litter fuel model and for litter with short grass fuel model were rather similar to each other. The mean particle densities of undergrowth for those fuel models were 789.53 and 763.34 kg m^{-3}, respectively, the minimum particle densities of undergrowth for those fuel models were 585.48 and 490.83 kg m^{-3}, respectively and the maximum particle densities of undergrowth for those fuel models were 1,129.49 and 1,005.69 kg m^{-3}, respectively. While, mean, minimum and maximum values of particle densities of undergrowth for tall grass fuel model were 862.96, 611.75 and 1,603.56 kg m^{-3}, respectively. In addition, results of the ANOVA followed by Duncan's multiple range test indicated that mean particle densities of undergrowths for litter fuel model and for litter with short grass fuel model were not significant differences. There were significant differences between mean particle densities of undergrowths for litter fuel model and for tall grass fuel model and between mean particle densities of undergrowths for litter with short grass fuel model and for tall grass fuel model.

Results of the study showed that, the particle densities of fuels in dry deciduous forest in Huai Kha Khaeng Wildlife Sanctuary from minimum to maximum were herb, litter, twig and undergrowth, respectively. According to Fons (1946), the ignition times for fuels in dry deciduous forest in Huai Kha Khaeng Wildlife Sanctuary from minimum to maximum were herbs, litter, twig and undergrowth, respectively.

1.4.5 Gross Fuel

Mean particle density of gross fuel was weighted by biomass as shown in equation (24). Values of mean, minimum, maximum and coefficient of variation of particle densities of gross fuel for litter fuel model, litter with short grass fuel model and tall grass fuel model were presented in Table 27.

Table 27 Particle density (ρ_p) of gross fuel for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	ρ_p of gross fuel for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	kg m^{-3}	382.81	370.35	300.22
Maximum	kg m^{-3}	539.84	597.50	595.57
Mean	kg m^{-3}	471.10^{a}	467.37^{a}	411.56^{b}
Coefficient of variation	%	8.54	10.67	14.35

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$ followed by Duncan's multiple range test) in particle densities of gross fuel for the fuel models.

Table 27 revealed that mean, minimum and maximum values of particle densities of gross fuel for litter fuel model and litter with short grass fuel model were rather similar to each other. The mean particle densities of gross fuel for those fuel models were 471.10 and 467.37 kg m^{-3}, respectively, the minimum particle densities of gross fuel for those fuel models were 382.81 and 370.35 kg m^{-3}, respectively and the maximum particle densities of gross fuel for those fuel models were 539.84 and 597.50 kg m^{-3}, respectively. While, mean, minimum and maximum values of particle densities of gross fuel for tall grass fuel model were 411.56, 300.22 and 595.57 kg m^{-3}, respectively.

In addition, results of the ANOVA followed by Duncan's multiple range test indicated that mean particle densities of gross fuel for litter fuel model and for litter with short grass fuel model were not significant differences. There were significant differences between mean particle densities of gross fuel for litter fuel model and for tall grass fuel model and between mean particle densities of gross fuel for litter with short grass fuel model and for tall grass fuel model. Mean particle density of gross fuel for tall grass fuel model was similar to particle density of fuel in dry deciduous dipterocarp forest at Sakaerat, Nakhon Ratchasima Province, 437.62 kg m^{-3} (Sathirasilapin, 1987).

1.5 Fuel Bed Depth

Fuel bed depth is sometimes called fuel bed bulk depth. Brown (1974) gave the definition of fuel bed depth that was the vertical continuous of fuel from the lowest of litter to the maximum of fuel height in the fuel bed, thus Albini and Brown (1978) defined fuel bed depth that it was the vertical perimeter of fuel, which connected to fire behavior. Litter fuel model, fuel bed depth was the accumulation of fallen leaves, that ranged from 7 to 12 cm with mean value of 10 cm. Tall grass fuel model, the fuel bed depth was the height of grass, that ranged from 50 to 70 cm with mean values of 60 cm. Litter with short grass fuel model as a heterogeneous fuel bed, the fuel depth was the height of equivalent of litter and grass, that ranged from 20 to 40 cm with mean values of 30 cm. Fuel bed depths for various fuel models were presented in Table 28.

Table 28 Fuel bed depths for various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Unit	Fuel bed depths for various fuel models		
		Litter	Litter with short grass	Tall grass
Minimum	cm	7	20	50
Maximum	cm	12	40	70
Mean	cm	10	30	60

1.6 Heat of Combustion

Heat of combustion or heat value was determined from 11 dominant fuels in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary as presented in Table 29. The values ranged from 4,138.31 to 4918.88 cal g^{-1} with mean value of 4,505.85 cal g^{-1}. The heat values of fuel in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary together with the recommendation by Chomchan and Panyaatanya (1981), were 4,500 cal g^{-1}. Heat values of forest fuel were mostly between 4,167 and 5,556 cal g^{-1} (Kaitpraneet, 1983).

Although heat values were difference between parts and species but the differences were only from 4 to 10 per cent, because the main substances in wood were cellulose and lignin (Chomchan and Panyaatanya, 1981). Furthermore, Neenan and Steinback (1979) found that heat values of hard wood species were not difference. All of 13 fuel models in USA used 8,000 Btu lb^{-1} or 4,444.46 cal g^{-1} (Andrews, 1986). Sompoh (1998) determined and reported that heat value in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary was 4,457.23 cal g^{-1}. Besides, heat value in dry deciduous dipterocarp forest at Sakaerat, Nakhon Ratchasima Province was 6,958 Btu lb^{-1} or 3,865.57 cal g^{-1} (Sathirasilapin, 1987).

Table 29 Heat values of fuels in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

No.	Botanical name	Heat value (cal g^{-1})
1	*Cycas circinalis* L.	4,785.40
2	*Dipterocarpus obtusifolius* Teijsm. ex Miq.	4,292.61
3	*Dipterocarpus tuberculatus* Roxb.	4,620.29
4	*Imperata cylindrica* Beauv.	4,264.89
5	*Shorea siamensis* Miq.	4,404.23
6	*Pterocarpus macrocarpus* Kurz	4,439.38
7	*Shorea obtusa* Wall. ex Blume	4,692.74
8	*Terminalia mucronata* Craib & Hutch	4,138.31
9	*Themeda* triandra Forsk.	4,219.44
10	*Vitex peduncularis* Wall. ex Schauer	4,788.20
11	*Xylia kerrii* Craib & Hutch.	4,918.88
	Mean	4,505.85
	Coefficient of variation (%)	5.91

1.7 Mineral Content and Effective Mineral Content

Mineral content (ash) and effective mineral content (silica free ash) were determined from 4 samples of tree leaves and 2 samples of grasses, that are indicators of dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary as presented in Table 30. Means of mineral content and effective mineral content of fuel in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary were 8.09 and 5.92 per cent, respectively. Mineral content of *Dipterocarpus tuberculatus* Roxb was the highest with value of 12.34 per cent, while *Shorea obtusa* Wall. ex Blume presented the lowest with value of 3.95 per cent. As for effective mineral contents of *Dipterocarpus obtusifolius* Teijsm. ex Miq. and *Dipterocarpus tuberculatus* Roxb presented high values of 8.97 and 8.04 per cent, respectively, while, *Shorea obtusa* Wall. ex Blume and *Themeda triandra* Forssk. presented low values of 3.18 and 3.66 per cent. Sathirasilapin (1987) determined mineral content and effective mineral content in dry deciduous dipterocarp forest at Sakaerat, Nakhon Ratchasima with values of 12 and 4 per cent, respectively. While, the values of mineral content and effective mineral content for the 13 fuel models were 5.5 and 1 per cent, respectively (Andrews, 1986).

Table 30 Mineral content and effective mineral content of fuel in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

No.	Botanical name	Mineral contents (%)	Effective mineral contents (%)
1	*Shorea obtusa* Wall. ex Blume	3.95	3.18
2	*Shorea siamensis* Miq.	9.00	7.42
3	*Dipterocarpus tuberculatus* Roxb.	12.34	8.04
4	*Dipterocarpus obtusifolius* Teijsm. ex Miq.	10.40	8.97
5	*Themeda triandra* Forssk.	7.72	3.66
6	*Imperata cylindrica* Beauv.	5.11	4.23
	Mean	8.09	5.92

1.8 Moisture Content of Extinction

Moisture content of extinction is required by the Rothermel's fire spread model, but it is not easily determined for most natural fuels. Rothermel (1972) used 30 per cent for surface fuel, because this value is the fiber saturation point of many dead fuels. Sathirasilapin (1987) used moisture content of extinction of 30 per cent for predicting fire behavior in dry deciduous dipterocarp forest at Sakaerat, Nakhon Ratchasima. Moisture content of extinction of the 13 fuel models were varies from 12 to 40 per cent (Andrews, 1986). Harvey *et al.* (1997) found that moisture content of extinction for fuel models in Swiss National Park were ranged from 16 to 44 per cent. This study used 30 per cent moisture content of extinction for all fuel models followed Rothermel (1972) and Sathirasilapin (1987).

2. Fuel Model

Fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary could be classified into 3 models namely: litter fuel model, litter with short grass fuel model and tall grass fuel model. The litter fuel model was mostly composed of falling leaves and twig of tree, the model was located in the area, where the crown covers were very dense and close. The litter with short grass fuel model was located in area, where the crown covers were lower than litter fuel model. The amounts of falling leaves and short grass fuel were equal to each other. The tall grass fuel model was located in opened crown cover, the fuels mostly were tall grasses such as *Themeda triandra* Forssk and *Imperata cylindrica* Beauv.

The fuel model was composed of 9 properties of fuel namely: loading, surface area to volume ratio, fuel bed depth, moisture content, moisture content of extinction, heat value, mineral content, particle density and effective mineral content. The input parameter values of fuel models were the study results of fuel properties while the units of parameters were metric followed Bachmann (2001). The set number of fuel properties for the fuels were presented in Table 31 and detailed as follows:

Table 31 Fuel model parameters for dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Fuel Parameters	Units	Fuel types	Fuel Models		
			Litter	Litter with short grass	Tall grass
Loading	kg ha^{-1}	Litter	3,858.27	3,605.25	1,926.90
		Twig	1,275.18	1,293.46	1,195.98
		Dead herb	138.77	434.04	2,625.30
		Live herb	178.43	642.33	985.41
		Undergrowth	338.58	378.64	451.00
Moisture content	%	Litter	8.92	8.45	8.75
		Twig	9.50	9.39	9.10
		Dead herb	25.23	20.92	15.34
		Live herb	137.99	99.87	52.01
		Undergrowth	145.82	128.06	118.99
Surface area to volume ratio	m^{-1}	Litter	8,446.84	8,599.85	7,311.59
		Twig	1,275.64	1,160.61	1,282.73
		Herbs	6,421.55	6,367.10	5,394.73
		Undergrowth	1,469.01	1,357.55	1,562.88
Particle density	kg m^{-3}	Litter	392.03	407.69	343.09
		Twig	646.30	623.50	598.52
		Herbs	368.26	378.27	350.26
		Undergrowth	789.53	763.34	862.96
Fuel bed depth	m		0.10	0.30	0.60
Heat value	kJ kg^{-1}		18,880	18,880	18,880
Mineral content	%		8.09	8.09	8.09
Effective mineral content	%		5.92	5.92	5.92
Moisture content of extinction	%		30	30	30

2.1 Litter Fuel Model

Results of the study on general characteristics of litter fuel model showed that the ground was more continuous with fallen leaves during dry season. The averages of density, diameter at breast height (DBH) and height of saplings were 1,900 stems ha^{-1}, 0.94 cm and 3.09 m, respectively. The averages of density, diameter at breast height (DBH), basal area and crown cover of trees were 559 stems ha^{-1}, 18.39 cm, 16.02 m^2ha^{-1} and 10,258.80 m^2ha^{-1}, respectively.

The input parameter values of the fuel model showed that loadings of litter, twig, dead herb, live herb and undergrowth were 3,858.27, 1,275.18, 138.77 178.43 and 338.58 kg ha^{-1}, respectively. Moisture contents of those were 8.92, 9.50, 25.23, 137.99 and 145.82 per cent, respectively. Surface area to volume ratios of litter, twig, herbs (dead and live) and undergrowth were 8,446.84, 1,275.64, 6,421.55 and 1,469.01 m^{-1}, respectively. Particle densities of those were 392.03, 646.30, 368.26 and 789.53 kg m^{-3}, respectively. Fuel bed depth, heat value, mineral content, effective mineral content and moisture content of extinction were 0.10 m, 18,880 kJ kg^{-1}, 8.09 per cent , 5.92 per cent and 30 per cent , respectively.

2.2 Litter with Short Grass Fuel Model

Results of the study on general characteristics of litter with short grass fuel model showed that the ground was more continuous with fallen leaves and dead short grasses such as *Apluda nutica* L., *Heteropogon contortus* (L.) Roem. & Schult. and *Themeda australis* Stapf during dry period. The averages of density, diameter at breast height (DBH) and height of saplings were 1,958.33 stems ha^{-1}, 0.92 cm and 3.14 m, respectively. The averages of density, diameter at breast height (DBH), basal area and crown cover of trees were 507 stems ha^{-1}, 18.44 cm, 16.83 m^2ha^{-1} and 9,111.38 m^2ha^{-1}, respectively.

The input parameter values of the fuel model showed that loadings of litter, twig, dead herb, live herb and undergrowth were 3,605.25, 1,293.46, 434.04, 642.33 and 378.64 kg ha^{-1}, respectively. Moisture contents of those were 8.45, 9.39, 20.92, 99.87 and 128.06 per cent, respectively. Surface area to volume ratios of litter, twig, herbs (dead and live) and undergrowth were 8,599.85, 1,160.61, 6,367.01 and 1,357.55 m^{-1}, respectively. Particle densities of those were 407.69, 623.50, 378.27 and 763.34 kg m^{-3}, respectively. Fuel bed depth, heat value, mineral content, effective mineral content and moisture content of extinction were 0.30 m, 18,880 kJ kg^{-1}, 8.09 per cent, 5.92 per cent and 30 per cent, respectively.

2.3 Tall Grass Fuel Model

Results of the study on general characteristics of tall grass fuel model showed that the ground cover was more continuous, with tall grasses and herbs. The grasses were dense and similar species to those in the *Shorea* associations, such as *Imperata cylindrica* Beauv., and *Themeda triandra* Forssk. The averages of density, diameter at breast height (DBH) and height of saplings were 1,569 stems ha^{-1}, 0.37 cm and 1.57 m, respectively. The averages of density, diameter at breast height (DBH), basal area and crown cover of trees were 153 stems ha^{-1}, 20.64 cm, 6.10 m^2ha^{-1} and 3,199.76 m^2ha^{-1}, respectively.

The input parameter values of the fuel model showed that loadings of litter, twig, dead herb, live herb and undergrowth were 1,926.90, 1,195.98, 2,625.30, 985.41 and 451.00 kg ha^{-1}, respectively. Moisture contents of those were 8.75, 9.10, 15.34, 52.01 and 118.99 per cent, respectively. Surface area to volume ratios of litter, twig, herbs (dead and live) and undergrowth were 7,311.59, 1,282.73, 5,394.73 and 1,562.88 m^{-1}, respectively. Particle densities of those were 343.09, 598.52, 350.26 and 862.96 kg m^{-3}, respectively. Fuel bed depth, heat value, mineral content, effective mineral content and moisture content of extinction were 0.60 m, 18,880 kJ kg^{-1}, 8.09 per cent, 5.92 per cent and 30 per cent, respectively.

