indexes on selection fire-resistance tree species, according to the main component analysis. Ignition time have positive correlation with water content and lignin content, and have negative correlation with rough grease content. Heat value relates to lignin content and benzene-ethanol extractive content linearly, it will increase with lignin content and benzene-ethanol extractive content growth.

By means of the fuzzy mathematics method, the fire-resistance of 12 tree species is put in order. That is *Schima superba, Castanopsis hystrix, Myria rubru Machilus pauhoi, Mytilaria laosensis, Michelia macclurei, schima sp., Cunninghamia lancedata* and *Pinus massniana.*

The result of cluster analysis also indicated that *Cunninghamia lancedata* and *Pinus massniana* have weak fire resistance, and *Schima superba, Castanopsis hystrix, Myria rubru* ,etc. have strong fire-resistance.

5.Acknowledge

The project is subsided with *ninth five years* project tackling key problem of the country. We special thank Prof. Fan Weicheng giving our help.

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Forest Fires in Boreal Forest – FROSTFIRE in Alaska Taiga

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ABSTRACT

This paper describes results of FROSTFIRE, a forest fire experiment carried out in July 1999 and also surveys results of the Donnelly Flats forest fire in June 1999. An investigation of the Donnelly Flats forest fire site found that the main burnt matter were branches with needles of black spruce and mosses and lichen which cover the ground. On the basis of these results, a vegetation investigation was carried out before the FROSTFIRE experiment. The following items were measured : weight of branches with needles of two black spruce trees and the thickness of mosses which covered the surface around the trees. Thunder storm observations by video camera from the Poker Flat mountain top recorded multiple lightning strikes. After the storm, three plumes from forest fires were observed in different directions and the probability of ignition of forest fires by the lightning is discussed. Finally, the combustion calculations using mean tree densities of black spruce and mean thickness of mosses estimate the quantity of CO_2 released in forest fires in Alaska.

KEYWORDS : Forest Fire, Boreal Forest, Taiga, Carbon Dioxide, FROSTFIRE, Lightning, Black Spruce, Moss

INTRODUCTION

The taiga is the common term for coniferous forest zones, and this kind of forest covers over one third of all woodland on the Earth. The Eurasian Continent has 55% of the taiga and North

America 40%. About two thirds of taiga grows on permafrost [1] . Forest fires occur frequently in taiga and has come to general notice because of global warming by carbon dioxide (CO_2) which has become an important issue. The average area burnt annually by forest fires in Canada since 1918 is about two million ha [2] . The maximum annual burnt area is nearly eight million ha, almost equal to the area of Hokkaido, a major island of Japan. To understand the effect of forest fires, forest fire experiments in actual forests have been carried out in Russia, Canada, the U.S.A., and elsewhere to answer questions such as "Is the forest a source of absorption or a source of emission of CO_2? " [3,4] . Especially, the effect of climatic variations due to forest fires and destruction of the taiga of the Far East in Russia will influence Japan directly as it is located at the edge of far eastern Russia. The forests ruined by forest fires in Russia become lakes and marsh called "Alas" if the ice content in the ground is high. Once Alas is formed, recovery to forest is very difficult. Further, methane gas bound in the permafrost is discharged by taiga fires [5] . As a result, forest fires in the taiga are related to decreases in fixed CO_2 due to the loss of forests, increases in the emission of CO_2 from the fires, and increases in the emissions of methane from the permafrost, overall making it impossible to disregard the effect on global warming. The authors made detailed observations of vegetation and thunder storms in the so-called FROSTFIRE experiment [6] area before the forest fire experiments. The weight of twigs and needles of black spruce were measured and several thermocouples were placed on a tree to measure temperatures during the fire. Survey results of a large-scale forest fire area near Delta Junction, Alaska [7] are also reported. The report focuses on basic questions like : What burns in the forest fire? And what is the ignition mechanism? The burning characteristic of forest fires and the discharge of carbon dioxide with forest fires is discussed.

