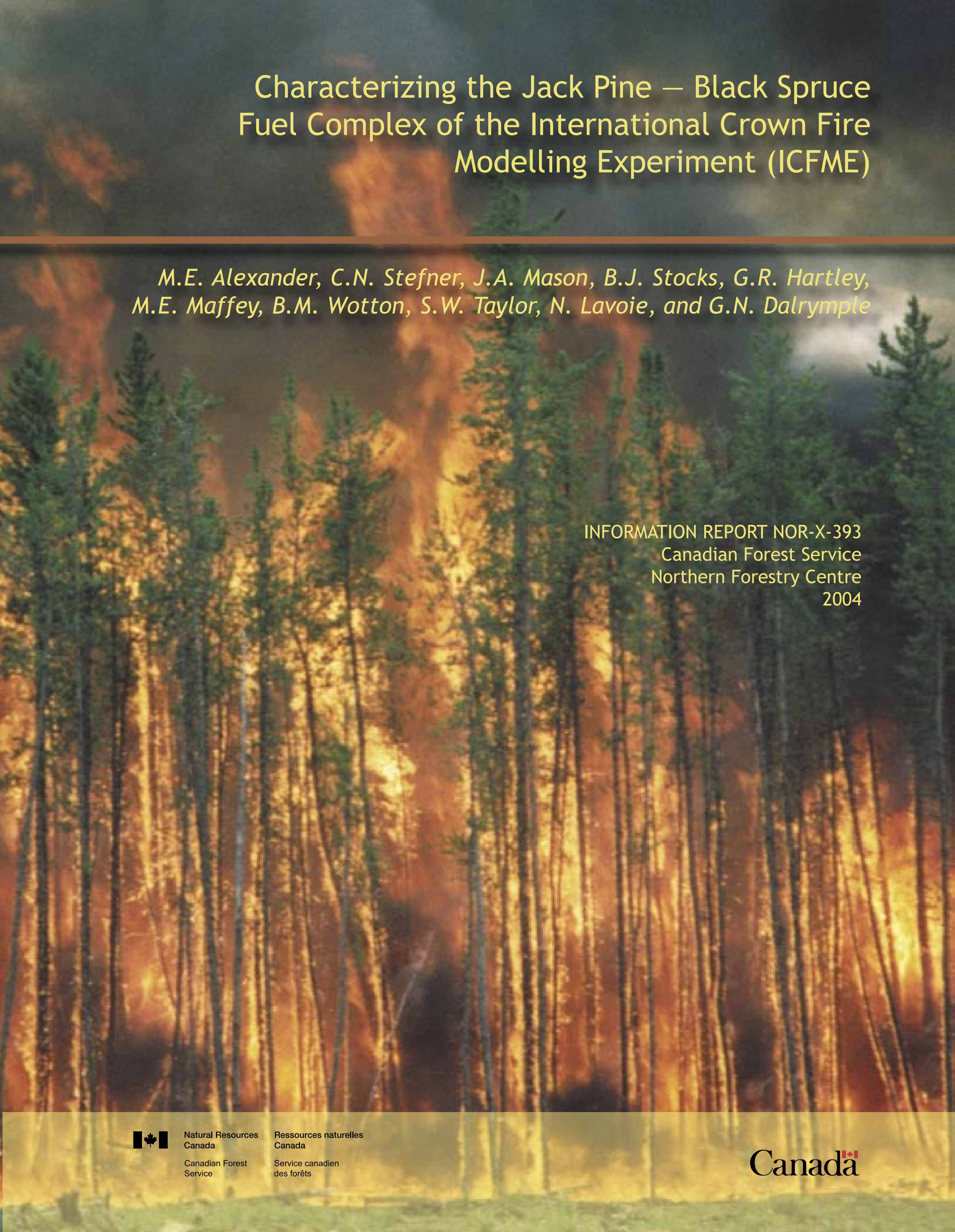
Characterizing the Jack Pine — Black Spruce Fuel Complex of the International Crown Fire Modelling Experiment (ICFME)

M.E. Alexander, C.N. Stefner, J.A. Mason, B.J. Stocks, G.R. Hartley, M.E. Maffey, B.M. Wotton, S.W. Taylor, N. Lavoie, and G.N. Dalrymple



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CHARACTERIZING THE JACK PINE – BLACK SPRUCE FUEL COMPLEX OF THE INTERNATIONAL CROWN FIRE MODELLING EXPERIMENT (ICFME)

M.E. Alexander, C.N. Stefner, J.A. Mason,[1] B.J. Stocks,[1] G.R. Hartley,[1]
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ABSTRACT

This report describes in detail the various sampling methods and techniques used in quantifying the ground, surface, ladder, and crown or canopy fuel characteristics of the jack pine (*Pinus banksiana* Lamb.) – black spruce (*Picea mariana* (Mill.) BSP) forest in the primary plots of the International Crown Fire Modelling Experiment (ICFME), located about 50 km northeast of Fort Providence, Northwest Territories. The approach involved both general sampling in the study area as a whole and the use of a systematic grid structure for the experimental plots that were to be burned. New data and information on the fuel properties of northern forests were acquired as part of this process (e.g., organic layer bulk density and allometric equations for estimating the dry weight of jack pine and black spruce crowns from stem diameter). Detailed descriptions and summaries of the characteristics of the forest floor, dead-down woody surface fuels by roundwood diameter size class, understory canopy ladder fuel, and overstory crown fuel for each of the primary plots within the ICFME are presented in tabular and graphic form. Representative values for the fuel complex represented by ICFME forest cover type are also given. Vertical fuel profiles were developed, which allowed for the visualization of the distribution and nature of the fine fuels according to height above the ground. The ICFME forest fuel complex exhibited a number of unique characteristics that distinguish it from other stand types dominated by jack pine that have been the subject of empirical, outdoor experimental fire behavior studies.

RÉSUMÉ

Ce rapport décrit en détail les diverses méthodes et techniques d'échantillonnage utilisées pour quantifier les caractéristiques des combustibles de profondeur, de surface, étagés, des cimes ou du couvert dans la forêt de pins gris (Pinus banksiana Lamb.) et d'épinettes noires (Picea mariana (Mill.) BSP) associée aux placettes principales de l'Expérience internationale de modélisation des feux de cimes (EIMFC), situées à une cinquantaine de kilomètres au nord-est de Fort Providence (Territoires du Nord-Ouest). La démarche comportait un échantillonnage général dans l'ensemble de la zone d'étude et l'utilisation d'une grille systématique pour les placettes à brûler. Elle a notamment permis d'obtenir de nouvelles données sur les propriétés des combustibles dans les forêts du nord (p. ex. densité apparente de la couche organique et équations allométriques pour estimer le poids sec des cimes de pins gris et d'épinettes noires à partir du diamètre de leur tige). Des descriptions détaillées et des résumés des caractéristiques de la couverture morte, du combustible de surface formé par les débris ligneux grossiers (par classe de diamètre des bois ronds), du combustible étagé du sous-étage et du combustible des cimes de l'étage dominant de chacune des placettes principales de l'EIMFC sont présentés sous forme de tableaux et de graphiques. Les valeurs représentatives du complexe combustible correspondant au type de couvert de l'EIMFC sont également présentées. On a également élaboré les

profils verticaux du combustible qui permettent de visualiser la répartition et la nature du combustible léger en fonction de la hauteur par rapport au sol. Le complexe combustible de l'EIMDC présentait certaines caractéristiques uniques qui le distinguent d'autres types de peuplements dominés par le pin gris où le comportement du feu a été étudié de manière empirique par le biais d'incendies expérimentaux allumés sur le terrain.

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INTRODUCTION

The ignition, buildup, and behavior of fire depends on fuels more than any other single factor. It is the fuel that burns, that generates the energy with which the fire fighter must cope, and that largely determines the rate and level of intensity of that energy. Other factors that are important to fire behavior (that is, moisture, wind, etc.) must always be considered in relation to fuels. In short, no fuel, no fire!

—Brown and Davis (1973)

The initial impetus and the primary objective of the International Crown Fire Modelling Experiment (ICFME) centered on the testing and calibration of a newly developed, physically based model for predicting the rate of advance and the flame front intensity of crown fires in conifer forests (Alexander et al. 2001). Two of the main input requirements of this new crown fire behavior model (Albini 1996) are the load and bulk density by size and location of all materials or particles constituting the conifer forest fuel complex. Preburn and postburn fuel loads are also needed to estimate fuel consumption and thus calculate the intensities of the ICFME experimental fires according to Byram's (1959) formula:

$$I = Hwr \tag{1}$$

where I = fire intensity (kilowatts per meter), H = low heat of combustion of the fuel (kilojoules per kilogram), w = quantity of fuel consumed in the active flame front (kilograms per square meter), and r = linear rate of fire spread (meters per second).