3. Fire Behavior

Fire behavior is the integrator of all of the weather elements, fuel bed properties, and topographic factors within the fire environment (Goldammer, 1993). The most common fire behavior descriptors are rate of fire spread, fire intensity and flame length. Rate of fire spread is the distance of fire advance per a unit of time. Head, flank and rear fires are the common orientations of fire advance. Rate of fire spread in the study was presented the observed distance of head, flank and rear fires in meter per a minute. Fire intensity is a measurement the rate of energy release by a fire. Fireline intensity also known as Byram's fireline intensity or frontal fire intensity was determined at the study. It indicated that the amount of heat energy released per a unit of time per a unit of length of fire front. Flame lengths were measured from the mid-point of base flame to tip of flame. Byram (1959) gave the relating flame length to fireline intensity as shown in equation (12). In addition, fire temperature, burning area and perimeter growths were also presented in the study. The fire behaviors and weather factors of 14 burning plots for litter fuel model, 8 burning plots for litter with short grass fuel model and 6 burning plots for tall grass fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary, were studied during fire season in 2007. Results of the study were presented in average, minimum and maximum values in Table 32 and detailed as follows:

3.1 Fire Behavior of Litter Fuel Model

Fire behavior of litter fuel model was shown in Table 32 and Figure 6. Average rate of head fire spread was 1.34 m min^{-1} with minimum and maximum values of 0.57 and 3.00 m min^{-1}, respectively. Average rate of flank fire spread was 0.48 m min^{-1} with minimum and maximum values of 0.30 and 0.77 m min^{-1}, respectively. Average rate of rear fire spread was 0.35 m min^{-1} with minimum and maximum values of 0.22 and 0.53 m min^{-1}, respectively. Average fireline intensity was 184.71 kWm^{-1} with minimum and maximum values of 78.44 and 412.86 kWm^{-1}, respectively. Average flame length was 0.86 m with minimum and maximum values of 0.60 and 1.28 m, respectively.

Table 32 Fire behaviors of various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Fire behaviors			Fuel models		
			Litter	Litter with short grass	Tall grass
Rate of spreads ($m\ min^{-1}$)	Head	Minimum	0.57	1.69	1.24
		Maximum	3.00	3.94	4.17
		Mean	1.34^a	2.75^b	2.39^b
	Flanks	Minimum	0.30	0.66	0.36
		Maximum	0.77	1.34	1.15
		Mean	0.48^a	0.98^b	0.76^b
	Rear	Minimum	0.22	0.36	0.31
		Maximum	0.53	0.80	0.67
		Mean	0.35^a	0.52^b	0.51^b
Fireline intensities (kWm^{-1})		Minimum	78.44	255.12	211.70
		Maximum	412.86	594.78	711.94
		Mean	184.71^a	414.76^b	408.61^b
Flame lengths (m)		Minimum	0.60	1.02	0.94
		Maximum	1.28	1.51	1.64
		Mean	0.86^a	1.27^b	1.24^b

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$ followed by Duncan's multiple range test) in fire behaviors of various fuel models.

Weather factors were determined during burning namely: temperature, relative humidity and wind velocity. Average air temperature was 35.27 °c with minimum and maximum values of 32.17 and 39.37 °c, respectively. Average relative humidity was 56.80 per cent with minimum and maximum values of 48.48 and 69.80 per cent, respectively. Average wind velocity was 3.10 km h^{-1} with minimum and maximum values of 1.41 and 4.51 km h^{-1}, respectively.

3.2 Fire Behavior of Litter with Short Grass Fuel Model

Fire behavior of litter with short grass fuel model was shown in Table 32 and Figure 7. Average rate of head fire spread was 2.75 m min^{-1} with minimum and maximum values of 1.69 and 3.94 m min^{-1}, respectively. Average rate of flank fire spread was 0.98 m min^{-1} with minimum and maximum values of 0.66 and 1.34 m min^{-1}, respectively. Average rate of rear fire spread was 0.52 m min^{-1} with minimum and maximum values of 0.36 and 0.80 m min^{-1}, respectively. Average fireline intensity was 414.76 kWm^{-1} with minimum and maximum values of 255.12 and 594.78 kWm^{-1}, respectively. Average flame length was 1.27 m with minimum and maximum values of 1.02 and 1.51 m, respectively.

Weather factors were determined during burning as follows: average air temperature was 33.88 °c with minimum and maximum values of 27.33 and 39.00 °c, respectively. Average relative humidity was 59.79 per cent with minimum and maximum values of 36.57 and 69.91 per cent, respectively. Average wind velocity was 4.47 km h^{-1} with minimum and maximum values of 2.88 and 5.47 km h^{-1}, respectively.

3.3 Fire Behavior of Tall Grass Fuel Model

Fire behavior of tall grass fuel model was shown in Table 32 and Figure 8. Average rate of head fire spread was 2.39 m min^{-1} with minimum and maximum values of 1.24 and 4.17 m min^{-1}, respectively. Average rate of flank fire spread was 0.76 m min^{-1} with minimum and maximum values of 0.36 and 1.15

m min^{-1}, respectively. Average rate of rear fire spread was 0.51 m min^{-1} with minimum and maximum values of 0.31 and 0.67 m min^{-1}, respectively. Average fireline intensity was 408.61 kWm^{-1} with minimum and maximum values of 211.70 and 711.94 kWm^{-1}, respectively. Moreover average flame length was 1.24 m with the minimum and maximum values of 0.94 and 1.64 m, respectively.

Weather factors were determined during burning as follows: average air temperature was 34.36 °c with minimum and maximum values of 28.00 and 37.56 °c, respectively. Average relative humidity was 66.87 per cent with minimum and maximum values of 49.60 and 76.43 per cent, respectively. Average wind velocity was 3.27 km h^{-1} with minimum and maximum values of 1.20 and 6.02 km h^{-1}, respectively.

Table 32 revealed that rate of head fire spread for litter with short grass fuel model presented the highest with value of 2.75 m min^{-1}. The nexts were tall grass fuel model and litter fuel model with the values of 2.39 and 1.34 m min^{-1}, respectively. Rate of flanks fire spread was the same as rate of head fire spread, rate of flanks fire spread for litter with short grass fuel model presented the highest with value of 0.98 m min^{-1}. The nexts were tall grass fuel model and litter fuel model with the values of 0.76 and 0.48 m min^{-1}, respectively. While, rates of rear fire spread for litter with short grass fuel model and tall grass fuel model presented closely with values of 0.52 and 0.51 m min^{-1}, respectively. However, results of the ANOVA followed by Duncan's multiple range test indicated that rates of head, flanks and rear fire spread for litter with short grass fuel model and for tall grass fuel model were not significant differences. But, the rates of head, flanks and rear fire spread between litter fuel model and litter with short grass fuel model and between litter fuel model and tall grass fuel model were significant differences.

Fireline intensity for litter with short grass fuel model presented the highest with value of 414.76 kWm^{-1}, followed by tall grass fuel model which presented with value of 408.61 kWm^{-1} and the lowest fireline intensity was litter fuel model with value of 184.71 kWm^{-1}. However, results of the ANOVA followed by

Duncan's multiple range test indicated that fireline intensities for litter with short grass fuel model and tall grass fuel model were not significant differences. But, the fireline intensities between litter fuel model and litter with short grass fuel model and between litter fuel model and tall grass fuel model were significant differences.

Trend of flame length was similarly to fireline intensity due to flame length was derived from fireline intensity in Bram's model. Flame length for litter with short grass fuel model presented the highest with value of 1.27 m, followed by tall grass fuel model which presented with value of 1.24 m and the lowest flame length was for litter fuel model with value of 0.86 m. However, results of the ANOVA followed by Duncan's multiple range test indicated that flame lengths for litter with short grass fuel model and tall grass fuel model were not significant differences. But, the flame lengths between litter fuel model and litter with short grass fuel model and between litter fuel model and tall grass fuel model were significant differences.

Figure 6 Fire behavior of litter fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Figure 7 Fire behavior of litter with short grass fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Figure 8 Fire behavior of tall grass fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

According to the fire suppression interpretation of Andrews (1980), fire behaviors in dry deciduous forest at Huai Kha Khaeng Wildlife Sanctuary were low to moderate fire intensities. Fire behaviors for litter fuel model was low to medium fire intensities with rate of fire spread ranged from 0.57 to 3 m min^{-1}, fireline intensities ranged from 78.44 to 412.86 kWm^{-1} and flame lengths ranged from 0.60 to 1.28 m. Fire behaviors for litter with short grass fuel model was medium fire intensities with rate of fire spread ranged from 1.69 to 3.94 m min^{-1}, fireline intensities ranged from 255.12 to 594.78 kWm^{-1} and flame lengths ranged from 1.02 to 1.51 m. Fire behaviors for tall grass fuel model was medium fire intensities with rate of fire spread ranged from 1.24 to 4.17 m min^{-1}, fireline intensities ranged from 211.70 to 711.94 kWm^{-1} and flame lengths ranged from 0.94 to 1.64 m.

The behaviors of head fire for all fuel models were the highest in the values of rate of spread, fireline intensity and flame length. The nexts of those were flanks fire and rear fire, respectively. The results should be applied by firefighters for planning of fire suppression and fire break construction. Fire suppression in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary could generally be attacked at the head, flanks and rear fires by firefighters using hand tools accompanying with backpack pumps. Hand line, at least 4 m wide could hold the fire.

The other studies of fire behaviors in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary had detailed as follows: Sompoh (1998) found that the fireline intensity and flame length were 110.71 kWm^{-1} and 0.70 m, respectively. Chaiwatana (2003) also found that rate of fire spread, fireline intensity and flame length were 0.95 m min^{-1}, 227.48 kWm^{-1} and 1.15 m, respectively. Akaakara *et al.* (2003) found that rate of spread, fireline intensity and flame length of natural fire were 2.70 m min^{-1}, 544 kWm^{-1} and 1.60 m, respectively. Himmapan (2004) found that rate of spread, fireline intensity, and flame length were 0.46 m min^{-1}, 55.25 kWm^{-1} and 0.50 m, respectively. While, Wanthongchai (2008) found that rate of spread,fireline intensity and flame length in frequently burned area were 2.70 m min^{-1}, 361.10 kWm^{-1}and 1.51 m, respectively, those fire behaviors in infrequently burned area were 2.60 m min^{-1}, 466.80 and 1.53 m, respectively and those fire behaviors in rarely burned area were 1.30 m min^{-1}, 291.10 kWm^{-1} and 1.27 m, respectively.

The studies of fire behaviors in dry deciduous dipterocarp forest at other sites had detailed as follows: Sathirasilapin (1987) found that rate of spread, fireline intensity and flame length at Sakaerat Forest, Nakhon Ratchasima Province were 4.46 m min^{-1}, 194.14 kW m^{-1} and 2.47 m, respectively, while Sunyaarch (1989) also found those fire behaviors from burning in February were 266.03 kWm^{-1}, 2.00 m min^{-1} and 2.58 m, respectively. Rate of spread and fireline intensity at Doi Sutap Pui National Park, Chiang Mai Province were 2.00 m min^{-1} and 49.26 kW m^{-1}, respectively (Akaakara and Kittisatho, 1992), Rate of spread, fireline intensity and flame length at Phu Kra Dueng National Park, Loei Province were 0.30–1.00 m min^{-1}, 57.77 kW m^{-1} and 0.30 – 0.70 m (Suthichat, 1996). Rate of head, flanks and rear fires at Kanchanaburi Province were 2.81, 0.59 and 0.40 m min^{-1}, respectively (Akaakara, 2002). Rate of spread, fireline intensity and flame length at Thap Lan National Park, Nakhon Ratchasima Province were 1.82 m min^{-1}, 385.90 kW m^{-1} and 1.22 m (Vichayasitakorn and Wiriya, 2006).

Table 33 Fire behavior descriptors in some dry deciduous dipterocarp forests in Thailand.

Forest plots	Fire behaviors			References
	Ros ($m\ min^{-1}$)	I_B (kWm^{-1})	Fl (m)	
HKKWS (Litter)	1.34	184.71	0.86	In the study
HKKWS (Litter with short grass)	2.75	414.76	1.27	In the study
HKKWS (Tall grass)	2.39	408.61	1.24	In the study
HKKWS	-	110.71	0.70	Sompoh (1998)
HKKWS	0.95	227.48	1.15	Chaiwatana (2003)
HKKWS (Natural fire)	2.70	544	1.60	Akaakara *et al.* (2003)
HKKWS	0.46	55.25	0.50	Himmapan (2004)
HKKWS (Frequently burned)	2.70	361.10	1.51	Wanthongchai (2008)
HKKWS (Infrequently burned)	2.60	466.80	1.53	Wanthongchai (2008)
HKKWS (Rarely burned)	1.30	291.20	1.27	Wanthongchai (2008)
Sakaerat	4.46	194.14	2.47	Sathirasilapin, 1987
Sakaerat	2.00	266.03	2.58	Sunyaarch (1989)
Chiang Mai	2.00	249.26	-	Akaakara and Kittisatho (1992)
Loei	0.30-1	57.77	0.30-0.70	Suthichat (1996)
Kanchanaburi	2.81	-	-	Akaakara (2000)
Tap Lan National Park	1.82	385.90	1.22	Vichayasitakorn and Wiriya (2006)

Abbreviations: Ros=Rate of spread, I_B=Fireline intensity, Fl=Flame length, HKKWS=Huai Kha Khaeng Wildlife Sanctuary.

Table 33 revealed that rates of spread of litter with short grass fuel model, tall grass fuel model, natural fire, frequently burned area and infrequently burned area in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary were similar with values of 2.75, 2.39, 2.70, 2.70 and 2.65 m min^{-1}, respectively. Rates of spread of litter fuel model and rarely burned area were similar with values of 1.34 and 1.30 m min^{-1}, respectively. While, rate of spread of Himmapan's study was the lowest with value of 0.46 m min^{-1} that was due to rain in dry period of study year (Himmapan, 2004). Litter with short grass fuel model, tall grass fuel mode, natural fire, frequently burned area and infrequently burned area were medium fire level according the fire suppression interpretation of Andrews (1980) with the values of 414.76, 408.61, 544, 361.10 and 466.80 kWm^{-1}, respectively. The other studies, fire intensities were low level. Thus, the results of flame lengths were resemble the fireline intensities due to they were derivative of fireline intensity.

The other sites, rate of spread at Sakaerat Forest, Nakhon Ratchasima Province presented the highest with value of 4.46 m min^{-1} (Sathirasilapin, 1987). While the study of Sunyaarch (1989), it was only 2 m min^{-1} that was closely to rate of spread at Doi Sutap Pui National Park, Chiang Mai Province(Akaakara and Kittisatho, 1992). While fire behaviors at Phu Kra Dueng National Park, Loei Province (Suthichat, 1996) were similar to Himmapan's (2004) study.

3.4 The Relationships between Fire Behaviors and Environmental Factors

Fire behavior is the manner in which a fire reacts to the influences of fuel, weather and topography. The study was focused only on fuel properties and some weather data due to the limitation of topographic factor in the study area. Table 34 presented results of the analysis of Pearson's correlation between fire behaviors and environmental factors.

Table 34 Correlations between fire behaviors and environmental factors in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

	Lol	Mod	Mol	Hei	Win	Rosh	Rosf	Rosr	I_B	Fl
Lol	1									
Mod	-0.119	1								
Mol	-0.049	0.180	1							
Hei	0.514*	-0.324	0.582**	1						
Win	0.426	-0.360	-0.528*	0.606**	1					
Rosh	0.370	-0.382	-0.589**	0.775**	0.839**	1				
Rosf	0.482*	-0.311	-0.425	0.770**	0.648**	0.724**	1			
Rosr	0.464*	-0.257	-0.354	0.682**	0.653**	0.508**	0.602**	1		
I_B	0.560**	-0.394	-0.633**	0.887**	0.749**	0.912**	0.764**	0.591**	1	
Fl	0.534*	-0.440*	-0.673**	0.864**	0.756**	0.903**	0.744**	0.607**	0.986**	1

Abbreviations: Lol=Live fuel loading, Mod=Moisture content of dead fuel, Mol=Moisture content of live fuel, Hei=Fuel bed depth, Rosh=Rate of head fire spread, Rosf=Rate of flanks fire spread, Rosr=Rate of rear fire spread, I_B=Fireline intensity, Fl=Flame length.
*and ** Correlations (Pearson's correlation coefficients) at 0.05 and 0.01 significant level, respectively.

Table 34 revealed that rate of head fire spread was correlated positively with wind velocity and fuel bed depth and correlated negatively with moisture content of live fuel. Rate of flanks fire spread was correlated positively with fuel bed depth and wind velocity and loading of live fuel. Rate of rear fire spread was correlated positively with fuel bed depth and wind velocity and loading of live fuel. Fireline intensity was correlated positively with fuel bed depth, wind velocity and loading of live fuel and correlated negatively with moisture content of live fuel. Flame length was correlated positively with fuel bed depth and wind velocity and loading of live fuel and correlated negatively with moisture content of live fuel and of dead fuel.