EXPERIMENT

Outline of the FROSTFIRE Experiment

FROSTFIRE is a cooperative research project planned by Alaska University Fairbanks, the USDA Forest Service, the U.S.A. Pacific Northwest Research Station, and others to clarify phenomena with forest fires in boreal forests. The forest fire experiment was carried out in the research area (Caribou-Poker Creeks Experimental Watershed) , in the vicinity of Fairbanks in Alaska July 8～15, 1999. The burn area was about 890ha (about 3km^2) mainly on Little Poker Creek, as shown in Figure 1. The experiment was finished when the burnt area reached about 40% of the total scheduled area [6] .

Measurements and Items for Observation

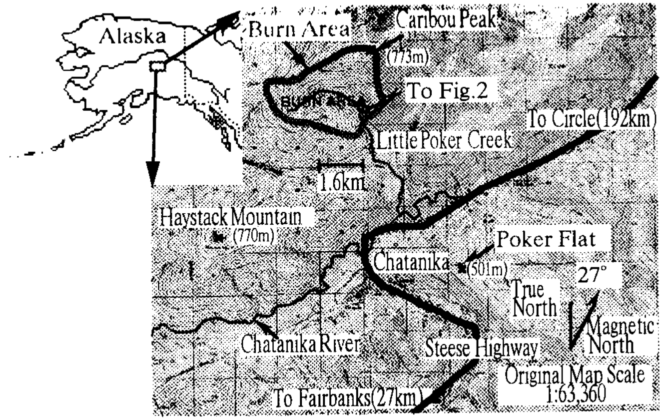

FIGURE 1 Map of the FROSTFIRE Experimental Site and Chatanika Area

Some fundamental questions must be clarified when considering forest fires : What is the fuel? How does it burn? What is the ignition mechanism? To answer these questions and to understand how a forest fire progresses, the following items were covered. Vegetation mapping before the fire test, estimates of the fuel weight, temperature measurements during the fire test, infrared image measurements by thermal camera, and reinvestigation after the fire test. Observation of lightning as the cause of ignition of forest fires in Alaska and on site investigation of a large forest fire were also carried out .

EXPERIMENTAL RESULTS AND DISCUSSION

Vegetation Survey

The climatic province in this research area is subarctic (Dfc) , and it is in a discontinuous permafrost terrain in the polar coniferous forest zone. The main trees in this area are black spruce, white birch, and alpine vegetation.
One (target) tree was chosen as a typical spruce forest tree of the FROSTFIRE experiment area. The location of the tree measured with the GPS was 65° 09'29" North Latitude, 147° 29'10" West Longitude, and the area around the target tree was chosen for investigation. The area is a square with side length ten meters. Vegetation mapping was made as shown in Figure 2. The area had seventy trees with heights exceeding one meter, sixty three trees out of the seventy were black spruce (density 0.63 black spruce /m^2) , and the remaining seven trees were white birch. The average diameter of the black spruce at breast-height was 6cm, and the average height 6.4m.

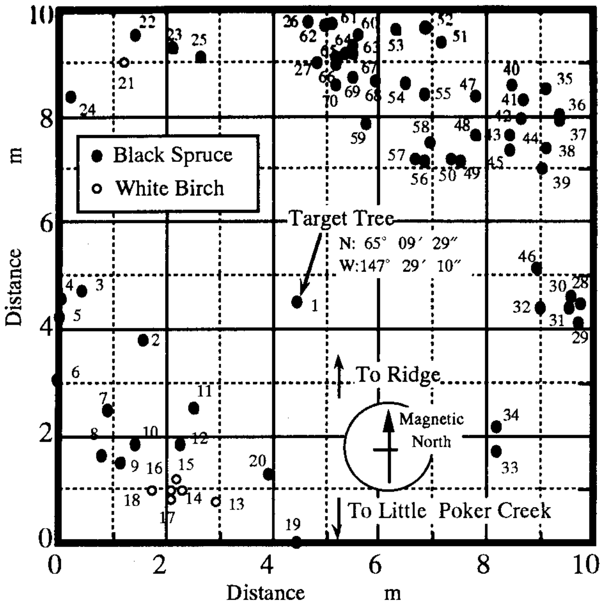

FIGURE 2 Vegetation Mapping at the FROSTFIRE Experimental Site

State of Forest in FROSTFIRE Experimental Site

Two black spruce near the area were cut off. Their height were 7.1m and 10.8m and the breast-height diameters were 9cm and 17cm. They were named No.1 and No.2 respectively. The base diameter of the two trees were 9.9 and 22.9cm and the two trees had 65 and 73 annual growth rings respectively.