The jack pine (*Pinus banksiana* Lamb.) – black spruce (*Picea mariana* (Mill.) BSP) forest type (Fig. 1) selected for the ICFME testing and calibration of this model contained nearly all of the fuels commonly associated with a natural forest stand (Brown and Davis 1973):

- duff (i.e., fermentation and humus layers), including buried punky wood;
- loose surface litter consisting primarily of needle cast and bark flakes;
- various species of ground-dwelling mosses and lichens;
- limited quantities of various species of other ground vegetation (i.e., shrubs, herbs, grasses, and sedges);
- dead-down woody surface fuels of various sizes (i.e., twigs, branches, limbs, and logs);
- conifer tree understory, consisting primarily of black spruce seedlings and small saplings;
- an overstory tree canopy consisting primarily of jack pine and black spruce stems (live and dead) and comprising bark flakes, needle foliage, and both live and dead twigs and branches; and
- fire-killed snags associated with the parent stand.

Because of this diversity, a variety of methods and techniques were used in determining the ground, surface, ladder, and crown fuel characteristics at the ICFME site. The approach involved both general sampling in the study area as a whole (e.g., forest floor and tree crown samples) and the use of a systematic grid structure for the experimental plots that would later be burned (e.g., stand structure and dead-down woody fuels). In designing the sampling scheme, careful consideration was given to minimizing the amount of trampling the ground and surface fuel bed by excessive foot travel within the plots (Alexander and Quintilio 1990).

The bulk of the preburn fuel sampling was carried out in 1995 and 1996. In terms of the understory and overstory tree canopies, it was assumed that the time lapsed between the initial measurements and the burning of a given plot was inconsequential given the slow growing conditions in this far northern forest. Dead-down woody surface fuels on each experimental plot were sampled within a day or two before burning.

This report has two main objectives. First, it provides a detailed overview of the preburn fuel-sampling methodology used to determine the fuel complex characteristics of the primary plots burned during the course of the ICFME. In this sense it serves as a companion document to Stocks et al. (2004), which reported on the fire behavior characteristics and associated burning conditions of those experimental fires. Second, it provides a comprehensive summary of the loads, bulk densities, and heights or depths of the various fuel components in support of the Albini (1996) model validation and for several other publications on the characteristics of the ICFME fires that have already been published (e.g., Cofer et al. 1998; Clark et al. 1999; Cohen 2000; Amiro 2001; Conny and Slater 2002; Ryan 2002; Amiro et al. 2003) or are yet to be published.

METHODS

Description of Study Area

The ICFME study area is located approximately 50 km northeast of Fort Providence, Northwest Territories (Fig. 2), just west of the 70.5-km signpost on Highway 3, which runs north from the Mackenzie River crossing near Fort Providence to Yellowknife. The latitude and longitude of the site are 61.6°N and 117.2°W, respectively. The immediate study area is roughly 90 ha in size and lies within the Upper Mackenzie Forest Section (B.23a) of the Boreal Forest Region (Rowe 1972) and the Hay River Lowland Ecoregion of the Taiga Plain Ecozone (Ecological Stratification Working Group 1995). The terrain is flat (Fig. 3), and the elevation is approximately 160 m above mean sea level. Soils in the study area are classified as stony gravelly loam to stony gravelly sandy clay loam (Day 1968).

The region has a dry, subhumid continental climate typified by short cool summers, long cold winters, and slightly more precipitation during the summer than the winter (Atmospheric Environment Service 1982, 1984, 1986; Phillips 1990). The annual precipitation is variable and low (approximately 300 mm), with about half of this falling as snow. Day length is reduced to 4 or 5 h during midwinter (December–January), when mean daily temperatures vary from –25°C to –30°C. In contrast, summer days are 19–21 h long (List 1951, pages 510–512; Wahl et al. 1987, page 29), which results in high levels of solar radiation and mean daily temperatures of 18°C to 21°C for the short growing season. The fire season generally lasts from early May, when the snow normally melts (Potter 1965), until the end of August or early September, when cooler weather and fewer daylight hours prevail, which reduces the fire danger. Continuous snow cover usually begins by the first week of October.

Plot Establishment

Plot sizes and their orientation at the ICFME study area were determined largely by the manner in which the site was fragmented by roads and seismic lines (Fig. 4). An attempt was made to lay out as many plots of the same size as possible. Ten square experimental burning plots (plots 1–9 and A) were established in early summer 1995 (Figs. 3 and 5). These are referred to as the primary plots of the ICFME project. Eight of the 10 original plots (plots 1–8) were 150 x 150 m in size (i.e., 2.25 ha) whereas plot A measured 75 x 75 m (i.e., 0.5625 ha) and plot 9 100 x 100 m (i.e., 1.0 ha). The primary ICFME plots were established for the sole purpose of testing and calibrating the Albini (1996) crown fire behavior model.

Inventory of Ground Vegetation

A total of 15 randomly located 1 x 1 m sampling quadrats (Fig. 6), further subdivided into quarters (i.e., sections or subquadrats measuring 0.25 x 0.25 m) were used to characterize the species composition, frequency, cover, and prominence of the small tree seedlings, shrubs, herbs, grasses, sedges, mosses, and lichens in each of the 150 x 150 m experimental plots (plots 1–8) before burning. Plots A and 9 had fewer quadrats (*n* = 6 and 10, respectively) because of their smaller size. The preburn vegetation inventory of all 10 plots was undertaken in August 1996; this “one-time” sampling was presumed to be sufficient to characterize the ground vegetation in the ICFME forest.

The frequency (*F*) and mean cover (*C*) of each species (both expressed as a percentage) were computed for each plot and for the study area as a whole. A prominence value (PV) was calculated for each species according to Beals’s (1960) formula:

$$PV = C\sqrt{F} \qquad (2)$$

Thus, the maximum PV is 1000.

Inventory of Overstory and Understory Tree Canopies

Understory and overstory trees were inventoried to determine both stand structure and fuel characteristics. A systematic sampling grid was employed (Fig. 7). In the 150 x 150 m plots (plots 1–8), all grid points were located 15 m in from the plot edge. The five rows of nine sample points (*n* = 45) had spacing of 15 m between sample points and 30 m between rows. A similar pattern was followed for plots 9 and A, except the grid points were located 5.0 or 7.5 m, respectively, in from the plot boundary (*n* = 28 and 15 sample points, respectively). All grid points were marked with metal pins placed in the ground to allow relocation after burning.

Tree stems exhibiting a diameter at breast height outside bark (DBHOB) equal to or greater than