Rate of head, flanks and rear fire correlated positively with wind velocity due to wind is directly affects the rate of oxygen supply to the burning fuel. In addition, at head and flanks fire, the strong wind will increase the rate of fire spread by tilting the flames closer to unburned fuel. This increases the heat flux to the unburned fuel by increasing effective flame radiation and heat convection. However, the backing rate of spread may be also increased with increasing wind speed, but the back fires spread more slowly than in head fires (Byram, 1959). The increase in the backing rate of spread might be due to increased supply of oxygen. While, the fuel bed depth affects the bulk density and always used in describing the compactness of fuel beds. The bulk density of a fuel bed can be used as a measurement of the oxygen availability and distance between particle across which heat must be transferred to ignite additional fuel (Fahnestock, 1960).

Fire behaviors correlated negatively with moisture content of live fuel that was due to the higher of fuel moisture content will prolong the fuel ignition. Any moisture released from the fuels that absorbs some heat energy from the fire and then limits combustion temperature. Fireline intensity and flame length correlated positively with loading of live fuel that were due to fireline intensity and flame length were determined by fuel loading with rate of fire spread and heat yield in Byram's (1959) formula as shown in equation (11) and (12), respectively.

Akaakara *et al.* (2003) found that rate of fire spread in dry deciduous dipterocarp forest at Huai Kha Kkhaeng Wildlife Sanctuary correlated positively with air temperature. Fireline intensity correlated positively with loading of undergrowth and air temperature. Flame length correlated positively with loading of grass. Besides, Bilgili and Saglam (2003) reported that rate of fire spread of maquis fuels in Turkey correlated positively with wind velocity and fuel bed depth.

Based on, results of the correlations between fire behaviors and environmental factors revealed that fire behaviors in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary correlated positively with wind velocity, fuel bed depth and loading of live fuel and correlated negatively with moisture content of live and dead fuel. As a results of the study, forest fire control and suppression in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary should be at top alert and took machine equipments to support fire control and suppression when wind was high speed. Reduce the fuel bed depth especially in tall grass fuel model and litter with short grass fuel model were strongly recommended that was due to there were high fuel bed depth of 0.60 and 0.30 m, respectively. The high fuel bed depth results in low bulk density, high porosity and air flow into the fuel bed for increasing oxygen supply. Further with high wind velocity, the fire behaviors would be increasing in severity. Suggestionally, live fuel loading should be reduced and high moisture content of live fuel should be maintained for fuel management.

3.5 Fire Temperature

Fire temperature is necessary to know for the firefighter safety. High fire temperature is increasing the difficulty for firefighters to approach the fire front. Finally, damaging effect of fire will also be increased by the high temperature. The fire temperatures were measured during fuels which were consumed in the burning plots by using Infrared Thermometer (Minolta Spot Thermometer, TA-0510). Results of the study were presented in Table 35.

Table 35 Fire temperatures of various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Fire temperatures of various fuel models (°c)		
	Litter	Litter with short grass	Tall grass
Minimum	471.83	476.29	421.36
Maximum	607.67	676.80	609.92
Mean	532.21[a]	593.47[b]	491.79[a]

Remark: Different letters (a, b, c) indicate significant differences (ANOVA, $P<0.05$ followed by Duncan's multiple range test) in fire temperatures for various fuel models.

Table 35 revealed that average fire temperature for litter with short grass fuel model was the highest with value of 593.47 °c and the minimum and maximum values were 476.29 and 676.80 °c, respectively. The next was average fire temperature for litter fuel model with value of 532.21 °c and the minimum and maximum values were 471.83 and 607.67 °c, respectively. The lowest was average fire temperature for tall grass fuel model with value of 491.79 °c and the minimum and maximum values were 421.36 and 609.92 °c, respectively. However, results of the ANOVA followed by Duncan's multiple range test indicated that average fire temperatures of litter fuel model and tall grass fuel model were not significant differences. But, average fire temperatures between litter fuel model and litter with short grass fuel model and between litter with short grass fuel model and tall grass fuel model were significant differences.

The results of Pearson's correlations revealed that fire temperature was correlated positively with fuel bed depth, wind velocity, rate of head fire spread, fireline intensity and flame length as shown in Table 36. Fire temperature correlated with wind velocity and fuel bed depth resembling rate of fire spread because of wind acts directly to the rate of oxygen supply to the burning fuel that accelerated the combustion. Consequently, the fire temperature was directly varied to wind velocity. While, the fuel bed depth affects the bulk density and it is always used in describing the compactness of fuel beds. The bulk density of a fuel bed can be used as a measurement of the oxygen availability and distance between particles across which heat must be transferred to ignite additional fuel (Fahnestock, 1960).

Table 36 Correlations between fire temperature and environmental factors in dry deciduous dipterocarp forest at Huai Khaeng Wildlife Sanctuary.

	Ftem	Hei	Win	Rosh	I_B	Fl
Ftem	1					
Hei	0.520*	1				
Win	0.431*	0.606**	1			
Rosh	0.445*	0.775**	0.839**	1		
I_B	0.460*	0.887**	0.749**	0.912**	1	
Fl	0.467*	0.864**	0.756**	0.903**	0.986**	1

Abbreviations: Ftem=Fire temperature, Hei=Fuel bed depth, Win=Wind velocity, Rosh=Rate of head fire spread, I_B=Fireline intensity, Fl=Flame length.

*and ** Correlations (Pearson's correlation coefficients) at significant level of 0.05 and 0.01, respectively.

Stott (1986) studied the spatial pattern of temperatures in experimental burns by using Thermocolor mica in dry deciduous dipterocarp forest at Lampang, Uthai Thani and Nakhon Ratchasima Provinces and found that the means of temperature of fire at ground for a slight coverage of undergrowth with a little amount of litter ranged from 275 to 350 °c, with moderate amount of litter was 400 °c and with heavy amount of litter was 700 °c. For 50-90 per cent coverage of undergrowth including; pygmy bamboos, herbs, sapling and small shrubs the temperature of fire at 0.5 m above the ground was 300 °c and at 1 m above ground ranged from 75 to 175 °c. For exceeded 95 per cent coverage of pygmy bamboos only the temperature of fire at 0.5-1.0 m above the ground was attained up to 900 °c. While, Sukwong and Dhamanitayakul (1977) determined fire temperature on the ground in dry deciduous dipterocarp forest at Sakaerat, Nakhon Ratchasima Province that was 316 °c. DeBano *et al.* (1977) reported that medium fire with temperature approximately 430 °c would burn the whole of litter on the ground. The study of fire temperatures in some dry deciduous diptrocarp forests in Thailand were presented in Table 37.

Table 37 Fire temperatures in some dry deciduous diptrocarp forests in Thailand.

Forest plots	Fire temperature (°c)	References
HKKWS (Litter)	532.21	In the study
HKKWS (Litter with short grass)	593.47	In the study
HKKWS (Tall grass)	491.79	In the study
Slight coverage of undergrowth and litter	275 - 350	Stott (1986)
Moderate amount of litter	400	Stott (1986)
Heavy amount of litter	700	Stott (1986)
50-90 % coverage of undergrowth at 0.5 m	300	Stott (1986)
50-90 % coverage of undergrowth at 1 m	75 - 175	Stott (1986)
Exceeded 95 % coverage of pygmy bamboos only at 0.5-1 m	900	Stott (1986)
Sakaerat	316	Sukwong and Dhamanitayakul (1977)

4. Burning Area and Perimeter Growths

The expected area and perimeter of a fire starting from an ignition point could be estimated from Van Wagner's fire growth model. The model assumed that the fire's shape was elliptical area for any combination of the linear rate of spread of head, flank and rear fires. Hence, the burning area is the area of ellipse and perimeter is the girth of ellipse. Burning area and perimeter growths are fire behaviors that used to assessment the damage of fire occurrence. In addition, burning area was used to assessment the values of fire damage.

4.1 Burning Area Growth

Burning area growth is amount of burning area per a unit of time. The study was expressed in hectare (ha) per an hour (h) as presented in Table 38.

Table 38 Burning area growths of various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Burning area growths of various fuel models (ha h^{-1})		
	Litter	Litter with short grass	Tall grass
Minimum	0.11	0.63	0.13
Maximum	1.23	1.87	5.24
Average	0.48^{a}	1.08^{b}	1.34^{b}

Remark: Different letters (a and b) indicate significant differences (ANOVA, P<0.05 followed by Duncan's multiple range test) in burning area growths for the fuel models.

Table 38 revealed that average burning area of tall grass fuel model was presented the highest value of 1.34 ha h^{-1} with the minimum and maximum values of 0.13 and 5.24 ha h^{-1}, respectively. The next was litter with short grass fuel model with average, minimum and maximum values of 1.08, 0.63 and 1.87 ha h^{-1}, respectively. The lowest burning growth was litter fuel model with those values of 0.48, 0.11 and 1.23 ha h^{-1}, respectively. Results of the ANOVA followed by Duncan's multiple range test indicated that the averages of burning area growth for tall grass fuel model and litter with short grass fuel model were not significant differences. While, the averages of burning area growths between litter fuel model and litter with short grass fuel model and between litter fuel model and tall grass fuel model were significant differences.

4.2 Perimeter Growth

Perimeter growth is the total of distance around burning area per a unit of time. The study was expressed in meter (m) per an hour (h) as presented in Table 39.

Table 39 Perimeter growths of various fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Descriptions	Perimeter growths of various fuel models (m h^{-1})		
	Litter	Litter with short grass	Tall grass
Minimum	151	378	222
Maximum	510	735	1,638
Mean	274[a]	558[b]	593[b]

Remark: Different letters (a and b) indicate significant differences (ANOVA, $P<0.05$ followed by Duncan's multiple range test) in perimeter growths for the fuel models.

Table 39 revealed that the results of perimeter growth resembled burning area growth. Average perimeter growth of tall grass fuel model presented the highest value of 593 m h^{-1} with the minimum and maximum values of 222 and 1,638 m h^{-1}, respectively. The next was litter with short grass fuel model with average, minimum and maximum values of 558, 378 and 735 m h^{-1}, respectively. The lowest perimeter growth was litter fuel model with those values of 274, 151 and 510 m h^{-1}, respectively. Results of the ANOVA followed by Duncan's multiple range test indicated that the averages of perimeter growth for tall grass fuel model and litter with short grass fuel model were not significant differences. While, the averages of perimeter growth between litter fuel model and litter with short grass fuel model and between litter fuel model and tall grass fuel model were significant differences.

Burning area and perimeter growths correlated positively with fuel bed depth and wind velocity and loading of live fuel and correlated negatively with moisture content of live fuel as presented in Table 40. The results were similar patterns to rate of fire spread that was due to the burning area and perimeter growths were derivatives from advance of head, flank and rear fire spread.

Table 40 Correlations between burning area and perimeter growths and environmental factors in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

	Lol	Mol	Hei	Win	Bag	Peg
Lol	1					
Mol	-0.049	1				
Hei	0.514*	0.582**	1			
Win	0.426	-0.528*	0.606**	1		
Bag	0.462*	-0.495*	0.835**	0.722**	1	
Peg	0.452*	-0.573**	0.840**	0.844**	0.961**	1

Abbreviations: Lol=Live fuel loading, Mol=Moisture content of live fuel, Hei=Fuel bed depth, Bag=Burning area growth, Peg=Perimeter growth.
*and ** Correlations (Pearson's correlation coefficients) at significant level of 0.05 and 0.01, respectively.

5. Verification and Adjustment of Fire Behavior Prediction

The verification and adjustment of fire behavior prediction followed Rothermel and Rinehart's method (Rothermel and Rinehart, 1983). Rates of fire spread of 28 burning plots were predicted by using Rothermel's fire spread model within actual wind velocity and slope of each burning plots. While burning area and perimeter growths were also predicted by using Van Wagner's fire growth model within actual wind velocity and slope of each burning plots. The linear regression analysis was applied to determine the relationships between rate of observed fire spread and rate of predicted fire spread. The results of the analysis were applied to adjust fire prediction of the fuel models.

5.1 Verification and Adjustment of Fire Spread

Rates of fire spreads of 28 burning plots were predicted by using Rothermel's fire spread model within actual wind velocity and slope of each burning plots as presented in Table 41.

Table 41 Rates of observed, predicted and adjusted fire spreads in various fuel models with actual environmental factors.

Burning plots	Fuel model	Wind velocity ($km\ h^{-1}$)	Slope (%)	Rate of fire spread ($m\ min^{-1}$)		
				Observed	Predicted	Adjusted
1	1	4.80	0	3.00	1.76	1.80
2	1	4.48	0	2.28	1.6	1.69
3	1	2.98	0	0.85	0.95	1.24
4	1	3.31	0	1.13	1.08	1.33
5	1	4.51	0	1.61	1.61	1.70
6	1	4.13	0	2.50	1.43	1.58
7	1	3.07	0	0.81	0.99	1.27
8	1	2.00	0	0.88	0.63	1.02
9	1	2.26	0	0.66	0.71	1.07
10	1	2.18	30	1.21	1.22	1.43
11	1	1.41	35	0.86	1.22	1.43
12	1	1.77	20	0.57	0.81	1.14
13	1	2.90	15	1.35	1.06	1.32
14	1	3.55	0	1.08	1.18	1.40

Table 41 (Continued)

Burning plots	Fuel model	Wind velocity (km h^{-1})	Slope (%)	Rate of fire spreads (m min^{-1})		
				Observed	Predicted	Adjusted
15	2	5.47	0	2.74	3.71	3.16
16	2	4.88	0	2.32	3.13	2.76
17	2	4.58	0	2.97	2.85	2.56
18	2	4.17	0	3.01	2.49	2.31
19	2	2.88	0	1.69	1.52	1.64
20	2	3.94	0	3.24	2.3	2.18
21	2	5.17	0	3.94	3.41	2.95
22	2	3.75	0	2.07	2.15	2.08
23	3	1.20	0	1.24	0.95	1.24
24	3	1.75	0	1.45	1.32	1.50
25	3	6.02	0	4.17	5.79	4.60
26	3	3.69	0	2.67	3.07	2.71
27	3	2.36	0	1.26	1.81	1.84
28	3	5.54	0	3.57	5.18	4.18
Average				1.97[a]	2.00[a]	1.97[a]
Coefficient of variation (%)				53.81	65.00	46.19

Remark: 1 Fuel model 1, 2 and 3 were litter fuel, litter with short grass and tall grass fuel models, respectively.

2 Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$) in rates of observed, predicted and adjusted fire spreads of the burning plots.

The verification and adjustment of rates of fire spread prediction by using Rothermel and Rinehart's method to determine the relationships between rate of observed fire spreads and rate of predicted fire spread through linear equation as presented in Figure 9 (a) and detailed as follow:

$$y_1 = 0.6944x_1 + 0.5819 \qquad r^2 = 0.7337 \qquad (30)$$

where, y_1 = Rate of observed fire spread (m min^{-1}).
x_1 = Rate of predicted fire spread (m min^{-1}).
r^2 = Coefficient of determination.

Result of the relationship as presented in equation (30) indicated that rates of observed fire spread in dry deciduous dipterocarp forest at Huai Khaeng Wildlife Santuary could be explained about 73.37 per cent of rate of predicted fire spread by using Rothermel's fire spread model.

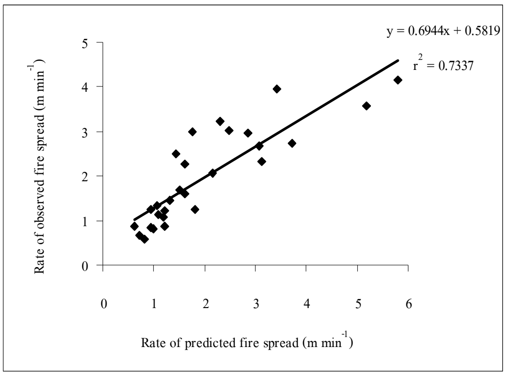
The equation (30) was applied to determined rate of adjusted fire spread from rate of predicted fire spread as also presented in Table 41. Linear regression between rates of observed fire spread and rates of adjusted fire spread were determined as presented in Figure 9 (b) and detailed follows:

$$y_1 = x_1' \qquad r^2 = 0.7337 \qquad (31)$$

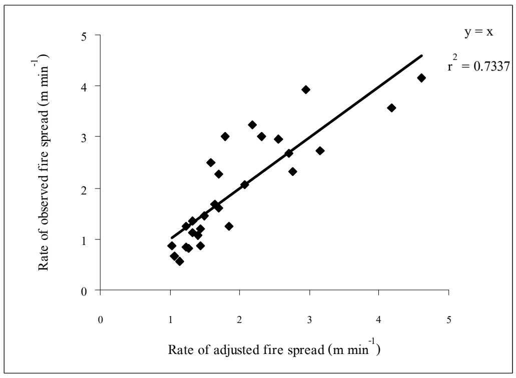
where, y_1 = Rate of observed fire spread (m min^{-1}).
x_1' = Rate of adjusted fire spread (m min^{-1}).
r^2 = Coefficient of determination.