Annual ring width of two trees was measured and plotted in Figure 3. Figure 3 shows that black spruce No.2 began to grow after two years from the last forest fire happened in 1924. Black spruce No.2 showed relatively high growth rate from 1930 to 1960. On the other hand, black spruce No.1 began to grow in the middle of 1930 and showed relatively slow growth rate, about from 0.5 to 1 mm. Figure 3 also shows that forest in FROSTFIRE experimental site is so-called mature forest because over 50 years passed after the fire.

The photograph in Figure 4 [6] is of typical spruce forest in the test area, the black spruce is lank and grow thickly (about three trees /m^2) . The black spruce spread branches in all directions at every height, pine bulk masses in the crown, and branches near the ground are nearly all dead and covered by lichen.

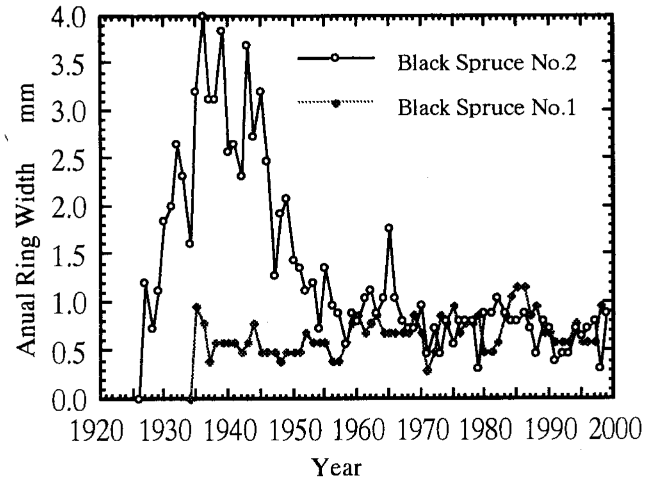

FIGURE 3 Annual Ring Width of Two Trees in the FROSTFIRE Experimental Site

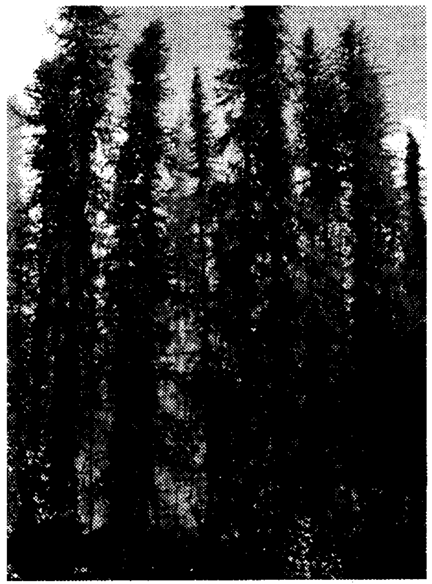

FIGURE 4 Typical Appearance of Black Spruce Forest at the Start of the Fire [6]

FIGURE 5 Typical Appearance of Black Spruce Forest after Forest Fire [6]

Measurement of Fuel

Investigation of a Large Forest Fire Site

On June 11th, 1999, there was a forest fire near Delta Junction, Alaska which kept burning for about a week, and consumed about 7300ha of forest. The authors visited this large-scale forest fire site [7] . Black spruce was the most common tree also in this forest, and the Figure 5 photograph [6] from the FROSTFIRE experiment looks very much like the forest at Delta Junction after the forest fire.

As a result of the inspection of the forest fire site, it was determined that :

1. The trunks of trees, except fallen trees, do not burn. The bark protects the trunks from flames.
2. Twigs with needles of black spruce burn (Figure 5) .
3. Thick branches do not burn (Figure 5) .
4. The bark is subject to slight burns, maybe depending on the fire conditions.
5. Moss which covers the ground at a thickness of about 10cm burns.
6. Lichen on branches and ground burn.

These results allow the conclusion that the main fuels of a forest fire in this kind of taiga are moss and lichen on the ground, foliage and twigs on the thick branches of trees. Thus, a forest fire in the taiga may be termed a "foliage, twig, and moss fire" rather than a "forest fire " .