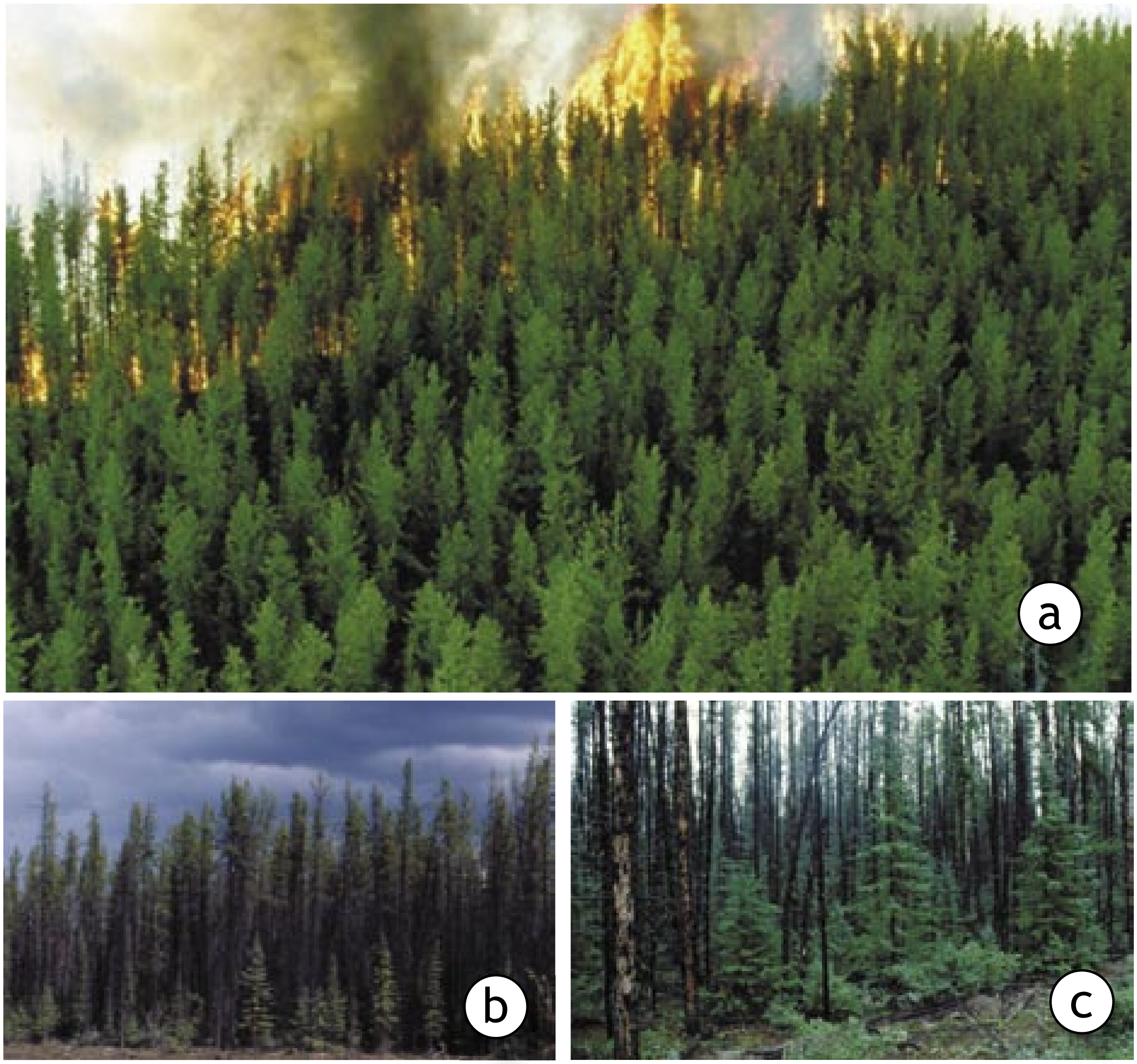

Figure 1. Aerial oblique (a), stand profile (b), and in-stand (c) views of the jack pine – black spruce fuel complex at the International Crown Fire Modelling Experiment study area.

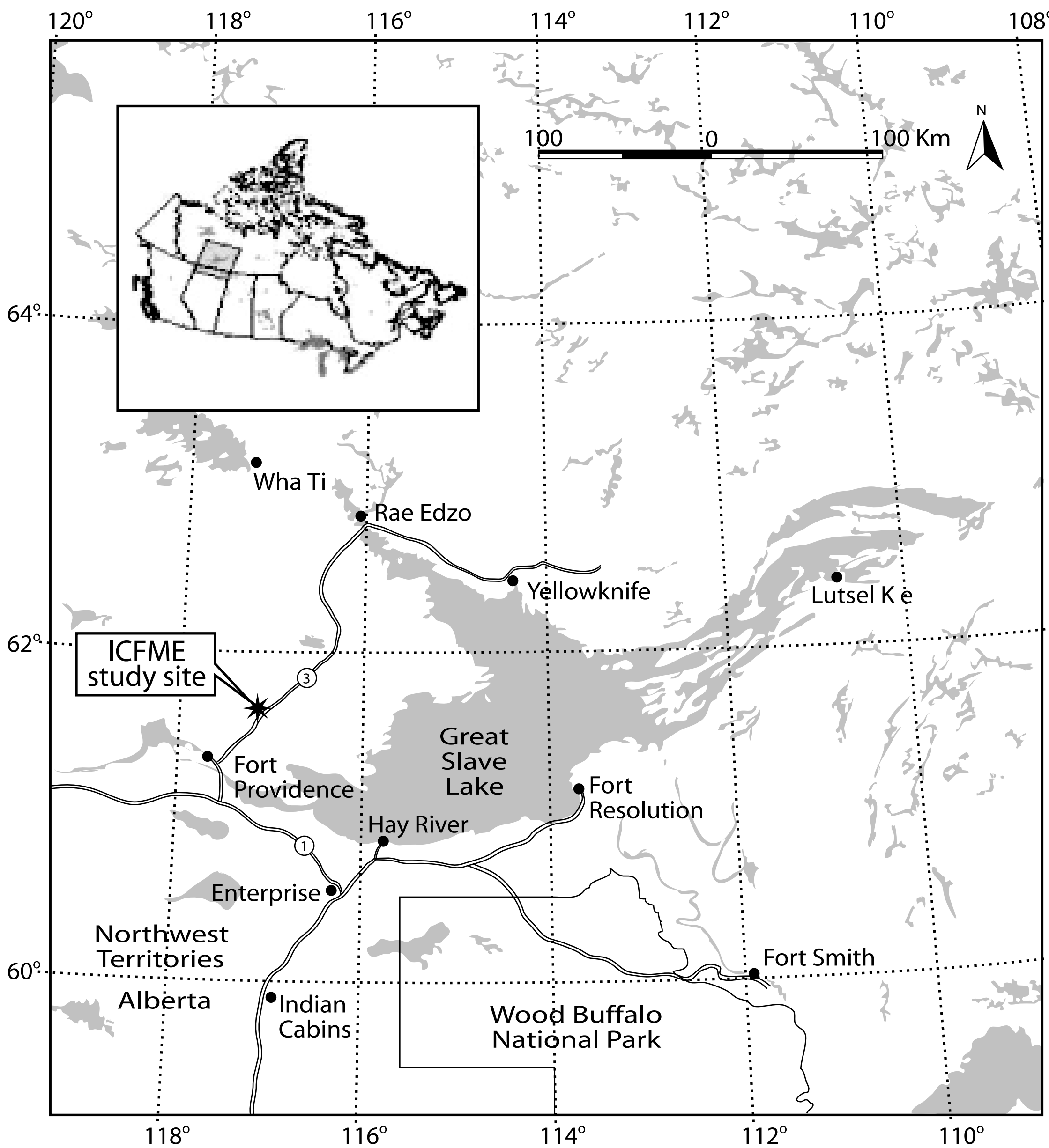

Figure 2. Geographic location of the International Crown Fire Modelling Experiment (ICFME) study area.

Figure 3. Aerial oblique view of the International Crown Fire Modelling Experiment study area.