Result of the equation (31) indicated that rate of observed fire spread was equal to rate of adjusted fire spread this was due to slope of the equation was 1. In addition, results of the verification and adjustment rate of fire spread as presented in Table 41 revealed that average rates of observed and adjusted fire spreads were equal to each other with values of 1.97 m min^{-1}. While, average rate of predicted fire spread presented with value of 2.00 m min^{-1}. However, results of the ANOVA indicated that average rates of observed, predicted and adjusted fire spreads were not significant difference at 0.05 level.

As the results, equation (30) could be applied to adjust rate of predicted fire spread of Rothermel's fire spread model in dry deciduous dipterocarp forest at Huai Khaeng Wildlife Santuary.



(a)



(b)

Figure 9 Relationships between rates of observed and predicted fires spreads (a) and between rates of observed and adjusted fires spreads (b) in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

5.2 Verification and Adjustment of Burning Area Growth

Rates of burning area growth of 28 burning plots were predicted by using Van Wagner's fire growth model within actual wind velocity and slope of each burning plots as presented in Table 42.

Table 42 Rates of observed, predicted and adjusted of burning area growths in various fuel models with actual environmental factors.

Burning plots	Fuel model	Wind velocity ($km\ h^{-1}$)	Slope (%)	Burning area growth ($ha\ h^{-1}$)		
				Observed	Predicted	Adjusted
1	1	4.80	0	0.69	0.80	0.71
2	1	4.48	0	0.70	0.72	0.65
3	1	2.98	0	0.59	0.45	0.41
4	1	3.31	0	0.49	0.50	0.45
5	1	4.51	0	1.23	0.73	0.65
6	1	4.13	0	0.45	0.65	0.58
7	1	3.07	0	0.41	0.46	0.42
8	1	2.00	0	0.36	0.33	0.31
9	1	2.26	0	0.46	0.36	0.33
10	1	2.18	30	0.13	0.56	0.50
11	1	1.41	35	0.12	0.55	0.50
12	1	1.77	20	0.11	0.39	0.36
13	1	2.90	15	0.15	0.49	0.45
14	1	3.55	0	0.79	0.54	0.49
15	2	5.47	0	0.70	1.92	1.67
16	2	4.88	0	1.05	1.55	1.35
17	2	4.58	0	0.81	1.38	1.21
18	2	4.17	0	1.58	1.18	1.04

Table 42 (Continued)

Burning plots	Fuel model	Wind velocity ($km\ h^{-1}$)	Slope (%)	Burning area growth ($ha\ h^{-1}$)		
				Observed	Predicted	Adjusted
19	2	2.88	0	1.00	0.69	0.62
20	2	3.94	0	1.87	1.07	0.95
21	2	5.17	0	0.98	1.72	1.50
22	2	3.75	0	0.63	0.99	0.88
23	3	1.20	0	0.13	0.44	0.41
24	3	1.75	0	0.19	0.60	0.54
25	3	6.02	0	5.24	3.46	2.98
26	3	3.69	0	0.81	1.51	1.32
27	3	2.36	0	0.43	0.82	0.73
28	3	5.54	0	1.21	2.97	2.57
Average				0.83[a]	0.99[a]	0.88[a]
Coefficient of variation (%)				67.16	67.78	65.00

Remark: 1 Fuel model 1, 2 and 3 were litter fuel, litter with short grass and tall grass fuel models, respectively.

2 Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$) in rate of observed, predicted and adjusted burning area growths of the burning plots.

The verification and adjustment of rate of burning area growth prediction of Van Wagner's fire growth model by using Rothermel and Rinehart's method were determined the relationships between rate of observed burning area growth and rate of predicted burning area growth through linear equation as presented in Figure 10 (a) and detailed as follow:

$$y_2 = 0.8801x_2 \qquad r^2 = 0.5626 \qquad (32)$$

where, y_2 = Rate of observed burning area growth (ha h^{-1})
x_2 = Rate of predicted burning growth (ha h^{-1})
r^2 = Coefficient of determination

Result of the relationship as presented in equation (32) indicated that rates of observed burning growth in dry deciduous dipterocarp forest at Huai Khaeng Wildlife Santuary could be explained about 56.26 per cent of predicted burning area growth by using Van Wagner's fire growth model.

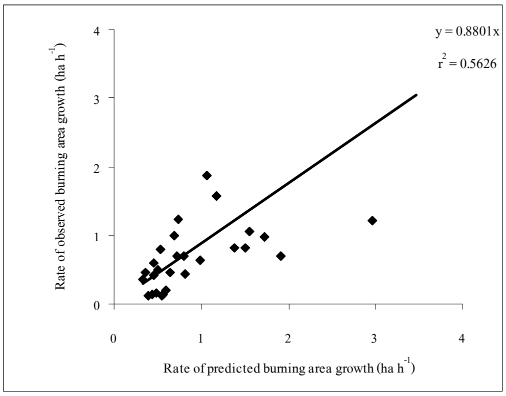
The equation (32) was applied to determined rate of adjusted burning area growth from rate of predicted burning area growth as also presented in Table 42. Linear regression between rates of observed burning area growth and rates of adjusted burning area growth were determined as presented in Figure 10 (b) and detailed as follow:

$$y_2 = 1.0066x_2' \qquad r^2 = 0.5586 \qquad (33)$$

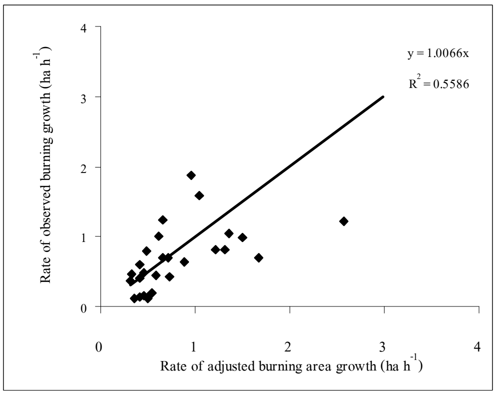
where, y_2 = Rate of observed burning area growth (ha h^{-1}).
x_2' = Rate of adjusted burning area growth (ha h^{-1}).
r^2 = Coefficient of determination.

Result of the equation (33) indicated that rate of observed burning area growth was rather similar to rate of adjusted burning area growth this was due to slope of the equation was 1.0066. In addition, results of the verification and adjustment rate of burning area growth revealed that average rates of observed, predicted and adjusted burning area growth were 0.83, 0.99 and 0.88 ha h^{-1}, respectively. As presented in Table 42 the average of adjusted burning area growth was presented the value similar to the average of observed burning area growth rather than the average of predicted burning area growth. However, results of the ANOVA indicated that average rates of observed, predicted and adjusted burning area growths were not significant difference at 0.05 level.

As the results, equation (32) could be applied to adjust rate of predicted burning area growth of Van Wagner's fire growth model in dry deciduous dipterocarp forest at Huai Khaeng Wildlife Santuary.



(a)



(b)

Figure 10 Relationships between rates of observed and predicted burning area growth (a) and between rates of observed and adjusted burning area growth (b) in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

5.3 Verification and Adjustment of Perimeter Growth

Rates of perimeter growth of 28 burning plots were predicted by using Van Wagner's fire growth model within actual wind velocity and slope of each burning plots as presented in Table 43.

Table 43 Rates of observed, predicted and adjusted of perimeter growth in various fuel models with actual environmental factors.

Burning plots	Fuel model	Wind velocity (km h^{-1})	Slope (%)	Perimeter growth (m h^{-1})		
				Observed	Predicted	Adjusted
1	1	4.80	0	510	334	429
2	1	4.48	0	398	317	407
3	1	2.98	0	210	246	320
4	1	3.31	0	232	260	337
5	1	4.51	0	407	319	409
6	1	4.13	0	453	299	385
7	1	3.07	0	215	250	324
8	1	2.00	0	168	210	275
9	1	2.26	0	167	218	286
10	1	2.18	30	216	276	357
11	1	1.41	35	178	275	356
12	1	1.77	20	151	230	300
13	1	2.90	15	247	258	334
14	1	3.55	0	290	271	351

Table 43 (Continued)

Burning plots	Fuel model	Wind velocity (km h^{-1})	Slope (%)	Perimeter growth (m h^{-1})		
				Observed	Predicted	Adjusted
15	2	5.47	0	475	536	678
16	2	4.88	0	495	477	606
17	2	4.58	0	719	449	570
18	2	4.17	0	735	412	524
19	2	2.88	0	367	309	397
20	2	3.94	0	673	392	500
21	2	5.17	0	620	506	641
22	2	3.75	0	378	376	480
23	3	1.20	0	222	245	319
24	3	1.75	0	238	287	370
25	3	6.02	0	1,638	741	932
26	3	3.69	0	504	471	597
27	3	2.36	0	294	340	435
28	3	5.54	0	664	682	859
Average				424[a]	357[a]	456[a]
Coefficient of variation (%)				70.75	37.82	36.62

Remark: 1 Fuel model 1, 2 and 3 were litter fuel, litter with short grass and tall grass fuel models, respectively.

2 Different letters (a, b, c) indicate significant differences (ANOVA, $p<0.05$) in rate of observed, predicted and adjusted perimeter growths of the burning plots.

The verification and adjustment of rate of perimeter growth prediction by using Rothermel and Rinehart's method were determined the relationships between rate of observed perimeter growth and rate of predicted perimeter growth through linear equation as presented in Figure 11 (a) and detailed as follow:

$$y_3 = 1.2721x_3 \qquad r^2 = 0.6352 \qquad (34)$$

where, y_3 = Rate of observed perimeter growth (m h^{-1})
x_3 = Rate of predicted perimeter growth (m h^{-1})
r^2 = Coefficient of determination

Result of the relationship as presented in equation (34) indicated that rate of observed perimeter growth in dry deciduous dipterocarp forest at Huai Khaeng Wildlife Sanctuary could be explained about 63.52 per cent of rate of predicted perimeter growth by using Van Wagner's fire growth model.

The equation (34) was applied to determined rate of adjusted perimeter growth from rate of predicted perimeter growth as also presented in Table 43. Linear regression between rates of observed perimeter growth and rates of adjusted perimeter growth was determined as presented in Figure 11 (b) and detailed as follow:

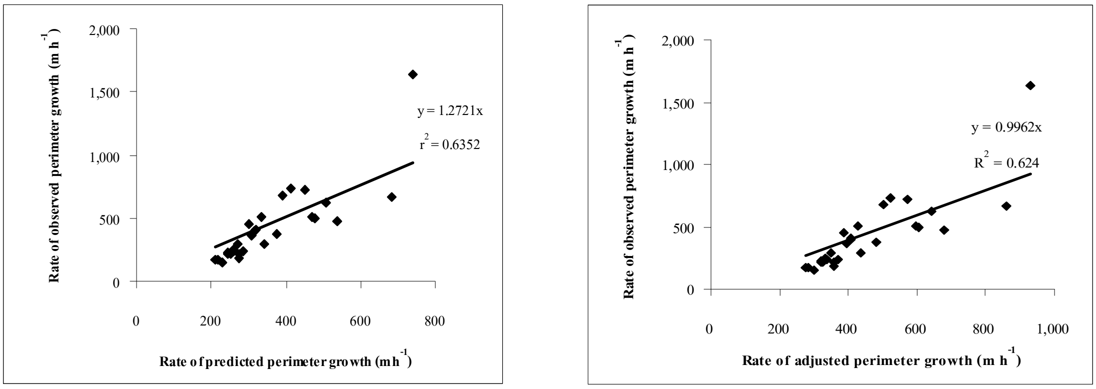
$$y_3 = 0.9962x_3' \qquad r^2 = 0.5586 \qquad (35)$$

where, y_3 = Rate of observed perimeter growth (m h^{-1}).
x_3' = Rate of adjusted perimeter growth (m h^{-1}).
r^2 = Coefficient of determination.

Result of the equation (35) indicated that rate of adjusted perimeter growth was rather similar to rate of observed perimeter growth this was due to slope of the equation was 0.9962. In addition, results of the verification and adjustment rate of perimeter growth revealed that average rates of observed, predicted and adjusted perimeter growth were 424, 357 and 456 m h^{-1}, respectively. As presented in

Table 43 the average of adjusted perimeter growth was presented the value similar to the average of observed perimeter growth rather than the average of predicted perimeter growth. However, results of the ANOVA indicated that average rates of observed, predicted and adjusted burning area growths were not significant difference at 0.05 level.

As the results, equation (34) could be applied to adjust rate of predicted perimeter growth of Van Wagner's fire growth model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.



(a) (b)

Figure 11 Relationships between rates of observed and predicted perimeter growth (a) and between rate of observed and adjusted perimeter growth (b) in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

6 Fire Behavior Predictions of Fuel Models

The Rothermel's fire spread model, that was applied by Bachmann (2001) was taken to determine rate of fire spread. Byram's model was applied to determine fire intensity and flame length. In addition, Van Wagner's fire growth model was applied to determine burning area and perimeter growths. The excel computer application was also applied to calculate the complex equation of fire behaviors. The fire behavior prediction namely rate of spread, fireline intensity, flame length, burning area and perimeter growths of litter fuel model, litter with short grass fuel model and tall grass fuel model, that were interacted with 0, 10, 20, 30 and 40 per cent slopes and 0, 3, 6, 9 and 12 km h^{-1} wind velocities were presented in Table 44, 45, 46, 47 and 48, respectively.

6.1 Rate of Fire Spread

Table 42 revealed that rate of fire spread predictions in all fuel models increased positively with the increasing of wind velocity and slope steepness. Wind directly affects the burning rate of forest fuel by influencing the rate of oxygen supply to burning fuel. Also, strong wind is increasing the rate of fire spread by tilting the flames forward so that unburned fuel receives energy by radiation and convection at an increasing rate. While, slope is decreasing angle between the flame front and the fuel bed. This increases the heat flux to the unburned fuel by increasing effective flame radiation and heat convection.

Rates of fire spread predictions for tall grass fuel model presented the highest with values ranged from 0.88 to 12.41 m min^{-1}. The next high rate of fire spread predictions were for litter with short grass fuel model with values ranged from 0.86 to 10.72 m min^{-1} and the lowest rates of fire spread predictions were for litter fuel model with values ranged from 0.79 to 6.24 m min^{-1}. The rates of fire spread predictions of the tall grass fuel model were the highest in values that was due to there were a lot of dead and live herbs, high surface area to volume ratio and low particle density, these two properties affected to decrease of ignition time, fuels are easily to ignite and burn. In addition, the highest fuel bed depth in the tall grass fuel model affected to bulk density, used in describing the compactness of fuel beds. The bulk density of a fuel bed can be used as a measure of the oxygen availability and distance between particle across which heat must be transferred to ignite additional fuel (Fahnestock, 1960).

6.2 Fireline Intensity

Table 43 revealed that trend of fireline intensity predictions in all fuel models increased positively with the increasing of wind velocity and slope steepness that was similar to rate of fire spread prediction, the reason was mainly due to fireline intensity was derived from rate of fire spread and loading of fuel in Byram's model as shown in equation (11)

Fireline intensity predictions for tall grass fuel model presented the highest with values ranged from 149 to 2,115 kWm^{-1}. The next high fireline intensity prediction was for litter with short grass fuel model with values ranged from 129 to 1,611 kWm^{-1} and the lowest fireline intensity prediction was for litter fuel model with values ranged from 109 to 861 kWm^{-1}. The results of fireline intensities were similar to rates of fire spread prediction that was due to fireline intensity was calculated by rate of fire spread with loading of available fuel and heat yield as presented in equation (11). In addition, the loading of gross fuel for tall grass fuel model was the highest with value of 7,184.59 kg ha^{-1}. The nexts high values of gross fuel loading were for litter with short grass fuel model and for litter fuel model with values of 6,353.72 and 5,789.23 kg ha^{-1}, respectively.