Gravimetry of Branches with Needles

The weight of branches and needles, and the number of branches of the two cut down black spruce trees (same trees in Figure 3) were measured at one meter intervals from bottom to top. The weight of branches with needles was about 1kg to several kg per meter of tree. The gross weight of the branches with needles was 9.67kg for the first tree and 39.1kg for the second tree, the total almost proportional to the square of the trunk diameter at breast height. Figure 6 has the dimensionless height of the two trees as the X-axis and

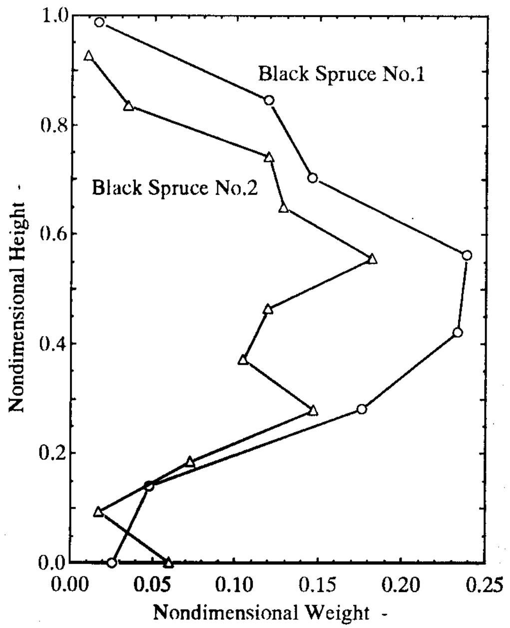

FIGURE 6 Weight Distribution of Black Spruce Twigs with Needles

the dimensionless weight as the Y-axis, and shows the weight distribution. Figure 6 shows that branches with needles in the central part of the trees were heavier than in the other parts.

Gravimetry of Twigs with Needles

It was noted that large branches usually do not burn during forest fires. Twigs with needles were removed from these moderately sized branches, and the weights were measured. The result showed that twigs comprised 70 - 75% of the total, indicating that about 25 - 30% of the weight of branches with needles remains unburned during usual forest fires.

Survey of Mosses

Mosses in the area of the Forest Fire has an average thickness of about 10cm, making the leaves, stems, and roots of the moss good heat insulators for the permafrost. However, during fires, flames remain on the moss surface and can easily spread over the moss surface as the moss acts as an insulator. This situation is observed in the lower part of Figure 3. Surface flames may help the ignition of black spruce twigs with needles. Smoldering combustion seems to start inside the moss. Smoldering in the moss layer is a relatively slow combustion which lasts longer because the moss layer is a good insulator. A 14 x 14 cm, 4 cm thick moss sample was collected at the FROSTFIRE experimental site, and the density in the natural dried state was 25 kg/m^3 .

Temperature History During FROSTFIRE Experiment

To measure temperature history during the FROSTFIRE experiment, totally six thermocouples were put on and near the above mentioned target tree. Four thermocouples were put on the north side trunk of the target tree. Their height were 0, 1, 2 and 3 m from the ground. They were used to measure temperature distribution of the height direction. Other two thermocouples were used to know the flame front direction. One was put on