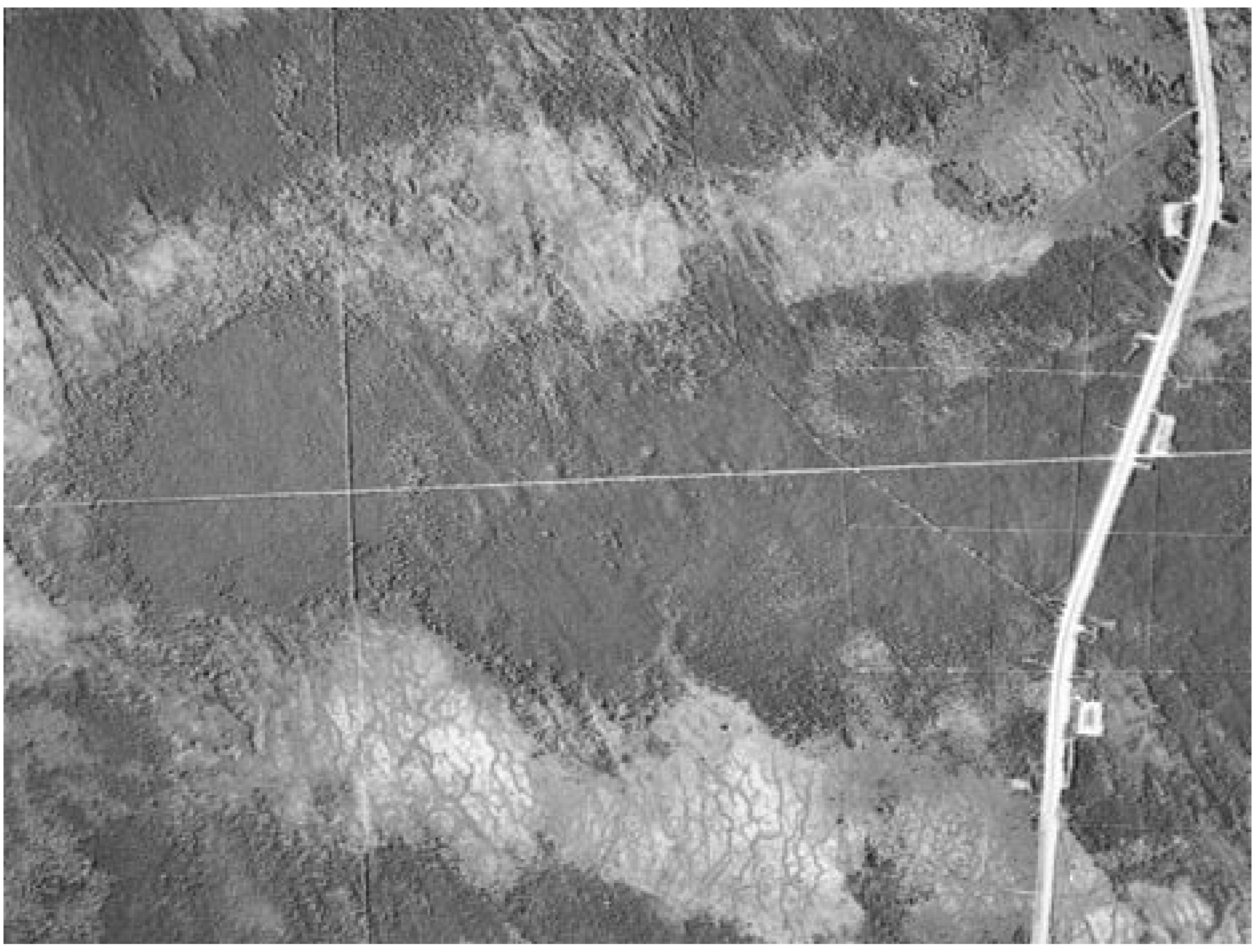

Figure 4. Aerial vertical view of the International Crown Fire Modelling Experiment study area before construction of fireguards around the plot boundaries. Photo courtesy of Government of Northwest Territories, Department of Resources, Wildlife and Economic Development.

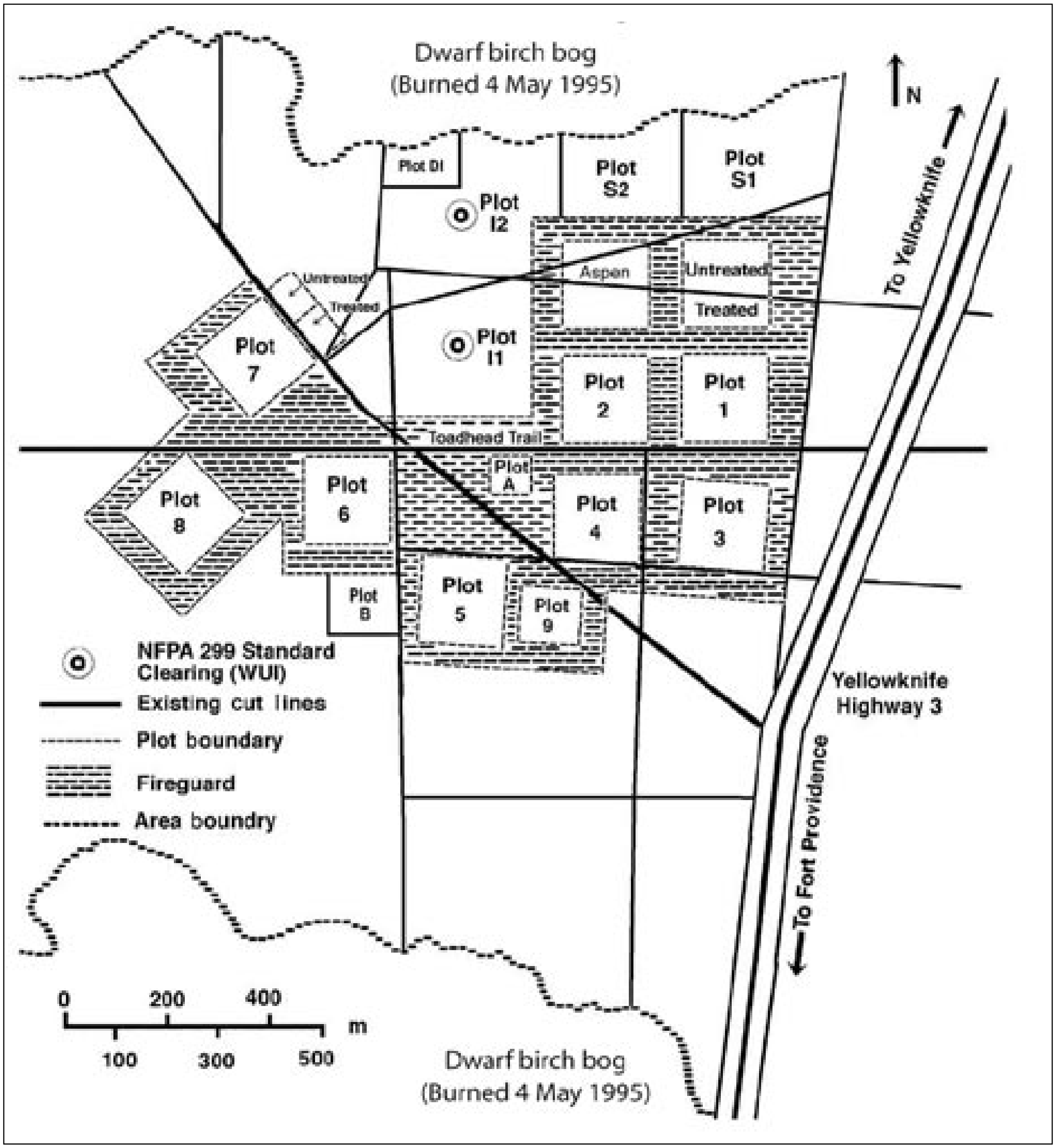

Figure 5. Plot layout for the International Crown Fire Modelling Experiment.
NFPA = National Fire Protection Association, WUI = wildland-urban interface.

Figure 6. The ground vegetation in each of the primary plots of the International Crown Fire Modelling Experiment was characterized on the basis of 1 x 1 m sampling quadrats.