Table 44 Rates of fire spread predictions interacted with various slopes and wind velocities for fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

slopes (%)	Rates of fire spread (m min^{-1})														
	Wind velocities (km h^{-1})														
	0			3			6			9			12		
	Fuel model			Fuel model			Fuel model			Fuel model			Fuel model		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
0	0.79	0.86	0.88	1.25	1.69	2.24	2.27	3.55	4.58	3.73	6.19	7.53	5.58	9.51	10.97
10	0.83	0.93	0.97	1.29	1.77	2.33	2.31	3.62	4.67	3.77	6.26	7.62	5.62	9.59	11.06
20	0.96	1.16	1.24	1.41	1.99	2.60	2.44	3.85	4.94	3.90	6.49	7.90	5.74	9.81	11.33
30	1.16	1.53	1.69	1.62	2.37	3.05	2.64	4.22	5.39	4.10	6.86	8.35	5.95	10.19	11.78
40	1.46	2.06	2.32	1.91	2.90	3.68	2.93	4.75	6.02	4.39	7.39	8.98	6.24	10.72	12.41

Remark: Fuel model 1 = Litter fuel model

Fuel model 2 = Litter with short grass fuel model

Fuel model 3 = Tall grass fuel model

Table 45 Fireline intensity predictions interacted with various slopes and wind velocities for fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Slopes	Fireline intensities (kW m^{-1})														
	Wind velocities (km h^{-1})														
	0			3			6			9			12		
	Fuel model			Fuel model			Fuel model			Fuel model			Fuel model		
(%)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
0	109	129	149	172	255	381	313	533	781	515	930	1,284	769	1,430	1,869
10	115	140	165	178	266	397	319	545	796	520	941	1,299	775	1,442	1,884
20	132	174	211	195	300	443	336	579	842	538	975	1,345	792	1,476	1,930
30	161	231	288	224	356	519	365	635	919	566	1,032	1,422	821	1,532	2,007
40	201	310	395	264	435	627	405	714	1,027	606	1,111	1,530	861	1,611	2,115

Remark: Fuel model 1 = Litter fuel model

Fuel model 2 = Litter with short grass fuel model

Fuel model 3 = Tall grass fuel model

Table 46 Flame length predictions interacted with various slopes and wind velocities for fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Slopes (%)	Flame lengths (m)														
	Wind velocities (km h^{-1})														
	0			3			6			9			12		
	Fuel model			Fuel model			Fuel model			Fuel model			Fuel model		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
0	0.69	0.75	0.80	0.85	1.02	1.23	1.12	1.44	1.71	1.41	1.86	2.15	1.70	2.26	2.56
10	0.71	0.78	0.84	0.87	1.04	1.25	1.13	1.45	1.73	1.42	1.87	2.16	1.71	2.27	2.57
20	0.76	0.86	0.94	0.90	1.10	1.32	1.16	1.49	1.77	1.44	1.90	2.20	1.72	2.30	2.60
30	0.83	0.98	1.08	0.96	1.19	1.42	1.21	1.56	1.85	1.48	1.95	2.26	1.75	2.34	2.64
40	0.92	1.12	1.25	1.04	1.31	1.55	1.27	1.64	1.94	1.52	2.01	2.33	1.79	2.39	2.71

Remark: Fuel model 1 = Litter fuel model

Fuel model 2 = Litter with short grass fuel model

Fuel model 3 = Tall grass fuel model

Table 47 Burning area growth predictions interacted with various slopes and wind velocities for fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Slopes	Burning area growth (ha h^{-1})														
	Wind velocities (km h^{-1})														
	0			3			6			9			12		
	Fuel model			Fuel model			Fuel model			Fuel model			Fuel model		
(%)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
0	0.21	0.24	0.25	0.41	0.65	0.99	1.01	2.00	2.96	2.15	4.73	6.44	4.02	9.29	11.63
10	0.23	0.27	0.28	0.43	0.69	1.05	1.04	2.06	3.05	2.19	4.82	6.56	4.07	9.41	11.78
20	0.28	0.37	0.41	0.50	0.83	1.24	1.12	2.26	3.33	2.30	5.09	6.93	4.21	9.76	12.24
30	0.37	0.56	0.65	0.61	1.08	1.58	1.27	2.61	3.82	2.50	5.56	7.56	4.45	10.35	13.02
40	0.52	0.87	1.04	0.78	1.46	2.11	1.49	3.13	4.54	2.77	6.42	8.48	4.79	11.21	14.14

Remark: Fuel model 1 = Litter fuel model

Fuel model 2 = Litter with short grass fuel model

Fuel model 3 = Tall grass fuel model

Table 48 Perimeter growth predictions interacted with various slopes and wind velocities for fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

Slopes	Perimeter growth ($m\ h^{-1}$)														
	Wind velocities ($km\ h^{-1}$)														
	0			3			6			9			12		
	Fuel model			Fuel model			Fuel model			Fuel model			Fuel model		
(%)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
0	227	241	245	321	408	510	516	748	929	780	1,205	1,433	1,101	1,763	2,003
10	236	256	264	329	422	527	524	761	945	787	1,218	1,448	1,108	1,776	2,018
20	262	303	318	354	465	577	547	801	992	809	1,256	1,493	1,129	1,813	2,063
30	304	377	407	394	535	658	585	867	1,069	845	1,320	1,569	1,164	1,875	2,137
40	362	477	525	449	631	771	637	958	1,177	896	1,408	1,674	1,214	1,962	2,240

Remark: Fuel model 1 = Litter fuel model

Fuel model 2 = Litter with short grass fuel model

Fuel model 3 = Tall grass fuel model

6.3 Flame Length

Table 44 revealed that trend of flame length predictions in all fuel models increased positively with the increasing of wind velocity and slope steepness that was similar to rate of fire spread prediction, this was due to flame length was derived from fireline intensity in Byram's model as shown in equation (12). Flame length prediction for tall grass fuel model presented the highest with values ranged from 0.80 to 2.71 m. The next high flame length prediction was for litter with short grass fuel model with values ranged from 0.75 to 2.39 m and the shortest flame length prediction was for litter fuel model with values ranged from 0.69 to 1.79 m.

6.4 Burning Area Growth

Table 45 revealed that burning area growth predictions of all fuel models increased positively with the increasing of wind velocity and slope steepness. This was due to the burning area was elliptical shape area for any combination of the linear rate of fire spread of head, flank and rear fires in Van Wagner's model as presented in equation (13). The influences of wind velocity and slope on rate of head fire spread was discussed previously. Regarding to, the influence of wind velocity on flanks and rear fires, this was due to wind directly affects the rate of oxygen supply to the burning fuel. Burning area growth predictions for tall grass fuel model presented the highest with values ranged from 0.25 to 14.14 ha h^{-1}. The next high burning area growth prediction was for litter with short grass fuel model with values ranged from 0.24 to 11.21 ha h^{-1} and the lowest burning area growth prediction was in litter fuel model with values ranged from 0.21 to 4.79 ha h^{-1}.

6.5 Perimeter Growth

Table 46 revealed that perimeter growth predictions of all fuel models increased positively with the increasing of wind velocity and slope steepness that was similar to burning area growth. This was due to perimeter growth was the girth of elliptical shape area for any combination of the linear rate of fire spread of head, flank and rear fire as same as burning area growth in Van Wagner's model as presented in equation (14). Perimeter growth predictions for tall grass fuel model presented the highest with values ranged from 245 to 2,240 m h^{-1}. The next high perimeter growth predictions was for litter with short grass fuel model with values ranged from 241 to 1,962 m h^{-1} and the lowest perimeter growth prediction was for litter fuel model with values ranged from 227 to 1,214 m h^{-1}.

Sathirasilapin (1987) applied the Rothemel's fire spread model to predict fire behaviors in dry deciduous dipterocarp forest at Sakaerat, Nakhon Ratchasima Province, that were interacted with 9-18 per cent fuel moisture contents, 0-40 per cent slopes and 0-10 mile h^{-1} wind velocities and found that rates of fire spreads ranged from 1.00 to 35.10 m min^{-1}, fireline intensities ranged from 79 to 3,154 kWm^{-1} and flame length ranged from 0.50 to 3.10 m. Harvey *et al*. (1997) reported fire behavior predictions for mixed conifers, mountain pine, dwarfed mountain pine, cultivated conifer forests, frequently burned area with fern and chestnut fuel model in the Swiss National Park (Engadine Valley) and the canton of Ticino (southern Alps) with no wind as follows: rates of fire spread were 0.16, 0.39, 0.23, 0.26, 1.47 and 0.47 m min^{-1}, respectively ; Fireline intensities were 22.39, 168.84, 145.90, 27.22, 204.75 and 29.77 kWm^{-1}, respectively; and flame lengths were 0.25, 0.69, 0.56, 0.35, 0.90 and 0.37 m, respectively.

7. Application for Fire Control and Suppression

The application for fire control and suppression in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary were integrated from fire intensity and flame length of predicted fire. Fire severity ratings were classified into 3 levels cited fire suppression interpretation of Andrews (1980) as presented in Table 49 namely low fire, medium fire and severe fire. Fireline intensity and flame length of low fire were less than 345.86 kWm^{-1} and less than 1.22 m, respectively. Fireline intensities of medium fire ranged from 345.86 to 1,729.30 kWm^{-1} and flame length of that ranged from 1.22 to 2.44 m. Fireline intensities of severe fire ranged from 1,729.30 to 3,458.60 kWm^{-1} and flame length of that ranged from 2.44 to 3.35 m.

7.1 Low Fire

Low fire of litter fuel model would be struck on 0 to 20 per cent slopes with 0 to 6 km h^{-1} wind velocities and on 30 to 40 per cent slopes with 0 to 3 km h^{-1} wind velocities. Litter with short grass fuel model would be struck on 0 to 20 per cent slopes with 0 to 3 km h^{-1} wind velocities and on 30 to 40 slopes with no wind. Tall grass fuel model would be only struck on 0 to 30 per cent slope with no wind.

Fires were low severity rating with rates of spread ranged from 0.79 to 2.44 m min^{-1}, fireline intensities ranged from 109 to 336 kWm^{-1}, flame lengths ranged from 0.69 to 1.16 m, burning area growth rates ranged from 0.21 to 1.12 ha h^{-1} and perimeter growth rates ranged from 227 to 547 m h^{-1}. Fire suppression that can generally be attacked at the head, flanks and rear fires by firefighters using hand tools such as swatter accompany with backpack pumps. Hand line, at least 4 m wide could hold the fire.

Table 49 Fire suppression interpretations of flame length and fireline intensity.

Flame length (m)	Fire line intensity (kW m^{-1})	Interpretation
≤ 1.22	≤ 345.86	- Fires can generally be attacked at the head or flanks by persons using hand tools. - Handline should hold the fire
1.22-2.44	345.86-1,729.30	- Fires are too intense for direct attack at the head by persons using hand tools. - Handline cannot be relied on to hold fire. - Equipment such as bulldozers, pumpers and retardant aircraft can be effective.
2.44-3.35	1,729.30-3,458.60	- Fires may present serious control problems-torching out, crowning, - Control efforts at the head will probably be ineffective.
≥3.35	≥ 3,458.60	- Crowning, spotting, and major fire runs are probable. - Control efforts at head of fire are ineffective.

Source: Andrews (1980)

7.2 Medium Fire

Medium fire of litter fuel model would be struck on 0 to 20 per cent slopes with wind velocities ranged from 6 to 12 km h^{-1} and on 30 to 40 per cent slopes with wind velocities ranged from 3 to 12 km h^{-1}. Litter with short grass fuel model would be struck on 0 to 20 per cent slopes with wind velocities ranged from 3 to 12 km h^{-1} and on 30 to 40 per cent slopes with no wind. Tall grass fuel model would be struck on 0 to 30 per cent slopes with 3 to 9 km h^{-1} wind velocities and on 40 per cent slope with wind velocity did not exceed 9 km h^{-1}.

Fires were moderate severity rating with rates of spread ranged from 3.05 to 10.72 m min^{-1}, fireline intensities ranged from 519 to 1,611 kWm^{-1}, flame lengths ranged from 1.42 to 2.39 m, burning area growth rates ranged from 1.58 to 11.21 ha h^{-1} and perimeter growth rates ranged from 658 to 1,962 m h^{-1}. Fires are too intense for direct attack at the head by firefighters using hand tools and handline cannot be relied on to hold the fire. Machine equipments such as fire engine, slip-on tank, water tank were strongly recommended to support fire control and suppression.

7.3 Severe Fire

Severe fire would be only struck for tall grass fuel model with wind velocity exceeded 9 km h^{-1}. Fires were high severity rating with rates of spread ranged from 10.97 to 12.41 m min^{-1}, fireline intensities ranged from 1,869 to 2,115 kWm^{-1}, flame lengths ranged from 2.56 to 2.71 m, burning area growth rates ranged from 11.63 to 14.14 ha h^{-1} and perimeter growth rates ranged from 2,003 to 2,240 m h^{-1}. Fires may presented serious control problems. Control efforts at the head will probably be ineffective. Indirected methods were strongly recommended to use in fire control and suppression with machine equipments as in medium fire. In addition, helicopter and fixed wing plane should be used in fire operation.

Fire ratings for litter, litter with short grass and tall grass fuel models were presented in Figure 12, 13 and 14, respectively.

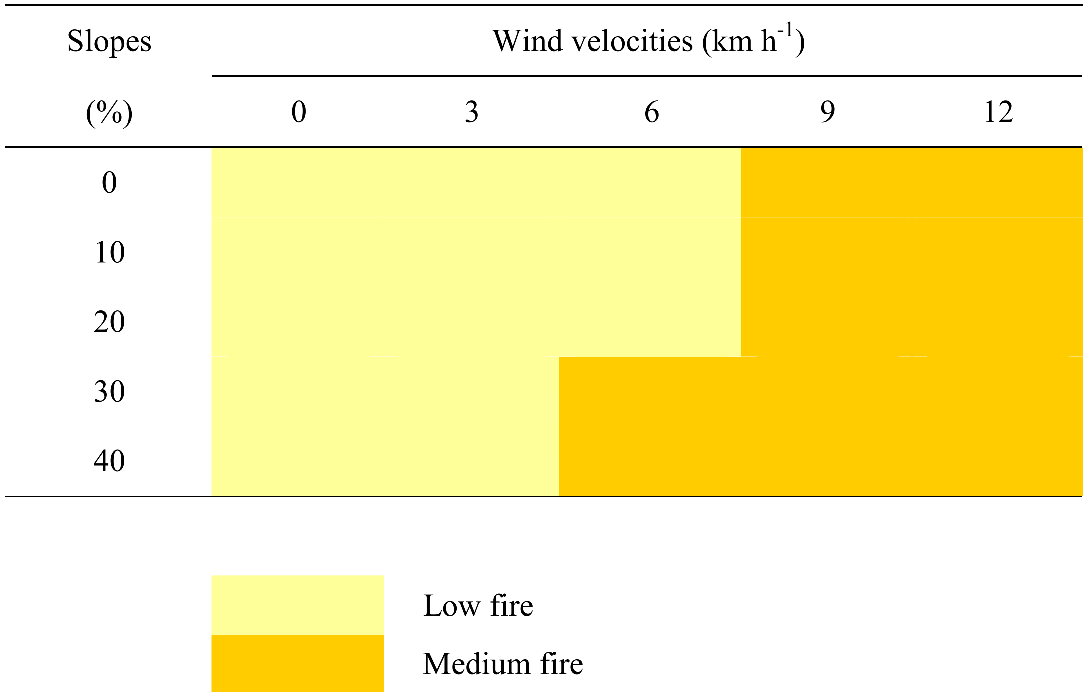


Figure 12 Fire rating for litter fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