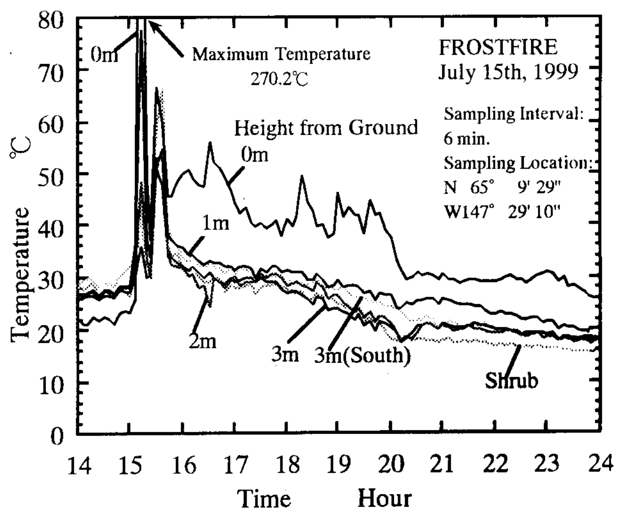

FIGURE 7 Temperature History During FROSTFIRE Experiment

the south side trunk of the target tree at the height of 3m and another one was put on the Shrub located at the south side of the target tree.
Temperature history during the FROSTFIRE experiment is shown in Figure 7. Sampling interval had to set at six minutes because no one could enter the experimental site during the fire. Due to long sampling interval, obtained results were not good. Maximum temperature was 270.2 ℃ observed at 0m or surface of moss layer. Temperature around 45 ℃ observed at 0m lasted about five hours after the flame front passed. This implied smoldering of moss layer.
Infrared images taken by thermal camera taken from Poker Flat (Figure 1) were also analyzed. Unfortunately, images were not good because there were disturbance by sun light reflection.

Observation of Forest Fire and Thunder

The FROSTFIRE experimental site can be seen from Poker Flat and observations were carried out from the roof of the rocket launch observation facilities at Poker Flat (Figure 1) when cumulonimbus clouds formed in the afternoon of July fourth, 1999.
Dozens of thunder claps and dozens of lightning strikes were noted and at about 14 : 20, a white mushroom shaped plume produced by a forest fire on the ridge in the mountain at azimuth about 238° was observed. A lightning shape and a typical plume from a forest fire are shown in Figures 8 and 9.
Afterwards, two plumes from other forest fires were also confirmed, one small and one relatively large. All the forest fires extinguished naturally after several hours. The probability of ignition by lightning is considered to be about 1/100, but it seemed higher here when small ignitions are included.
Lightning locations near FROSTFIRE experimental site on July fourth, 1999 are plotted In Figure 10. Lightning location data were obtained from the database of BLM lightning network [7] . From Figure 10, it will be noted that lightning locations are concentrated to the north west

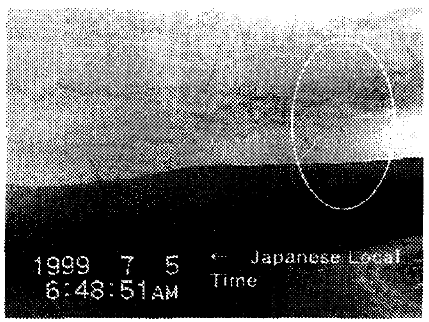

FIGURE 8 Lightning Shape Recorded by Video

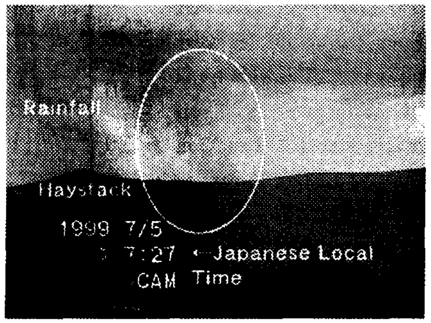

FIGURE 9 Typical Plume from Forest Fire

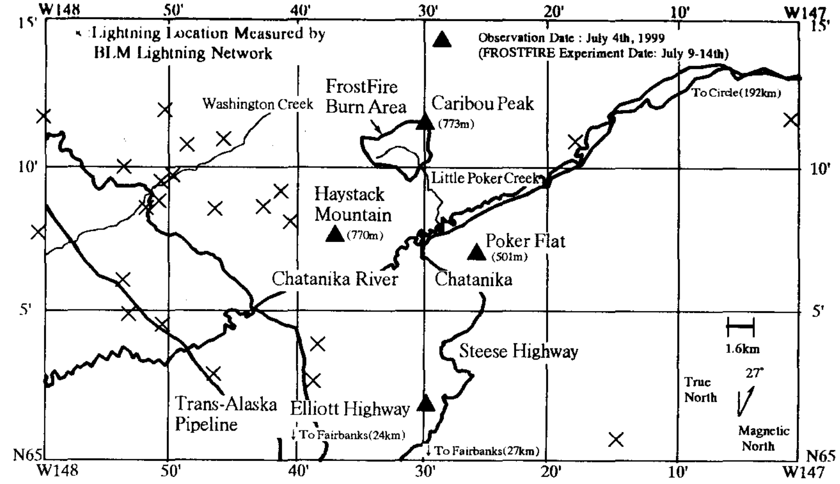

FIGURE 10 Lightning Locations Near FROSTFIRE Experimental Site

region of Mt. Haystack, the regions of along Elliott Highway, Trans-Alaska pipeline and Washington Creek. This implies that specified landscape and man-made structures may easily interact with lightning.
There are further questions such as what is ignited by the lightning ? And how does the lightning ignite trees or moss ? Further observations will be made to establish the lightning ignition mechanism.