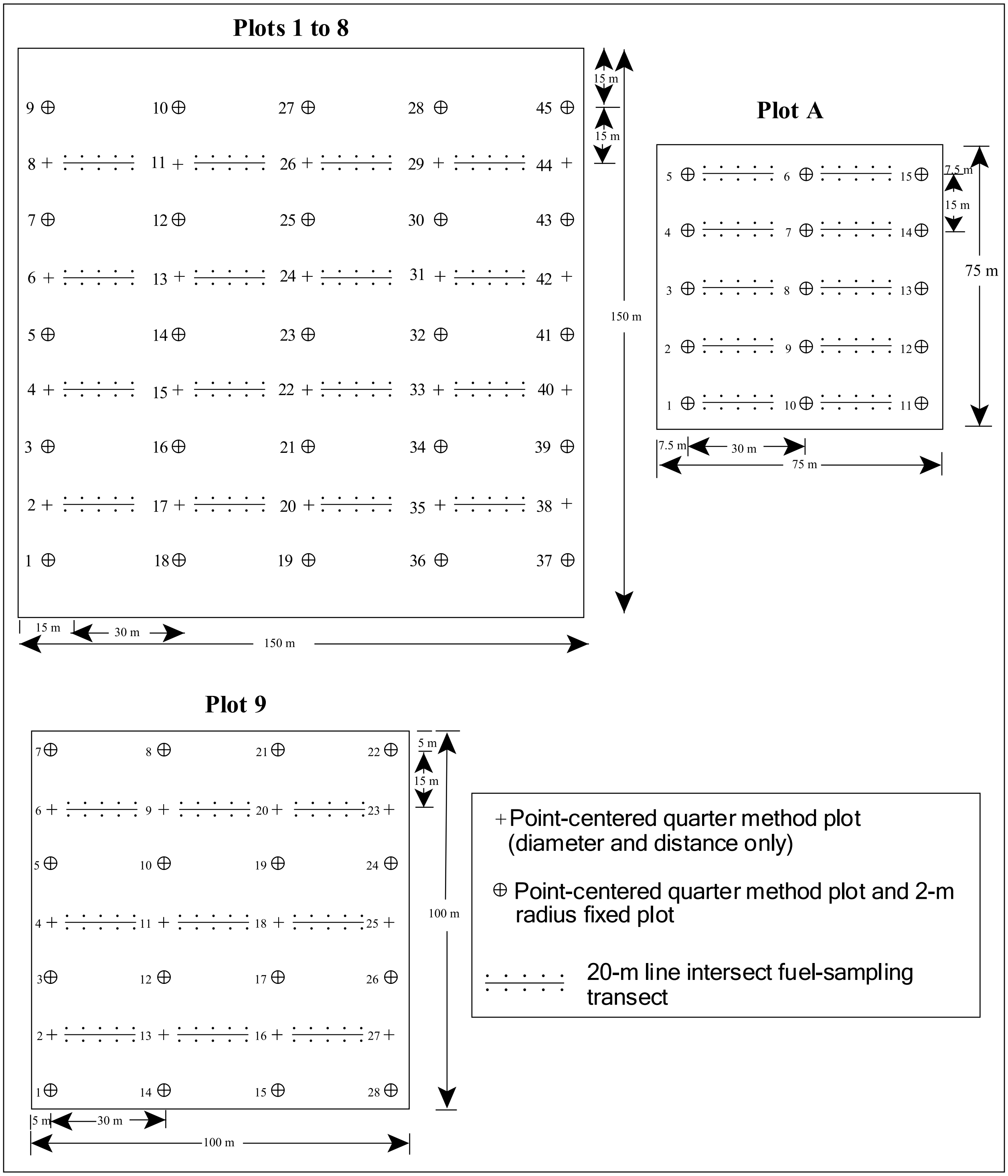

Figure 7. Internal sampling grids for the primary plots of the International Crown Fire Modelling Experiment. Depth-of-burn and postburn duff depth measurements were taken at each indicated point along the 20-m line intersect fuel-sampling transects.

3.0 cm were regarded as part of the overstory canopy. The overstory trees on each of the experimental plots were inventoried at the grid points (Fig. 7) using the point-centered quarter method as originally developed by Cottam and Curtis (1956); see Mueller-Dombois and Ellenburg (1974, pages 111–114) for calculation procedures. This method consisted of measuring the distance from the grid point to the nearest stem in each of the four quarters (Fig. 8). In addition, the species and condition (live or dead) of each of the four sampled stems were noted and the DBHOB, total height, and live crown base height (LCBH) were measured. The latter two measurements were determined with a Haga altimeter or clinometer and a measurement tape; heights were computed by means of simple geometry (see, for example, Avery 1967, page 78).

Understory tree stems less than 3.0 cm DBHOB were sampled using a 2-m radius fixed plot (Avery 1967) at every other grid point ($n = 25$ for the 150 x 150 m plots) (Fig. 7). For each sampled stem, the species and condition (live or dead) were noted and the LCBH (if applicable), height, and DBHOB (if applicable) were measured. The diameter at ground level outside bark (DGLOB) was measured on all stems less than 1.3 m in height.

In mid-June 2000, permanent sample plots were established in plot 3 (preburn) and plot 7 (postburn; burned July 1998) by L. Smith (inventory forester, Forest Development Services, Forest Management Division, Department of Resources, Wildlife and Economic Development, Hay River, Northwest Territories, personal communication, e-mail, 2000) using the standards in the National Forest Inventory (NFI) report "A plot-based national forest inventory design for Canada—an interagency partnership project" (NFI design version 2.0, 31 March 1999), available from the NFI web site <http://www.pfc.cfs.nrcan.gc.ca/monitoring/inventory/canfi/docs/design2_e.pdf>.

Sampling of the Organic Layer

The bulk density of the forest floor layer (i.e., litter and duff) was characterized with a 30 x 30 cm sampling frame (cf. Brown 1966; Loomis 1977; Sackett 1979; Barney et al. 1981). Core and auger sampling methods (e.g., Woodard and Martin 1980; Nalder and Wein 1998; Miyhanishi and Johnson 2002) were tried but were unsuitable because of the stoniness of the site.

The full depth of the organic layer was measured to the nearest 0.1 cm at the midpoint on all four sides of the sampling frame (Fig. 9), and the layer was then sectioned into 2-cm depth class intervals as per Stocks (1987a, 1987b, 1989) with a sharp, thin-blade knife. The 2-cm criterion for forest floor sampling is now regarded as standard within the Canadian Forest Service (CFS) fire research group (cf. Lawson and Dalrymple 1996). The forest floor layer was sampled this way rather than according to classical soil science horizons (i.e., L, F, and H layers) so that the resulting data could be used in conjunction with the depth of burn to determine forest floor fuel consumption (McRae et al. 1979).

The individual 2-cm layers were bagged separately in the field and taken to the laboratory, where they were oven dried for 24 h. A total of one hundred 30 x 30 cm organic layer samples were collected from three different areas near the primary plots before the construction of fireguards. All of the samples were "ashed" to determine the percentage of inorganics (i.e., small rocks and mineral soil) following the procedures for direct estimation of organic matter by loss on ignition outlined by Kalra and Maynard (1991, pages 25–27). The oven-dry weights of the samples were then adjusted for the proportion of inorganic matter to define the amount of organic matter or fuel available for combustion.

Measurements of the depth of burn and depth of organic matter remaining after each ICFME experimental fire (Stocks et al. 2004) were used to determine the preburn forest floor depth (McRae et al. 1979). In most of the plots, this involved more than 100 sample points and was judged sufficient to produce errors of 10% to 15% or less (Brown 1974a). This procedure avoided the need to further trample and disturb fuels within the plot before burning (Alexander and Quintilio 1990). Given the preburn depth and the data on fuel weight per unit area for each 2-cm layer, it was possible to estimate the preburn forest floor load.

Inventory of Dead-down Woody Surface Fuel

The line intersect method (LIM) was employed to sample the weight per unit area of twigs, limbs, branches, smaller stems, and large logs lying on the ground surface (Van Wagner 1968, 1982; Brown 1974a; McRae et al. 1979). For the larger 150 x 150 m plots (plots 1–8), 16 LIM transects were established as part of the grid sampling structure, whereas 10 and 9 transects were established on plots A and 9, respectively (Fig. 7). It might appear from Figure 7 that there was an error in experimental design in the application of the LIM, namely orientation bias, which would violate one of the basic tenants of the statistical assumptions behind the sampling technique; specifically, the transects are

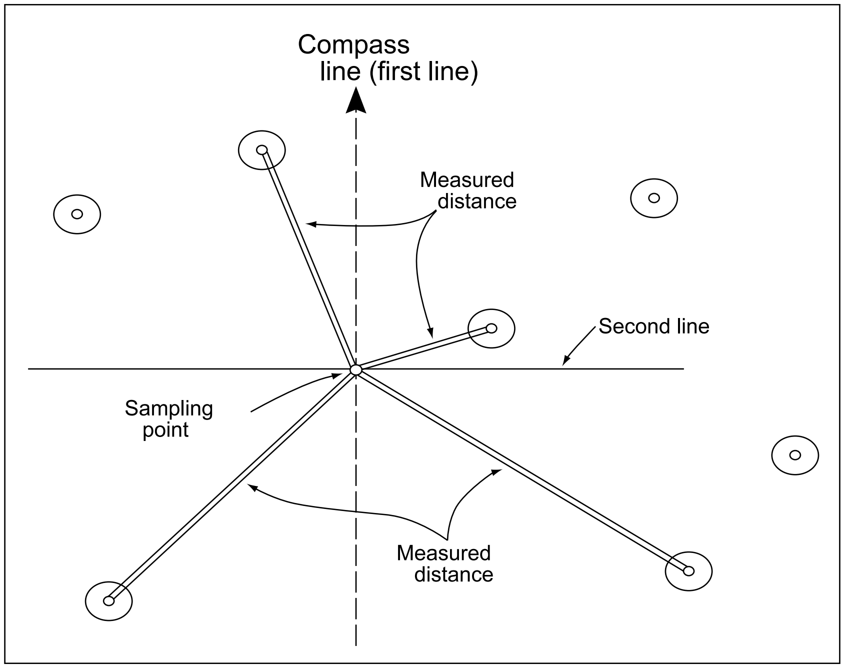

Figure 8. The point-centered quarter method was employed to sample the overstory canopy in the primary plots of the International Crown Fire Modelling Experiment. Reprinted, with permission, from Mueller-Dombois and Ellenberg (1974).

Figure 9. The fire-fuel properties of the forest floor layer in the International Crown Fire Modelling Experiment study area were determined from 30 x 30 cm samples taken down to the mineral soil.

oriented in a single direction (Fig. 7). Strictly speaking, they should be randomly oriented to ensure that if the dead-down woody surface fuels had a consistent orientation, this would be accurately captured in the orientation of the lines. This is certainly an important issue in some logging slash situations and in certain natural situations (e.g., blowdown from a windstorm). However, in natural forest stands piece orientation can generally be considered random. In applying the LIM, Van Wagner (1982, page 4) noted that "For field application the most convenient unbiased layout is a mechanical grid imposed on the map. Starting points can then be located on the ground by pacing from identifiable landmarks. Orientation of lines … can be set beforehand … ." This was in fact the approach taken in applying the LIM to the inventory of dead woody surface fuels on the primary ICFME plots.