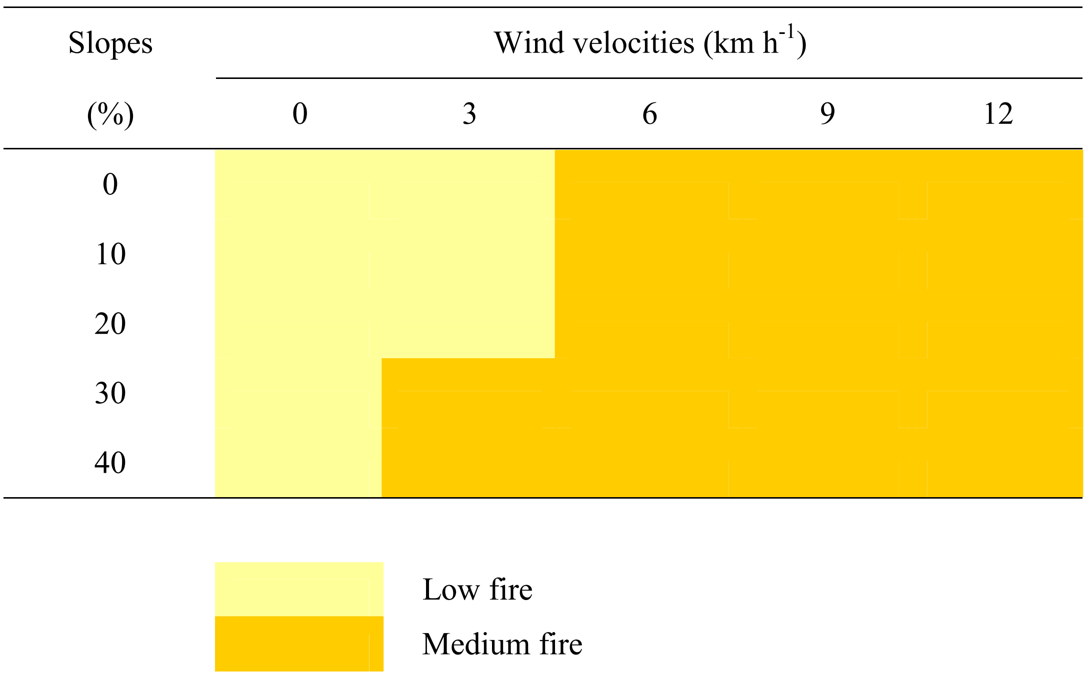


Figure 13 Fire rating for litter with short grass fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

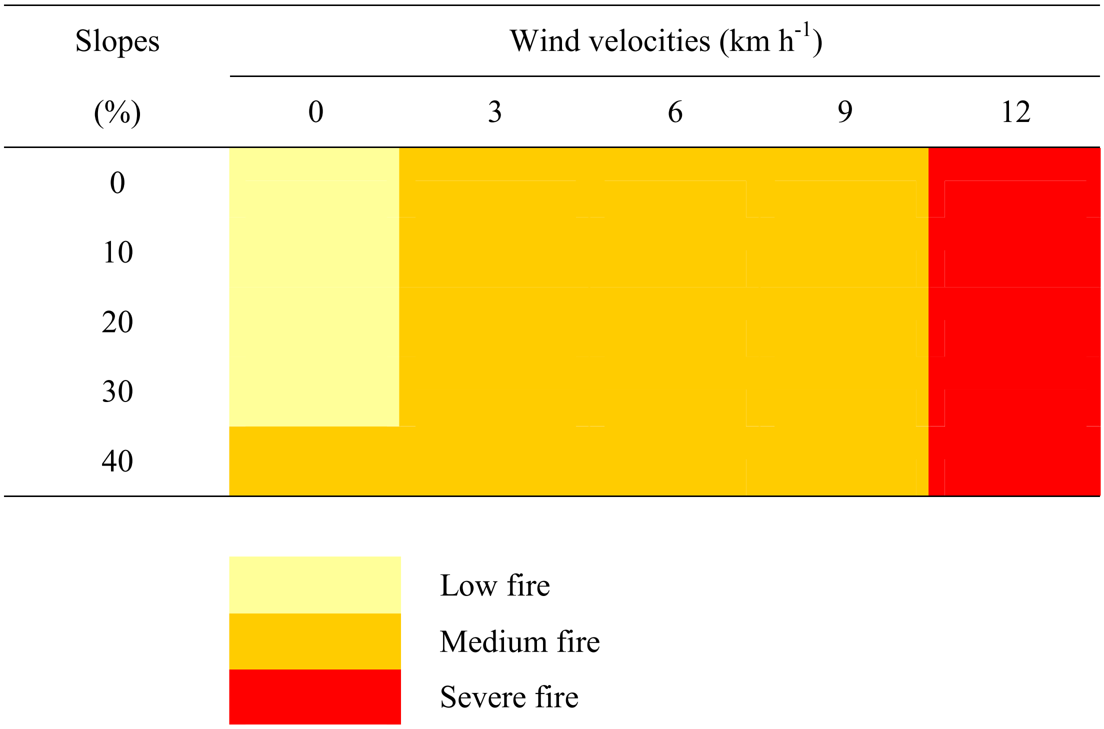


Figure 14 Fire rating for tall grass fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

CONCLUSIONS

The study of fuel model and fire behavior prediction in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary could be concluded as follows:

1. Fuel Properties

Fuel model in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary was classified into 3 models namely litter, litter with short grass and tall grass. Fuels were classified into 2 categories dead fuel and live fuel. Dead fuel included litter, twig and dead herb. Live fuel included live herb and undergrowth. Fuels properties of dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary included loading, moisture content, surface area to volume ratio, particle density, fuel bed depth, heat of combustion, mineral content, effective mineral content and moisture content of extinction were be expressed as follows:

1.1 Loading

Means of litter loads for litter, litter with short grass and tall grass fuel models were 3,858.27, 3,605.25 and 1,926.90 kg ha^{-1}, respectively. Means of twig loads for those were 1,275.18, 1,293.46 and 1,195.98 kg ha^{-1}, respectively. Means of dead herb loads for those were 138.77, 434.04 and 2,625.30 kg ha^{-1}, respectively. Means of live herb loads for those were 178.43, 642.33 and 985.41 kg ha^{-1}, respectively. Means of undergrowth loads for those were 338.58, 378.64 and 451.00 kg ha^{-1}, respectively. Means of gross fuel loads for those were 5,789.23, 6,353.72 and 7,184.59 kg ha^{-1}, respectively. Loading of litter correlated positively with density, basal area and crown cover of tree. On the contrary, dead and live herbs loadings correlated negatively with density, basal area and crown cover of tree.

1.2 Moisture Content

Mean moisture contents of litter for litter, litter with short grass and tall grass fuel models were 8.92, 8.45 and 8.75 per cent, respectively. Mean moisture contents of twig for those were 9.50, 9.36 and 9.10 per cent, respectively. Mean moisture contents of dead herb for those were 25.23, 20.92 and 15.34 per cent, respectively. Mean moisture contents of live herb for those were 137.99, 99.87 and 52.01 per cent, respectively. Mean moisture contents of undergrowth for those were 145.82, 128.06 and 118.99 per cent, respectively. Mean moisture contents of gross fuel for those were 21.39, 25.04 and 23.15 per cent, respectively.

1.3 Surface Area to Volume Ratio

Mean surface area to volume ratios of litter for litter, litter with short grass and tall grass fuel models were 8,446.84, 8,599.85 and 7,311.59 m^{-1}, respectively. Mean surface area to volume ratios of twig for those were 1,275.64, 1,160.61 and 1,282.73 m^{-1}, respectively. Mean surface area to volume ratios of dead and live herbs for those were 6,421.55, 6,367.10 and 5,394.73 m^{-1}, respectively. Mean surface area to volume ratios of undergrowth for those were 1,469.01, 1,357.55 and 1,562.88 m^{-1}, respectively. Mean surface area to volume ratios of gross fuel for those were 7,937.95, 7,853.29 and 5,998.82 m^{-1}, respectively.

1.4 Particle Density

Mean particle densities of litter for litter, litter with short grass and tall grass fuel models were 392.03, 407.69 and 343.09 kg m^{-3}, respectively. Mean particle densities of twig for those were 646.30, 623.50 and 598.52 kg m^{-3}, respectively. Mean particle densities of dead and live herbs for those were 368.26, 378.27 and 350.26 kg m^{-3}, respectively. Mean particle densities of undergrowth for those were 789.53, 763.34 and 862.96 kg m^{-3}, respectively. Mean particle densities of gross fuel for those were 471.10, 467.37 and 411.56 kg m^{-3}, respectively.

1.5 The Other Properties

Fuel bed depths of litter, litter with short grass and tall grass fuel models were 0.10, 0.30, 0.60 m, respectively. Heat of combustion, mineral content, effective mineral content and moisture content of extinction were 4,505.85 cal g^{-1}, 8.09 per cent, 5.92 per cent and 30 per cent, respectively.

2. **Fuel Model**

2.1 Litter Fuel Model

Loadings of litter, twig, dead herb, live herb and undergrowth were 3,858.27, 1,275.18, 138.77, 178.43 and 338.58 kg ha^{-1}, respectively. Moisture contents of those were 8.92, 9.50, 25.23, 137.99 and 145.82 per cent, respectively. Surface area to volume ratios of litter, twig, herbs (dead and live) and undergrowth were 8,446.84, 1,275.64, 6,421.55 and 1,469.01 m^{-1}, respectively. Particle densities of those were 392.03, 646.30, 368.26 and 789.53 kg m^{-3}, respectively. Fuel bed depth was 0.10 m.

2.2 Litter with Short Grass Fuel Model

Loadings of litter, twig, dead herb, live herb and undergrowth were 3,605.25, 1,293.46, 434.04, 642.33 and 378.64 kg ha^{-1}, respectively. Moisture contents of those were 8.45, 9.39, 20.92, 99.87 and 128.06 per cent, respectively. Surface area to volume ratios of litter, twig, herbs (dead and live) and undergrowth were 8,599.85, 1,160.61, 6,367.10 and 1,357.55 m^{-1}, respectively. Particle densities of those were 407.69, 623.50, 378.27 and 763.34 kg m^{-3}, respectively. Fuel bed depth was 0.30 m.

2.3 Tall Grass Fuel Model

Loadings of litter, twig, dead herb, live herb and undergrowth were 1,926.90, 1,195.98, 2,625.30, 985.41 and 451.00 kg ha^{-1}, respectively. Moisture contents of those were 8.75, 9.10, 15.34, 52.01 and 118.99 per cent, respectively. Surface area to volume ratios of litter, twig, herbs (dead and live) and undergrowth were 7,311.59, 1,282.73, 5,394.73 and 1,562.88 m^{-1}, respectively. Particle densities of those were 343.09, 598.52, 350.26 and 862.96 kg m^{-3}, respectively. Fuel bed depth was 0.60 m.

All of fuel models: heat of combustion, mineral content, effective mineral content and moisture content of extinction were 18,880 kJ kg^{-1}, 8.09 per cent, 5.92 per cent and 30 per cent, respectively.

3. **Fire Behavior**

Fire behaviors in dry deciduous dipterocarp forest at Huai Kha Kkaeng Wildlife Sanctuary. Rates of fire spreads for litter, litter with short grass and tall grass fuel models were 1.34, 2.75 and 2.39 m min^{-1}, respectively. Fireline intensities of those were 184.71, 414.76 and 408.61 kWm^{-1}, respectively. Flame lengths of those were 0.86, 1.27 and 1.24 m, respectively. Fire temperature of those were 532.21, 593.47 and 491.79 °c. Burning area growths of those were 0.48, 1.08 and 1.34 ha h^{-1}, respectively. Perimeter growths of those were 274, 558 and 593 m h^{-1}, respectively.

Rate of head fire spread correlated positively with wind velocity and fuel bed depth and correlated negatively with moisture content of live fuel. Rates of flanks fire spread correlated positively with fuel bed depth, wind velocity and loading of live fuel. Rate of rear fire spread correlated positively with fuel bed depth, wind velocity and loading of live fuel. Fireline intensity correlated positively with fuel bed depth, wind velocity and loading of live fuel and correlated negatively with moisture content of live fuel. Flame length correlated positively with fuel bed depth, wind velocity and loading of live fuel and correlated negatively with moisture content of live fuel and of dead fuel.

4. **Fire Behavior Prediction**

Predicted values of rate of fire spread, burning area growth and perimeter growth were accurate about 73.79, 15.92 and 62.36 per cent, respectively of those observed values.

The fire behavior predictions of the fuel models, that were interacted with 0, 10, 20, 30 and 40 per cent slope and 0, 3, 6, 9, 12 km h^{-1} wind velocities as follows:

Rates of fire spread prediction for litter fuel model ranged from 0.79 to 6.24 m min^{-1}, for litter with short grass fuel model ranged from 0.86 to 10.72 m min^{-1} and for tall grass fuel model ranged from 0.88 to 12.41 m min^{-1}.

Fireline intensity predictions for litter fuel model ranged from 109 to 861 kWm^{-1}, for litter with short grass fuel model ranged from 129 to 1,611 kWm^{-1} and for tall grass fuel model ranged from 149 to 2,115 kWm^{-1}.

Flame length predictions for litter fuel model ranged from 0.69 to 1.79 m, for litter with short grass fuel model ranged from 0.75 to 2.39 m and for tall grass fuel model ranged from 0.80 to 2.71 m.

Burning area growth predictions for litter fuel model ranged from 0.21 to 4.79 ha h^{-1}, for litter with short grass fuel model ranged from 0.24 to 11.21 ha h^{-1} and for tall grass fuel model ranged from 0.25 to 14.14 ha h^{-1}.

Perimeter growth predictions for litter fuel model ranged from 227 to 1,214 m h^{-1}, for litter with short grass fuel model ranged from 241 to 1,962 m h^{-1} and for tall grass fuel model ranged from 245 to 2,240 m h^{-1}.

5. **The Application for Fire Control and Suppression**

Fire severity ratings in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary were classified into 3 levels followed fire suppression interpretation of Andrews (1980) as follows:

5.1 Low Fire

Low fire of litter fuel model would be struck on 0 to 20 per cent slopes with 0 to 6 km h^{-1} wind velocities and on 30 to 40 per cent slopes with 0 to 3 km h^{-1} wind velocities. Litter with short grass fuel model would be struck on 0 to 20 per cent slopes with 0 to 3 km h^{-1} wind velocities and on 30 to 40 slopes with no wind. Tall grass fuel model would be only struck on 0 to 30 per cent slope with no wind. Fire suppression that can generally be attacked at the head, flanks and rear fires by firefighters using hand tools such as swatter accompany with backpack pumps. Hand line, at least 4 m wide could hold the fire.

5.2 Medium Fire

Medium fire of litter fuel model would be struck on 0 to 20 per cent slopes with wind velocities ranged from 6 to 12 km h^{-1} and on 30 to 40 per cent slopes with wind velocities ranged from 3 to 12 km h^{-1}. Litter with short grass fuel model would be struck on 0 to 20 per cent slopes with wind velocities ranged from 3 to 12 km h^{-1} and on 30 to 40 per cent slopes with no wind. Tall grass fuel model would be struck on 0 to 30 per cent slopes with 3 to 9 km h^{-1} wind velocities and on 40 per cent slope with wind velocity did not exceed 9 km h^{-1}. Fires are too intense for direct attack at the head by firefighters using hand tools and handline cannot be relied on to hold the fire.

5.3 Severe Fire

Severe fire would be only struck for tall grass fuel model with wind velocity exceeded 9 km h^{-1}. Fires were high severity rating with rates of fire spread ranged from 10.97 to 12.41 m min^{-1}, fireline intensities ranged from 1,869 to 2,115 kWm^{-1}, flame lengths ranged from 2.56 to 2.71 m, burning area growth rates ranged from 11.63 to 14.14 ha h^{-1} and perimeter growth rates ranged from 2,003 to 2,240 m h^{-1}. Fires may presented serious control problems. Control efforts at the head will probably be ineffective.

RECOMMENDATIONS

1. The gross fuel load for tall grass fuel model showed the highest value, the nexts were litter with short grass fuel model and litter fuel model respectively. The high fuel load directly affected to fire intensity. The decreasing of fuel loads in tall grass fuel model was the first priority to concern for forest fire control and suppression in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

2. Litter was fine fuels and herbs were fine to medium fuels, that strongly affected to fire behaviors more than twig and undergrowth, that were medium to coarse fuels. In addition, the ignition time of fuels from minimum to maximum were herbs, litter, twig and undergrowth, respectively. Hence, dead herb was the highly dangerous fuel in dry deciduous forest in Huai Kha Khaeng Wildlife Sanctuary due to, easy to ignite and highly affect to fire behaviors.