Heat Energy Generated by Forest Fires

Calorific Value of Twigs with Needles

Considering the tree density of the black spruce, that the weight of twigs with needles is proportional to the square of the diameter of the trunk, the proportion of combustibles that are twigs with needles etc., it is possible to estimate the calorific value per unit area of spruce forest by the following equation, assuming that all combustibles are cellulose :
(Heat generated by combustion of twigs with needles per unit area, kJ/m^2) = (number of trees per unit area, number of trees/m^2) X (mean weight of combustible material, kg/tree) X (mean calorific value of combustible material, kJ/kg) ≒ 2kg/m^{2}X16,090 kJ/kg=32,180 kJ/m^2

Calorific Value of Moss

The calorific value of moss including lichen on the forest floor can be similarly calculated by using the following equation when the mean thickness of the moss cover is assumed as 10cm :
(Heat generated by combustion of moss per unit area, kJ/m^2) = (moss density, kg/m^3) X

(mean thickness of moss, m) X (mean calorific value of combustible material, kJ/kg) '. 25kg/m^2 X 0.1m X16,090 kJ/kg=40,225 kJ/m^2

Maximum Heat Generated by Forest Fires

If the above mentioned twigs with needles and mosses including lichen were completely burnt, the maximum heat generated by a forest fire will be the sum of the above two values.
(Maximum heat generated by forest fire per unit area, kJ/m^2) =32,180 kJ/m^2 + 40,225 kJ/m^2 =72.4MJ/m^2
It becomes 11.3MJ/m^3 per meter of tree, when an average height of 6.4m is considered.

Head Fire Rate of Spread

Generally, the head fire rate of spread (m/min, HFRS for short) is used to express the rate of spread of forest fires. The HFRS in surface fires is 0.6~3.4 m/min, and becomes about 6m/min in the most intense crown fire. As a result, a one meter square area will be burnt out in 17.6~100 seconds when the fire is a surface fire and the progress is linear.

Carbon Dioxide Quantity Discharged from Forest Fire

When it is assumed that cellulose is completely burnt in air, the amount of discharged carbon dioxide can be calculated as 2.16 kg/kg of fuel. With this result, the maximum CO_2 discharge in a forest fire in a boreal forest will be 9.7 kg/m^2 (26.6 tC/ha). However, combustion conditions of usual forest fires are very far from complete combustion because black and white smoke is always observed and the layer of unburned charcoal on the ground is not thin. The establishment of more accurate estimates of CO_2 discharge from forest fires seems to remain as a future problem. Here an accurate estimate appears very important when attempting to determine whether forests are CO_2 emission or absorption sources.
Finally, it may be important to compare CO_2 quantity discharge from forest fires with that from human activities. It is said that one Japanese discharged 2.65t CO_2 (0.72tC) in 1995 [8]. This means that CO_2 quantity discharged from one hectare forest fire is equivalent with that from 37 Japanese activities. Thus, two million ha, the average area burnt annually by forest fires in Canada since 1918, is equivalent with that from 7.3 million Japanese activities. These values are obtained under ideal condition. Actual values may be smaller.

CONCLUSIONS

The FROSTFIRE forest fire experiment in the taiga zone of Alaska, U.S.A., has helped clarify the conditions of boreal forest fires by conducting field research of the vegetation, thunderstorm

observations before the fire, observation of large forest fire areas, etc. This year, 2000, Russian taiga field research is scheduled to observe forest fires occurring in the Russian taiga.

The research reported here has been conducted as a science research activity of Japan. The project title is "Permafrost disturbance and induced emissions of greenhouse gases - tasks for predictive and controlling technique establishment - " supported by the Agency of Science and Technology, JAPAN. The project leader is Professor M. Fukuda, Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan.

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