In all cases, the LIM transects were established, wherever possible, at least one tree length in from the plot edge and in an east–west (plots A, 1–6, and 9) or southeast–northwest (plots 7 and 8) direction. Transects were located 5.0 m from the understory–overstory inventory grid pins. Each transect measured 20 m in length, and a metal pin was placed in the ground every 5.0 m to allow relocation of the transects after burning, for the purposes of determining fuel consumption (McRae et al. 1979).

All dead-down woody fuels less than 7.0 cm in diameter were tallied with the aid of a "go-no-go" gauge (Brown 1974a; McRae et al. 1979) along the entire 20-m length of each LIM transect. The following roundwood diameter size classes were used, in accordance with the broad framework established by the CFS fire research group (McRae et al. 1979; Van Wagner 1982): <0.5, 0.5–1.0, 1.0–3.0, 3.0–5.0, and 5.0–7.0 cm. (It is acknowledged that these class limits should, strictly speaking, be mutually exclusive, i.e., they should be expressed as <0.50, 0.50–0.99, 1.00–2.99, 3.00–4.99, and 5.00–6.99 cm [McRae et al. 1979]. The present approach is taken in the interest in simplicity.)

For downed logs equal to or greater than 7.0 cm in diameter, the intersect diameter of all the pieces falling along the 20-m LIM transects was measured to the nearest 0.1 cm with a caliper and characterized according to the degree of decay as either sound or rotten (which included a punky condition) (Brown 1974a; McRae et al. 1979). Sound pieces were also identified (where possible) as to the tree species of origin.

The sampling intensities established for inventorying dead-down woody surface fuels on the ICFME plots were judged sufficient to produce errors of 10% to 15% or less (Brown 1974a). However, it was readily acknowledged that there could be far more variation in the large dead-down woody debris (Brown 1974a; Brown et al. 1982; Delisle et al. 1988).

For roundwood pieces less than 7.0 cm in diameter, the following equation was used to calculate fuel loads for each diameter size class, given that there was no slope involved:

$$W = \frac{\pi^2 \, G \sec(h) \, n \, \mathrm{QMD}^2}{8L} \qquad (3)$$

where W = fuel load (tonnes per hectare), G = specific gravity (grams per cubic centimeter), h = piece tilt angle (degrees), n = the number of intercepts over the length of the transect, QMD is the quadratic mean diameter (centimeters), and L = length of transect (meters), which in this case was 20 m. The values for G, h, and QMD given in Nalder et al. (1999) were used; these are based in part on sampling carried out in the general ICFME area (Nalder et al. 1997).

For roundwood pieces equal to or greater than 7.0 cm in diameter, the following equation was used to calculate fuel loads, given that there was no slope involved:

$$W = \frac{\Sigma d^2 \; G}{8L} \qquad (4)$$

where Σd^2 = sum of the squared diameters for intercept roundwood pieces equal to or greater than 7.0 cm in diameter (centimeters squared). In this case, h was assumed to be zero and the G values used were those determined by Delisle and Woodard (1988) for sound and rotten material.

Sampling of Tree Crown Biomass

The only study of tree crown biomass for jack pine and black spruce in the Northwest Territories is that of Singh (1984). However, his predictive equations for fine fuels were for some reason poorly correlated with DBHOB. Furthermore, as shown by Green and Grigal (1978) for jack pine and Grigal and Kernik (1984) for black spruce, regional differences do exist. As Bond-Lamberty et al. (2002) noted, generalized equations (such as those of Green and Grigal 1978 and Grigal and Kernik 1984) appear to work well for total aboveground biomass, but needles and roundwood material tend to be much more site-specific. In addition, there was also the matter of adherence to the metric roundwood diameter size classes established by the CFS fire research group (McRae et al. 1979; Van Wagner 1982) and the desire to depict the vertical fuel distribution of the ICFME forest and individual plots in terms of crowning potential (e.g., LaMois 1958; Sando and Wick 1972). As a result of all these factors, it was considered necessary to undertake a tree crown biomass study in the ICFME study area, following in part the procedures established by Walker and Stocks (1975), Stocks (1980), and other tree crown biomass investigators.

A selection of jack pine and black spruce trees encompassing the range in DBHOB in the general study area were selected for destructive sampling. The DBHOB (if applicable), DGLOB, total height, and LCBH of each sampled stem were recorded. In addition, a cross-sectional disk was taken at ground level for stand-aging purposes. Once the disk was air-dry, it was sanded, and a bionocular microscope was used to determine tree age.

Each sampled stem was felled and cut into 1-m sections (Fig. 10), and the various crown materials in each section were separated by condition (live or dead) and roundwood diameter size class (i.e., <0.5, 0.5–1.0, or 1.0–3.0 cm), bagged up in the field, and transported to the laboratory, where they were allowed to air dry for several weeks; the needles were then separated from the live roundwood. Needles and roundwood materials were then oven dried in the laboratory for 24 h, and a final oven-dry weight determination was made. No subsampling estimation of any kind (e.g., Brown 1965) was undertaken in this tree crown biomass study.

The oven-dry weights of the various crown fuel components were then regressed against DBHOB or DGLOB. The resulting allometric equations were of the following general form:

$$Y = \mathrm{a}X^{\mathrm{b}} \tag{5}$$

where Y = oven-dry weight of the fuel component (kilograms) and X = DBHOB (centimeters) or DGLOB (centimeters), depending on the stem height. Coupling the tree crown biomass regression equations with the stand inventory data made it possible to estimate the understory and overstory crown fuel loads and bulk densities (Cruz et al. 2003a).

Construction of Vertical Fuel Profiles

Vertical fuel profiles were constructed to quantify and graphically depict the vertical distribution of the fine fuels within the understory and overstory canopies in each of the primary ICFME plots. The destructive sampling of jack pine and black spruce stems in the tree crown biomass study allowed separate treatment, for each species, of the following five crown fuel components: needles, live branches (<0.5 and 0.5–1.0 cm in diameter), and dead branches (<0.5 and 0.5–1.0 cm in diameter).

The first step in constructing the vertical fuel profiles was to calculate the total dry weight per tree for each crown fuel component. This was accomplished by means of the allometric equations derived from the tree crown biomass sampling, with the total dry weight per tree as a function of DBHOB or DGLOB being used for black spruce trees less than 1.3 m in height. To simplify the calculations, the tree diameters were divided into 2-cm DBHOB classes, and the central or midpoint value of each class was used in the calculation.

The next step in constructing the profiles was to distribute the total dry weight vertically for each crown fuel component. Most of the work published on the vertical distribution of biomass in a forest stand can be classified into three general approaches, which are sometimes combined. The first approach uses an averaging procedure whereby, for each DBHOB class, the average dry weight of a component is obtained from the sample trees for each vertical section (e.g., Schreuder and Swank 1974). The second approach involves regressions of, for example, the dry weight or a fraction of the total dry weight by crown segment, whorl, or branch as a function of variables such as height or fraction of total crown height (e.g., Kinerson et al. 1974; Ek 1979; Snell and Max 1985; Hashimoto 1990, 1991; Gillespie et al. 1994; Gilmore and Seymour 1997). In the third approach, the dry weight of a fuel component is distributed vertically into a tree or a stand according to an assumed or calculated distribution model (e.g., Stephens 1969; Kinerson and Fritschen 1971; Sando and Wick 1972; Gary 1978; Beadle et al. 1982; Hagihara and Hozumi 1986; Maguire and Bennett 1996; Baldwin et al. 1997; Xu and Harrington 1998).

The second approach was selected since it suited this study's sampling methodology and the general stand characteristics of the ICFME plots. Moreover, it allowed for the extrapolations necessary for the few stems in the plots that had a DBHOB larger than that of the destructively sampled trees. It also required fewer trees in each diameter size class than the first approach. Its main advantage over the third approach was to simplify the analysis for the relatively complex structure of the ICFME forest (i.e., two distinct layers, the jack pine – black spruce overstory and the black spruce understory).

Figure 10. Tree crown biomass sampling in the International Crown Fire Modelling Experiment study area involved the dissection of individual live and dead fuel components along the entire stem in 1-m intervals.