3. Rate of fire spread, fire temperature, burning area growth and perimeter growth were correlated to wind velocity. Fire suppression should be high carefulness while fire strike with strong wind velocity. Fire break should be constructed wider than in the normal situation and should top alert and took machined equipments to support fire control and suppression.

4. Fire weather information especially wind velocity and topographic information should be obtained for fire danger rating assessment in fire control and suppression.

5. Fire behaviors in dry deciduous forest at Huai Kha Khaeng Wildlife Sanctuary were low to moderate fire intensities. Based on results of the study, fire suppression could generally be attacked at the head, flanks and rear fires by firefighters using hand tools accompany with backpack pumps. Hand line, at least 4 m wide could hold the fire. Should top alert and took machined equipments to support fire control and suppression when wind velocity was high.

6. Fire behavior of tall grass fuel model was the highest values of rate of fire spread, fire intensity, flame length, burning area growth and perimeter growth. The fire behavior of the tall grass fuel model was the highest that were due to having a lot of dead and live herbs, high surface area to volume ratio and low particle density, these two properties affected to decrease of ignition time, fuels were easily to ignite and burn. In addition, the highest fuel bed depth in the tall grass fuel model affected to bulk density, used in describing the compactness of fuel beds. The bulk density of a fuel bed can be used as a measure of the oxygen availability and distance between particle across which heat must be transferred to ignite additional fuel. As the results, herb fuel in tall grass fuel model should be reduced for reducing fire intensity, especially dead herb load due to there was the highest in values of loads and low moisture content.

7. Litter fuel type was the highest surface area to volume ratio, low moisture content and low particle density, these properties highly affected to fire behavior. Hence, during dry season the leaves of tree were fallen to form heterogeneous fuel bed, especially for litter fuel model was the highest in values of litter fuel type. Reduction of litter load and construction of fire break at least 4 m of wide for separating the continuous of fuel bed were the recommendations for fuel management.

8. Fire behaviors correlated positively with fuel bed depth and loading of live fuel and correlated negatively with moisture content of live and dead fuel, then reduce the fuel bed depth and loading of live fuel and maintain high moisture content of live and dead fuel were recommended for fuel management.

9. At the resembling rate of fire spread for all fuel models, fireline intensity and flame length of tall grass fuel model would be expressed the highest in value. The nexts were litter with short grass fuel model and litter fuel model, respectively. Firefighters should take high carefulness for fire suppression in tall grass fuel model especially while fire struck with high wind velocity.

LITERATURE CITED

Akaakara, S. 2002. **Fuel Characteristics and Fire Behavior in Dry Dipterocarp Forest, in Kanchanaburi Province.** Forest Fire Control Office, Royal Forest Department, Bangkok. (in Thai).

Akaakara, S., K. Wiriya, T. Tongtan. 2003. **Fire Behaviors in Dry Dipterocarp Forest at Huai Kha Khaeng Wildlife Sanctuary**. Huai Kha Khaeng Forest Fire Research Centre, Department of National Park, Wildlife and Plant Conversation, Bangkok. (in Thai).

Akaakara, S., K. Wiriya, T. Tongtan and P. Nuchaiya. 2004. **Fuel Characteristics in Dry Dipterocarp Forest at Huai Kha Khaeng Wildlife Sanctuary**. Huai Kha Khaeng Forest Fire Research Centre, Department of National Park, Wildlife and Plant Conversation, Bangkok. (in Thai).

Akaakara, S. and S. Kittisatho. 1992. **Fuel Characteristics in Dry Dipterocarp Forest, Suthep-Pui National Park, Chiang Mai Province.** Royal Forest Department, Bangkok. (in Thai).

Albini, F.A. 1976. Estimating Wildfire Behavior and Effects. **USDA Forest Service General Technical Report INT-30**, Intermountain Forest and Range Experiment Station Ogden, Utah.

Albini, F.A. and J.K. Brown. 1978. Predicting Slash Depth for Fire Modeling. **USDA Forest Service Research Paper INT–206.** Intermountain Forest and Range Experiment Station, Ogden, Utah.

Alexander, M.E. 1982 Calculating and Interpreting Forest Fire Intensities. **Canadian Journal Botany.** 60 (4): 349-357.

Allgöwer, B., D. Calogine, A. Camia, P. Cuinas, P. Fernandes, A. Francesetti, C. Hernando, B. Kotz, N. Koutsias, H. Lindberg, D. Molina, F. Morsdorf, L.M. Ribeiro, E. Rigolot and O. Seroguillaume. 2002. **EUFIRELAB: Methods for Wildland Fuel Description and Modelling: A State of the Art.** Available Source: http://eufirelab.org January 9, 2005.

Andrews, P. L. 1980. Testing the fire behavior model p. 70-77. *In* **Proceedings Sixth Conference on Fire and Forest Meteorology.** Society of American Foresters. Seattle, W.A.

Andrews, P. L. 1986. BEHAVE: fire behavior prediction and fuel modeling system: Burn subsystem, Part 1. **USDA Forest Service, General Technical Report INT-194.** Intermountain Forest and Range Experiment Station, Ogden Utah.

Bachmann, A. 2001. **Collection of Derivatives of the Rothermel Model**. Available Source: http://www.geo.unizh.ch/gis/research/edmg/fire/unc.html, August 9, 2005.

Beaufait, W. R. 1965. Characteristics of back fires and head fires in a pine needle fuel bed. **USDA Forest Service Research Note INT-39.** Intermountain Forest and Range Experiment Station Ogden, Utah.

Bilgili, E. and B. Saglam. 2003. **Fire Behavior in Maquis Fuels in Turkey.** Faculty of Forestry, Karadeniz Technical University, Trabzon, Turkey. Available Source: http://www.sciencedirect.com, May 27, 2007.

Bodrozic, L., J. Marasovic and D. Stipanicev. 2006. **Fire modeling in forest fire management.** Department for Modeling and Intelligent Systems. Faculty of Electrical Engineering, Machine Engineering and Naval Architecture, University of Split.

Brown, J.K. 1972. Field test of a rate of spread model in slash fuels. **USDA Forest Service, Research Paper INT-116.** Intermountain Forest and Range Experiment Station, Ogden Utah.

Brown, J.K. 1974. Handbook for inventorying downed woody material. **USDA Forest Service, General Technical Report INT-16.** Intermountain Forest and Range Experiment Station, Ogden Utah.

Brown, A.A. and K.P. Davis. 1973. **Forest Fire: Control and Use**. McGraw-Hill Book Company, New York.

Burgan, R.E., and R.C. Rothermel, 1984. BEHAVE: Fire Behavior Prediction and Fuel Modeling System–Fuel Subsystem. **USDA Forest Service, General Technical Report INT-167**. Intermountain Forest and Range Experiment Station, Ogden, Utah. Available Source: http://www.fs.fed.us/fmsc, January 23, 2005.

Byram, G.M. 1959. Combustion of Forest Fuels. Chapter 3, 61-69. *In* K.P. Davis, 1959, **Forest Fire**: **Control and Use**. McGraw-Hill Book Company, New York.

Byram, G.M., H.B. Clements, M.E. Bishop and R.M. Nelson. 1966. Project fire model. **An experimental study of model fires.** Final report, USDA Southeastern Forest Experiment Station.

Carlton, D.W. 2003. **The Impact of Changing the Surface Fire Spread Model**. Availab Source: http://fire.org/Download/Carton_Model_Impacts.pdf, January 23, 2004.

Chandler, C., P. Cheney, P. Thomas, L. Trabaud and D. Williams. 1983. **Fire in Forest (Vol.1) Forest Fire Behavior and Effects.** John Wiley and Sons, New York.

Chomchan, A. and V. Panyaatanya, 1981. **Energy from Wood.** Royal Forest Department, Bangkok. (in Thai)

Countryman, C.M. 1964. Mass Fires and Fire Behavior . **USDA Forest Service Research Paper PSW-19.** Pacific Southwest Forest and Range Experiment Station Berkley, California.

Countryman, C.M. 1971. This humidity business: **What it is all about and its use in fire control.** USDA Forest Service, Pacific Southwest Forest and Range Experiment Station Berkley, California.

Countryman, C.M. and C.W. Philpot. 1970. Physical Characteristics of Chamise as a Wildland Fuel. **USDA Forest Service Research Paper PSW-66.** Pacific Southwest Forest and Range Experiment Station Berkley, California.

Curry, J.R. and W.L. Fons. 1938. Rate of spread of surface fires in the ponderosa pine type in California. **Journal of Agriculture Research.** 57(4): 239-268.

De Bano, L.F., P.H. Dunn and C.F. Conrad. 1977. Fire's Effects on Physical and Chemical Properties of Chaparral Soils. **Proceeding Environment Consequences Fire Fuel Management Mediterranean Ecosystem**. U.S. Forest Service General Technical Report WO-3.

De Bano, L.F., D.G. Neary and P.E. Ffolliott. 1998. **Fire's Effects on Ecosystem**. John Wiley and Sons, New York.

Faculty of Forestry. 1991. **Forest Fire and Effect of Fire on Forest System in Thailand.** Kasetsart University, Bangkok. (in Thai).

Faculty of Forestry. 2000. Reviewing Fire Management Policy in the Conservation of the Thung Yai and Huai Kha Khaeng Wildlife Sanctuaries and World Heritage Areas of Thailand. **A Final Report Submitted to National Committee for the Protection of the World Cultural and Natural Heritage of Thailand.** Kasetsart University, Bangkok.

Fahnestock, G.R. 1953. Relative humidity and fire behavior in logging slash. **USDA Forest Service Research Note 126.** Northern Rocky Mountain Forest and Range Experiment Station.

Fahnestock, G.R. 1960. Logging slash flammability. **USDA Forest Service Research Paper INT - 58.** Intermountain Forest and Range Experiment Station, Ogden Utah.

Fang, J.B. and F.R. Steward. 1969. Flame spread through randomly packed fuel particles. **Combustion and Flame.** 13(4): 392-398.

Fischer, W.C. 1982. Photo guide for appraising downed woody fuels in Montana forests: Grand Fir-Lach-Douglas-Fir, Western Hemlock, Western Hemlock-Western Redcedar, and Western Redcedar cover types. **USDA Forest Service, General Technical Report INT-96**. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Fons, W.L. 1946. Analysis of Fire Spread in Light Fuels. **Journal of Agriculture Research.** 72(3): 92-121.

Forest Fire Control Office. 2006. **Burned Area Statistics in Thailand**. Department of National Park Wildlife and Plant Conservation, Bangkok. (in Thai).

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

Goldammer, J.G. 1993. Fire Management. pp. 1221 – 1268. *In* P.Laslo, ed. **Tropical Forestry Handbook volume 1 – 2.** Springer – Verlag, New York.

Harvey, S., M. Ruegsegger and B. Allower. 1997. **Fuel Models for Switzerland (Swiss National Park).** Department of Geography, Division of Spatial Data Handling, Zurich, Switzerland.

Hernando, C. 2004. Physical, chemical and thermal characteristics of the wildland fuel particles. **EUFIRELAB: Deliverable D-02-02_A**. Available Source: http://www.eufirelab.org, April 12, 2007.

Himmaphan, W. 2005. **Behavior, Effect and Smoke Composition of Burning Fire in Dry Deciduous Dipterocarp Forest at Huay Kha Khaeng Wildlife Sanctuary.** Doctoral Thesis, Kasetsart University.

Hodgson, A. 1968. Control Burning in Eucalypt Forest in Victoria, Australia. **Journal of Forest.** 66 (8): 46-58.

Huai Kha Khaeng Forest Fire Research Center. 2006. **Climatic Data Report in 2005** Department of National Park Wildlife and Plant Conservation, Bangkok. (in Thai).

Husch, B., C.I. Miller and T.W.Beers. 1982. **Forest Mensuration, 3rd Edition**. John Wiley and Sons, New York.

Kaitpraneet, S. 1983. **Forest Fire and Controls**. Faculty of forestry. Kasetsart University, Bangkok. (in Thai).

Keane R.E., R. Burgan and J.V. Wagtendonk. 2001. Mapping wildland fuels for fire management acroos multiple scales: Integrating remote sensing, GIS and biophysical modeling. **International Journal of Wildland Fire.** 10: 301-309.

Kelsey. R.G., F. Shafizadeh and D.P. Lowery. 1979. Heat Content of Bark, Twigs and Foliage of Nine Species of Western Conifers. **USDA Forest Service Research Note INT–261.** Intermountain Forest and Range Experiment Station, Ogden, Utah.

Koehler, A. 1924. **The Properties and Uses of Wood.** Mc Graw-Hill Book Company, New York.

Konev, E.U. and A.I. Sukhinin. 1977. The analysis of flame spread through forest fuel. **Combustion and Flame.** 28 (3): 217-227.

Kutintara, U. 1998. **ECOLOGY: Fundamental Basics in Forest**. Faculty of Forestry, Kasetsart University, Bangkok. (in Thai)

McArthur, A.G. 1966. Weather and grassland fire behaviour. **Australia Forestry and Timber Bureau**, Leaflet No. 100, Canberra.

Mendes-Lopes, J.M.C., J.M.P. Ventura and J.M.P. Amaral. 1998. Rate of spread and flame characteristics in a bed of pine needles. pp. 497-511. *In* III International Conference On Forest Fire Research 14^{th}. **Conference on Fire and Forest Meteorology Vol. I.**, Luso.

Mutch R.W. and C.W. Philpot. 1970. Relation of silica content to flammability in grasses. **Forest Science**. 16 (1): 64-65.

Neenan, M. and K. Steinbeck. 1979. Caloric Values for Young Sprouts of Nine Hardwood Species. **Forest Science.** 25 (3).

Noble, I.R., G.B. Bary and A.M. Gill. 1980. MCARTHUR,S fire-danger meters expressed as equations. **Australia Journal Ecology**. 5:201-203.

Nord, E.C. and C.M. Countryman. 1972. Fire Relations. In: C.M. McKell, J.P. Blaisdell and J.R. Goodin (eds.), Wildland Shurbs Their Biology and Utilization. An International Symposium, Utah State University, Logan, Utah. **USDA Forest Service General Technical Report INT-1.**

Philpot, C.W. 1969. The Effect of Extractive Content on the Burning Rate of Aspen Leaves. **USDA Forest Service Research Paper INT–91.** Intermountain Forest and Range Experiment Station, Ogden, Utah.

Pyne, S.J., P.L. Andrews and R.D. Laven. 1996. **Introduction to Wildland Fire, 2nd Edition**. John Wiley & Sons, Inc., New York.

Robertson, J.W., Jr. 1980. **Backing fire spread rates on slopes in wood cribs**. M.S. Thesis, University of Washington, Seattle.

Rothermel, R.C. 1972. **A Mathematical Model for Predicting Fire Spread in Wild Fuels**. USDA Forest Service. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Rothermel, R.C. and H. E. Anderson. 1966. Fire spread characteristics determined in laboratory. **USDA Forest Service Research Paper INT-30.** Intermountain Forest and Range Experiment Station Ogden, Utah.

Rothermel, R.C. and G.C. Rinehart. 1983. Field Procedures for Verification and Adjustment of Fire Behavior Predictions. **General Technical Report INT-142.** USDA Forest Service. Intermountain Forest and Range Experiment Station Ogden, Utah.

Samran, S. 1992. **Relationship of fuel moisture content and micro-climate in Dry Dipterocarp Forest at Phu Phan National Park, Sakon Nakhon.** Royal Forest Department, Bangkok. (in Thai).

Samran, S., S. Homsud and T. Tongtan. 2002. **Fuel Characteristics in Dry Dipterocarp Forest, Huai Kha Khaeng Wildlife Sanctuary**. Royal Forest Department, Bangkok. (in Thai).

Sathirasilapin, M. 1987. **Fire Behavior of Dry Dipterocarp Forest at Sakaerat, Amphoe Pak Thong Chai, Changwat Nakhon Ratchasima.** M.S. Thesis, Kasetsart University. (in Thai)

Schroeder, M.J. and C.C. Buck. 1970. Fire Weather**. USDA Forest Service. Handbook 360**.