To distribute vertically the total dry weight per tree of the individual fuel components, the ratio of the cumulative dry weight (from the crown apex) of each fuel component to its total dry weight for the sampled tree (R_W) was obtained for each 1-m section of each sampled tree. The ratio of the corresponding length along the tree to the total tree height (R_H) was also obtained. Those two variables, with values between 0 and 1, were fitted to the following curve for each tree species and condition and each crown fuel component:

$$R_W = \frac{a}{1 + exp\ [b - c\ (R_H)]} \qquad (6)$$

This analysis allowed derivation of the three coefficients *a*, *b*, and *c*.

By means of Equation 6, the variable R_W of each crown fuel component was then calculated for each 1-m height section of the diameter classes. This cumulative value was transformed into the fraction of the total dry weight per section and multiplied by the total dry weight of the corresponding crown fuel component for the tree to obtain the sectional dry weight. Finally, using the tree inventory data for each plot, the stem density (number per hectare) per 2-cm diameter size class of the live and dead jack pine and black spruce trees was calculated and multiplied by the corresponding dry weight per tree of each crown fuel component in each section. The results, summed over the diameter classes and converted into kilograms per square meter, provided the vertical distribution of the fuel load per plot, for each crown fuel component. Calculations were performed for each plot on a composite basis and for individual fuel components for the entire site on the basis of sampling carried out on the 10 primary ICFME plots.

RESULTS AND DISCUSSION

In this presentation of the results of preburn fuel sampling of the primary plots at the ICFME study area, frequent mention is made of the fuel characteristics determined in two previous benchmark fire behavior studies in mature (Stocks 1989) and immature (Stocks 1987a) jack pine stands in Ontario both of which are summarized in Stocks and Hartley (1995). Both studies involved twelve 0.4-ha experimental plots. Results from those studies can be compared with characteristics of the ICFME fuel complex (Tables 1, 2). These two experimental fire behavior studies largely formed the basis for the C-3 (Mature Jack or Lodgepole Pine) and C-4 (Immature Jack or Lodgepole Pine) fuel types in the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992; De Groot 1993; Hirsch 1996, 1998; Taylor et al. 1997). The ICFME jack pine – black spruce fuel complex appears to exemplify certain characteristics of both these fuel types.

Characteristics of Ground Vegetation

The species composition, cover, frequency, and prominence of the understory vegetation in the 10 primary ICFME plots, based on a total of one hundred and thirty-six 1 x 1 m sampling quadrats (Appendix 1), is summarized in Table 3. Plant nomenclature follows Johnson et al. (1995). The dominant understory vegetation for the primary ICFME plots consisted of red pixie-cup (*Cladonia borealis*), feathermoss (*Pleurozium schreberi*), marsh reed grass (*Calamagrostis canadensis*), reindeer lichen (*Cladina mitis*), and kinnikinnick (*Arctostaphylos uva-ursi*), although there was some variation among plots (Appendix 1). The ICFME site was judged to most closely resemble the jack pine – bearberry lichen (a1.1) plant community type or ecosite phase in the Boreal Mixedwood and Boreal Highlands ecological areas of northern Alberta (Beckingham and Archibald 1996).

The actual fuel load contributed by shrubs and herbaceous plants in each plot was not sampled, for two reasons. First, the understory vegetation in each plot was relatively sparse (Table 3). Therefore, the information to be gained from destructive fuel weight sampling was not considered worth the impact associated with trampling of the ground and surface fuels that would have been needed to acquire this information (Alexander and Quintilio 1990). Also, on the basis of some limited sampling in an area adjacent to ICFME plot 7, it was estimated that the understory vegetation fuel load on most of the primary ICFME plots would not, on average, have exceeded 0.03 kg/m^2 (N. Lavoie, unpublished data).

Stocks (1987a, 1989) reported understory vegetation fuel loads of less than 0.09 kg/m^2 in immature and mature jack pine stands in north-central Ontario. In New Brunswick, MacLean and Wein (1977) found that understory fuel loads varied from approximately 0.1 to nearly 0.6 kg/m^2 on the basis of sampling in 12 jack pine stands ranging in age from 7 to 57 years.

Table 1. General fuel characteristics for the primary plots of the International Crown Fire Modelling Experiment (ICFME) and for jack pine dominated fuel complexes in two other major outdoor experimental fire behavior studies

Characteristic	ICFME jack pine – black spruce	Stocks (1987a) immature jack pine	Stocks (1989) mature jack pine
Forest floor layer			
Depth (cm)	5.75	4.58	6.52
Load (kg/m^2)	4.718	1.284	1.695
Bulk density[a] (kg/m^3)	81.8	27.4	25.8
Surface fuel loads (kg/m^2) by roundwood diameter size class[b]			
<1.0 cm	0.066	0.086	0.084
1.0– 3.0 cm	0.171	0.162	0.059
3.0– 7.0 cm	0.518	0.098	0.521
<7.0 cm	0.757	0.346	0.664
>7.0 cm	0.739	1.825	0.708
Canopy height (m)			
Understory	1.5	0.0	2.0[c]
Overstory	12.2	10.0	20.0
Live crown layer (m)			
LCBH (m)	6.6	4.0[c]	12.0[c]
Vertical depth (m)	4.0	6.0[c]	8.0[c]
Understory canopy fuel load (kg/m^2)			
Needles only	0.118	0.0	NA[d]
Needles + <0.5 cm[e]	0.371	0.0	NA
Needles + <1.0 cm[e]	0.431	0.0	NA
Overstory canopy fuel load (kg/m^2)			
Needles only	0.610	NA	0.666
Needles + <0.5 cm[e]	1.219	NA	NA
Needles + <1.0 cm[e]	1.529	NA	0.970[f]
Total standing profile fuel load (kg/m^2)			
Needles only	0.729	0.789	1.156
Needles + <0.5 cm[e]	1.589	NA	NA
Needles + <1.0 cm[e]	1.960	1.384	1.459[f]
Understory canopy bulk density (kg/m^3)			
Needles only	0.05	0.0	NA[d]
Needles + <0.5 cm[e]	0.11	0.0	NA
Needles + <1.0 cm[e]	0.17	0.0	NA
Overstory canopy bulk density (kg/m^3)			
Needles only	0.09	0.13	0.08
Needles + <0.5 cm[e]	0.16	NA	NA
Needles + <1.0 cm[e]	0.20	0.23	0.12[f]
Total standing profile bulk density (kg/m^3)			
Needles only	0.07	0.08	0.06
Needles + <0.5 cm[e]	0.12	NA	NA
Needles + <1.0 cm[e]	0.17	0.14	0.07[f]

[a]Organic matter only.
[b]Actual size classes were <1.00, 1.00–2.99, and 3.00–6.99 cm.
[c]From Van Wagner (1993).
[d]Black spruce exists in both the understory and overstory, although the relative contributions of each from a fuel load standpoint are unknown.
[e]Roundwood diameter size class(es).
[f]Includes only dead roundwood fuels.
Note: LCBH = live crown base height, NA = not available.

Table 2. General tree and stand structure charateristics for the primary plots of the International Crown Fire Modelling Experiment (ICFME) in comparison to two other fire behavior studies in jack pine dominated fuel complexes

Tree and stand structure characteristics by species and condition	ICFME jack pine-black spruce	Stocks (1987a) immature jack pine	Stocks (1989) mature jack pine
Overstory canopy			
DBHOB (cm)			
Live jack pine	10.1 ± 2.0	5.1 ± 2.1	13.3 ± 4.0
Dead jack pine	6.2 ± 1.2	1.7 ± 0.8	NA
Live black spruce	5.0 ± 1.0	–	5.9 ± 3.5
Dead black spruce	5.4 ± 1.2	–	NA
Stem height (m)			
Live jack pine	12.2 ± 1.0	9.5 - 10.0	18 - 20
Dead jack pine	8.4 ± 0.9	4.5 - 5.5	NA
Live black spruce	5.5 ± 0.3	–	1 - 13
Dead black spruce	5.6 ± 1.3	–	NA
Basal area (m^2/ha)			
Live stems	26.3 ± 6.2	18.6	35.2
Dead stems	5.8 ± 2.0	2.2	NA
Basal area (%)			
Live jack pine	88.7 ± 11.2	89.4	88.6
Dead jack pine	90.3 ± 11.7	10.6	NA
Live black spruce	11.4 ± 11.2	0	11.4
Dead black spruce	9.7 ± 11.7	0	NA
Density (no./ha)			
Live stems	4115 ± 827	9276	2057
Dead stems	1806 ± 689	10 229	NA
Density (%)			
Live jack pine	69.8 ± 22.8	100	65.3
Dead jack pine	89.0 ± 11.0	100	NA
Live black spruce	30.2 ± 22.8	0	34.7
Dead black spruce	11.1 ± 11.01	0	NA
Spacing between (m)			
Live stems	1.6 ± 0.2	1.0	2.2
Dead stems	2.5 ± 0.6	1.0	NA
Live & dead stems	1.3 ± 0.2	0.7	NA
Understory canopy			
Stem height (m)			
Live black spruce	1.5 ± 0.3	NA	NA
Dead black spruce	2.2 ± 0.9	NA	NA
Density (no./ha)			
Live black spruce	4561 ± 2185	NA	NA
Dead black spruce	1085 ± 599	NA	NA

Note: In the above tabulation generally the mean and standard deviation are given (e.g., 10.1 ± 2.0) but in some cases only the mean value or the range in values are given (e.g., 18 - 20). NA = not available, dashes indicate no samples.