Scott, J. H. 1999. NEXUS: A system for assessing crown fire hazard. **Fire Management Notes.** 59(2): 20-24. Available Source: http://www.fire.org/nexus/, June 23, 2005.

Scott, J H. and R.E. Burgan. 2005. Standard Fire Behavior Fuel Model: a comprehensive set for use with Rothermel's surface fire spread model. **General Technical Report RMRS-GTR-153.** Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. Available Source: http://www.treesearch.fs.fed.us/pubs/9521, July 20, 2005.

Sompoh, B. 1998. **Fuel Complex in Dry Deciduous Dipterocarp and Mixed Deciduous Forest at Huai Kha Khaeng Wildlife Sanctuary, Changwat Uthai Thani.** M.S. Thesis, Kasetsart University. (in Thai).

Spurr, S.H. 1952. **Forest Inventory**. The Ronald Press Company, New York.

Steward, F.R. 1971. A mechanistic fire spread model. **Combustion Science and Technology**. 4 (4): 177-186.

Steward, F.R. 1974. Fire spread through a fuel bed. *In* **P. L. Blackshear, (ed.) Heat transfer in fires: Thermophysics, social aspect, economic impact.** John Wiley & Sons.

Stott, P. 1986. The spatial pattern of dry season fires in the savanna forest of Thailand. **Journal Biogeography.** 13: 315-335.

Sukwong, S. and P. Dhamanitayakul. 1977. Fire Ecology Investigations in Dry Dipterocarp Forest. *In* **Proceeding. 1977. National Forestry Conference**. Royal Forest Department, Bangkok.

Sunyaarch, S. 1989. **Effects of fire on Vegetation and Soil in Dry Dipterocarp Forest, Sakaerat, Nakhon Ratchasima.** M.S. Thesis, Kasetsart University. (in Thai)

Van Wagner, C.E. 1969. A simple fire–growth model. **The Forestry Chronicle.** 45 (110.2): 103–104.

Van Wagner, C.E. 1977. Condition for the start and spread of crown fire. **Canadian Journal of Forest Research.** 7: 23-24.

Wade, D.D. 1986. Linking fire behavior to its effect on living plant tissue. *In* **Proceeding Annual Convention Society of American Foresters**. Birmingham, AL. Unpaged.

Wanthongchai, K. 2008. **Effects of different burning frequencies on fire behaviour, nutrient dynamics, soil properties, and vegetation structure and composition in dry dipterocarp forest, Huay Kha Khaeng Wildlife Sanctuary, Thailand.** Doctoral Thesis, Freiburg University.

Wiriya, K. 2006. **Fuel characteristics in dry deciduous dipterocarp forest of Thailand.** Forest Fire Control Office, Department of National Park, Wildlife and Plants Conservation, Bangkok. (in Thai).

US Forest Service. 1956. Glossary of Terms Used in Forest Fire Control. **USDA Forest Service Handbook.**

USDA Forest Service. 2000. **Users, Guide to BehavePlus.** USDA Forest Service Rocky Mountain Research Station, Missoula Fire Sciences Laboratory.

APPENDIX

Appendix The equation of Rothermel's fire spread model, applied by Bachmann (2001) for predicted rate of fire spread of fuel models in dry deciduous dipterocarp forest at Huai Kha Khaeng Wildlife Sanctuary.

1. List of Symbols

$w0_{li}$	Fuel loading of litter fuel (kg m^{-2})
$w0_{tw}$	Fuel loading of twig fuel (kg m^{-2})
$w0_{dh}$	Fuel loading of dead herb fuel (kg m^{-2})
$w0_{lh}$	Fuel loading live herb fuel (kg m^{-2})
$w0_{un}$	Fuel loading of undergrowth fuel (kg m^{-2})
sv_{li}	Surface area to volume ratio of litter fuel (m^{-1})
sv_{tw}	Surface area to volume ratio of twig fuel (m^{-1})
sv_{dh}	Surface area to volume ratio of dead herb (m^{-1})
sv_{lh}	Surface area to volume ratio of live herb fuel (m^{-1})
sv_{un}	Surface area to volume ratio of undergrowth fuel (m^{-1})
m_{li}	Fuel moisture content of litter fuel (%)
m_{tw}	Fuel moisture content of twig fuel (%)
m_{dh}	Fuel moisture content of dead herb fuel (%)
m_{lh}	Fuel moisture content of live herb fuel (%)
m_{un}	Fuel moisture content of undergrowth fuel (%)
d	Fuel bed depth (m)
ρ_p	Particle density (kg m^{-3})
heat	Particle low heat content (kJ kg^{-1})
s_t	Total mineral content (%)
s_e	Effective mineral content (%)
mx	Moisture content of extinction, dead fuel (%)
wsp	Wind velocity (m s^{-1})
wdr	Wind direction (°)
slp	Slope (rad)
asp	Aspect (°)

υ	Split angle between upslope direction and direction where the wind is blowing to (rad)
ρ_b	Bulk density (kg m^{-3})
β	Packing ratio
β_{opt}	Optimal packing ratio
$beta_{ratio}$	Ratio mean/optimal packing ratio
w_n	Net fuel loading
η_s	Mineral damping coefficient
η_M	Moisture damping coefficient
ξ	Propagating flux ratio
A	Auxiliary function
Γ	Potential reaction velocity (s^{-1})
Γmax	Maximum reaction velocity (s^{-1})
I_r	Reaction intensity (kWm^{-2})
$\emptyset s$	Slope factor
B,C,E	Auxiliary functions
$\emptyset w$	Wind factor
vx, vy	Vector components
vl	Amount of the sum of the wind and slope factor, i.e. $\|\emptyset s + \emptyset w\|$

2 Rothermel's Model

Generally, the weighting parameters that are formulated in the original paper of Rothermel (1972, p.29-30) have been simplified in this paper. This could be done by assuming a constant particle density ρ_p for any size class and category.

Note: The original equation numbers are referenced in square brackets, i.e [R(27)] Denotes equation (27) in the paper of Rothermel (1972). Similarly, [Albini, p.89] points to page 89 in the publication of Albini (1976)

Auxiliary Functions

$$sw_{li} = sv_{li}w0_{li}$$

$$sw_{tw} = sv_{tw}w0_{tw}$$

$$sw_{dh} = sv_{dh}w0_{dh}$$

$$sw_{lh} = sv_{lh}w0_{lh}$$

$$sw_{un} = sv_{un}w0_{un}$$

$$sw_{d} = sw_{li} + sw_{tw} + sw_{dh}$$

$$sw_{l} = sw_{lh} + sw_{un}$$

$$sw_{t} = sw_{d} + sw_{l}$$

$$s2w_t = sv^2{}_{li} \,.\, w0_{li} + sv^2{}_{tw} \,.\, w0_{tw} + sv^2{}_{dh} + w0_{dh} + sv^2{}_{lh} \,.\, w0_{lh} + sv^2{}_{un} \,.\, w0_{un} \quad (1)$$

$$sw2_d = sv_{li} \,.\, w0^2{}_{li} + sv_{tw} \,.\, w0^2{}_{tw} + sv_{dh} \,.\, w0^2{}_{dh} \quad (2)$$

$$sw2_l = sv_{lh} \,.\, w0^2{}_{lh} + sv_{un} \,.\, w0^2{}_{un} \quad (3)$$

$$sw2_t = sv2_d + sw2_l \quad (4)$$

$$swm_d = sw_{li} \,.\, m_{li} + sw_{tw} \,.\, m_{tw} + sw_{dh} \,.\, m_{dh} \quad (5)$$

$$swm_l = sw_{lh} \,.\, m_{lh} + sw_{un} \,.\, m_{un} \quad (6)$$

Characteristic surface-to-volume ratio [R(71,72)]

$$\sigma = \frac{s2w_t}{sw_t}$$

$$= \frac{sv^2{}_{li} \,.\, w0_{li} + sv^2{}_{tw} \,.\, w0_{tw} + sv^2{}_{dh} \,.w0_{dh} + sv^2{}_{lh} \,.\, w0_{lh} + sv^2{}_{un} \,.\, w0_{un}}{sv_{li} \,.\, w0_{li} + sv_{tw} \,.\, w0_{tw} + sv_{dh} \,.\, w0_{dh} + sv_{lh} \,.\, w0_{lh} + sv_{un} \,.\, w0_{un}}$$

Mean Bulk Density [R(74)]

$$\rho_b = \frac{w0_{li} + w0_{tw} + w0_{dh} + w0_{lh} + w0_{un}}{d} \quad (7)$$

Packing Ratios

Mean Packing Ratio [R(31,73)]

$$\beta = \frac{\rho_b}{\rho_p} \tag{8}$$

Optimal Packing Ratio [R(37)]

$$\beta_{opt} = 8.8578 \cdot \sigma^{-0.8189} \tag{9}$$

Net Fuel Loading [R(60), adjusted by Albini (1976). (p.88)]

$$wn_{li} = w0_{li} \cdot [1-(s_t/100)] \tag{10}$$

$$wn_{tw} = w0_{tw} \cdot [1-(s_t/100)] \tag{11}$$

$$wn_{dh} = w0_{dh} \cdot [1-(s_t/100)] \tag{12}$$

$$wn_{lh} = w0_{lh} \cdot [1-(s_t/100)] \tag{13}$$

$$wn_{un} = w0_{un} \cdot [1-(s_t/100)] \tag{14}$$

[R(59)]

$$wn_d = [1-(s_t/100)] \cdot (sw2_d/sw_d) \tag{15}$$

$$wn_l = [1-(s_t/100)] \cdot (sw2_l/sw_l) \tag{16}$$

Mineral Damping Coefficient [R(62)]

$$\eta_s = 0.174 \cdot (s_e/100)^{-0.19} \tag{17}$$

Moisture Damping Coefficient

Ratio of “Fine” Fuel Loadings, Dead/Living [Albini, p.89]

$$hn_{li} = 0.20482 \cdot w0_{li} \cdot \exp(-452.76/sv_{li}) \quad (18)$$

$$hn_{tw} = 0.20482 \cdot w0_{tw} \cdot \exp(-452.76/sv_{tw}) \quad (19)$$

$$hn_{dh} = 0.20482 \cdot w0_{dh} \cdot \exp(-452.76/sv_{dh}) \quad (20)$$

$$hn_{lh} = 0.20482 \cdot w0_{lh} \cdot \exp(-1640.42/sv_{lh}) \quad (21)$$

$$hn_{un} = 0.20482 \cdot w0_{un} \cdot \exp(-1640.42/sv_{un}) \quad (22)$$

$$hn_{d} = hn_{li} + hn_{tw} + hn_{dh} \quad (23)$$

$$hn_{l} = hn_{lh} + hn_{un} \quad (24)$$

$$W = hn_{d}/hn_{l} \quad (25)$$

Moisture Content of “Fine” Dead Fuel [Albini, p.89]

$$hnm_{d} = hn_{li} \cdot m_{li} + hn_{tw} \cdot m_{tw} + hn_{dh} \cdot m_{dh} \quad (26)$$

$$M\,f_{dead} = hnm_{d}/hn_{d} \quad (27)$$

Moisture of Extinction of Living Fuel [R(88), Albini, p.89]

$$Mx_{live} = (2.9 \cdot W\,(1-(Mf_{dead}/mx))-0.226) \cdot 100 \quad (28)$$

Moisture Ratios [R(65,66)]

$$rm_{l} = swm_{l}/(sw_{l}\,Mx_{live}) \quad (29)$$

$$rm_{d} = swm_{d}/(sw_{d} \cdot mx) \quad (30)$$

Moisture Damping Coefficients [R(64)]

$$\eta M_{d} = 1 - 2.59 \cdot rm_{d} + 5.11 \cdot rm^{2}_{d} - 3.52 \cdot rm^{3}_{d} \quad (31)$$

$$\eta M_{l} = 1 - 2.59 \cdot rm_{l} + 5.11 \cdot rm^{2}_{l} - 3.52 \cdot rm^{3}_{l} \quad (32)$$

$$\eta M = wn_{d} \cdot \eta M_{d} + wn_{l} \cdot \eta M_{l} \quad (33)$$

Reaction Velocity

Maximum Reaction Velocity [R(36,68)]

$$\Gamma_{max} = \frac{0.16828 . \sigma^{1.5}}{29{,}700+0.5997 . \sigma^{1.5}} \tag{34}$$

A [R(70), Albini p.88]

$$A = 340.53 . \sigma^{-0.7913} \tag{35}$$

Potential Reaction Velocity [R(38)]

$$\Gamma = \Gamma_{max} . (\beta/\beta_{opt})^{A} . \exp(A . (1-(\beta/\beta_{opt}))) \tag{36}$$

Reaction Intensity [R(27,58), Albini, p.89]

$$I_r = \Gamma . \text{heat} . \eta_s . \eta M \tag{37}$$

Propagating Flux Ratio [R(42)]

$$\xi = \frac{\exp[(0.792+0.37597 . \sqrt{\sigma}) . (\beta+0.1)]}{192+0.0791 . \sigma} \tag{38}$$

Heat Sink

Effective heating number [R(14,77)]

$$\varepsilon_{li} = \exp(-452.76/sv_{li}) \tag{39}$$

$$\varepsilon_{tw} = \exp(-452.76/sv_{tw}) \tag{40}$$

$$\varepsilon_{dh} = \exp(-452.76/sv_{dh}) \tag{41}$$

$$\varepsilon_{lh} = \exp(-452.76/sv_{lh}) \tag{42}$$

$$\varepsilon_{un} = \exp(-452.76/sv_{un}) \tag{43}$$

Heat of Preignition [R(12,78)]

$$Q_{li} = 581.5+25.957 \,.\, m_{li} \quad (44)$$

$$Q_{tw} = 581.5+25.957 \,.\, m_{tw} \quad (45)$$

$$Q_{dh} = 581.5+25.957 \,.\, m_{dh} \quad (46)$$

$$Q_{lh} = 581.5+25.957 \,.\, m_{lh} \quad (47)$$

$$Q_{un} = 581.5+25.957 \,.\, m_{un} \quad (48)$$

Heat Sink [R(77)]

$$hskz = sv_{li} \,.\, w0_{li} \,.\, \varepsilon_{li} \,.\, Q_{li} + sv_{tw} \,.\, w0_{tw} \,.\, \varepsilon_{tw} \,.\, Q_{tw} + sv_{dh} \,.\, w0_{dh} \,.\, \varepsilon_{dh} \,.\, Q_{dh} + sv_{lh} \,.\, w0_{lh} \,.\, \varepsilon_{lh} \,.\, Q_{lh} + sv_{un} \,.\, w0_{un} \,.\, \varepsilon_{un} \,.\, Q_{un} \quad (49)$$

$$hsk = \rho_b\,(hskz/sw_t) \quad (50)$$

Slope and Wind

Slope Factor [R(80)]

$$\varnothing s = 5.275 - \beta^{-0.3} \,.\, \tan(slp)^2 \quad (51)$$

Wind Factor [R(79,82,83,84)]

$$B = 0.02526 \,.\, (\sigma \,.\, 0.3048)^{0.54} \quad (52)$$

$$C = 7.47 \,.\, \exp(-0.133 \,.\, (\sigma \,.\, 3048)^{0.55}) \quad (53)$$

$$E = 0.715 \,.\, \exp(-0.000359 \,.\, 0.3048 \,.\, \sigma) \quad (54)$$

$$\varnothing w = C \,.\, (3.281 \,.\, 60 \,.\, wsp)^B \,.\, (\beta/\beta_{opt})^{-E} \quad (55)$$

Combined Slope and Wind Factor

$$vx = \varnothing s + \varnothing w \,.\, \cos(\vartheta) \quad (56)$$

$$vy = \varnothing w \,.\, \sin(\vartheta) \quad (57)$$

$$vl = \sqrt{vx^2 + vy^2} \quad (58)$$

Spread Direction

$$sdr = \arcsin(vy/vl) \tag{59}$$

Effective Wind Speed [R(79)]

$$efw = \frac{(vl/(C \,.\, (\beta/\beta_{opt}))^{-E})^{1/B}}{196.85} \tag{60}$$

Rate of Spread [R(52)]

$$ros = \frac{I_r \,.\, \xi \,.\, (1 + vl)}{hsk} \tag{61}$$