Table 3. General ground vegetation characteristics for the primary plots of the International Crown Fire Modelling Experiment[a]

Species[b]	Common name	*F* (%)	*C* (%)	PV
Trees and shrubs				
Arctostaphylos uva-ursi	Kinnikinnick	65	9.7	78.2
Arctostaphylos rubra	Bearberry	2	0.8	1.1
Picea mariana	Black spruce	1	T	0.0
Potentilla spp.	Cinquefoil	20	1.2	5.4
Rosa acicularis	Prickly rose	38	1.5	9.2
Salix spp.	Willow	18	2.2	9.3
Shepherdia canadensis	Canada buffaloberry	4	0.2	0.4
Herbaceous plants				
Anemone mutifida	Cut-leaved anemone	1	0.1	0.1
Aster sibiricus	Arctic aster	1	T	0.0
Calamagrostis canadensis	Marsh reed grass	43	3.6	23.6
Coptis trifolia	Goldenthread	T	T	0.0
Cornus canadensis	Bunchberry	14	0.5	1.9
Primula incana	Mealy primrose	9	0.2	0.6
Pyrola virens	Wintergreen	24	1.2	5.9
Stellaria media	Common chickweed	13	0.3	1.1
Mosses and lichens				
Cladina mitis	Reindeer lichen	49	8.0	56.0
Cladonia borealis	Red pixie-cup	78	7.9	69.8
Dicranum scoparium	Broom moss	52	5.7	41.1
Peltigera apthosa	Freckle pelt	23	2.4	11.5
Pleurozium schreberi	Feather moss	81	19.0	17.1

[a]A value of 0.0 indicates a value of less than 0.05.

[b]Plant nomenclature follows Johnson et al. (1995).

Note: *F* = frequency, *C* = cover, PV = prominence value (from 0 to 1000) (Beals 1960), T = trace. Table 3 is based on the data given in Appendix 1.

Characteristics of Trees and Stands

On the basis of aging of the cross sections of jack pine and black spruce taken during the tree crown biomass sampling in early 1995, the ICFME experimental burning site was determined to be 65 years old (i.e., ca. 1931 origin). Significant quantities of charred snags and dead-down logs would substantiate the stand's fire origin. However, an intensive search for a fire-scarred veteran or parent tree in the immediate area surrounding the ICFME study area failed to produce a single sample; any dead standing or downed tree stems were either too heavily charred or too rotten to be of use in determining the age of the parent stand. However, fire history sampling adjacent to the ICFME study area (De Groot and Chowns 1994) supports the claim that the ICFME forest is a ca. 1931 fire origin stand.

In the overstory, 1132 live stems and 476 dead stems were measured in 403 point-centered quarter method plots. In the understory, 1362 live stems and 169 dead stems were measured in two hundred and thirty-one 2-m radius fixed plots. The tree and stand structure characteristics for both the living and the dead components of the overstory canopy in each of the primary ICFME plots are summarized in Tables 4 and 5, respectively. Jack pine and black spruce were the only major overstory species, the former being dominant. The jack pine overstory averaged about 10 cm DBHOB and 12 m in height. Jack pine contributed approximately 90% of the live (roughly 26 m^2/ha) and dead (nearly 6 m^2/ha) stand basal area, as well as the dead tree density (mean 1806 stems/ha), but only some 70% of the live stem density (mean 4115 stems/ha). For the ICFME forest as a whole, the corresponding spacing between live stems and dead stems was on average 1.6 and 2.5 m, respectively, and less than 1.5 m for all stems combined.

As a fuel complex, the primary plots constituting the ICFME forest represented, for the most part, a much shorter (Table 1), more dense stand type than has been the case in previous experimental burning studies in more southerly areas of Canada, where the overstory jack pine trees ranged from 18 to 20 m tall with 500 to 2500 stems/ha (Quintilio et al. 1977; Weber et al. 1987; Stocks 1989). The one exception is the study of 28-year-old immature jack pine by Stocks (1987a), in which the trees had a comparable height to those in the ICFME but nearly four times the overall stem density.

Characteristics of the Forest Floor

The forest floor samples contained various amounts of inorganic materials at all depths (Table 6), consistent with previously reported findings (e.g., Brown 1966; Moir and Grier 1969; Muraro 1971). However, many investigators have either failed to remove the inorganic constituents from their forest floor samples or failed to explicitly note whether these constituents have been removed (e.g., Crosby 1961; Brown 1974b; Barney et al. 1981; Hirsch and Pengelly 2000; Hely et al. 2001). As Kiil (1974) pointed out, the humus (H) layer of the forest floor can contain substantial quantities of inorganic matter. In this study, the inorganic materials in some of the samples constituted more than half of the weight per unit area (Table 6). Muraro (1971) found that the mineral soil or inorganic content in individual samples could range up to 60%. This degree of variability would preclude any kind of constant adjustment factor.

As expected, the total forest floor weight per unit area increased with preburn depth (Table 6). After the initial 100 samples were collected there appeared little reason to collect further samples to increase the sample size in the lower levels (especially below 4.0 cm), as the average depth of burn for any of the ICFME experimental fires did not exceed 2.6 cm (Stocks et al. 2004).

The forest floor weight per unit area by 2-cm depth class in the primary ICFME plots was generally 2 to 3 times heavier than that reported by Stocks (1987a, 1989) in immature and mature jack pine stands in Ontario. The ICFME values reported in Table 6 are, however, comparable to those found in a study of stands of balsam fir (*Abies balsamea* (L.) Mill.) killed by spruce budworm (Stocks 1987b), the only other study to date in a natural forest stand that employed the 2-cm depth class criteria for forest floor sampling.

The forest floor layer in the ICFME primary plots had an average thickness of 5.8 cm based on 1363 depth measurements (Table 7). On the basis of depth measurements and fuel loads by 2-cm depth class, it was estimated that the weight per unit area for the forest floor layer would be slightly less than 5.0 kg/m^2 and in turn the bulk density of the entire profile would be approximately 82 kg/m^3 for the organic matter only and about 92 kg/m^3 for the combined organic matter and inorganic materials (Table 7). Both the organic and total bulk densities are

Table 4. Overstory tree characteristics for the primary plots of the International Crown Fire Modelling Experiment

	Diameter at breast height outside bark (cm)				Stem height (m)													
	Jack pine				Black spruce				Jack pine				Black spruce				Live stems	
	Live		Dead		Live		Dead		Live		Dead		Live		Dead			
Plot	Mean ± SD	*n*	Mean ± SD	*n*	Mean ± SD	*n*	Mean ± SD	*n*	Mean ± SD	*n*	Mean ± SD	*n*	Mean ± SD	*n*	Mean ± SD	*n*	Mean ± SD	*n*
A	13.4 ± 3.2	32	6.7 ± 2.7	15	5.0 ± 2.7	13	– –	0	13.1 ± 1.5	32	7.1 ± 2.2	15	5.3 ± 2.7	13	– –	0	10.9 ± 4.1	45
1	11.9 ± 3.5	67	7.4 ± 3.0	35	4.7 ± 1.2	70	6.8 ± 2.0	8	13.2 ± 2.3	34	9.4 ± 2.0	23	5.6 ± 1.4	35	7.5 ± 2.8	7	9.3 ± 4.3	69
2	13.1 ± 4.1	79	8.4 ± 3.4	33	4.8 ± 2.3	59	5.0 ± 2.4	7	13.8 ± 2.2	47	10.2 ± 2.5	21	5.5 ± 2.5	28	6.8 ± 2.4	3	10.7 ± 4.6	75
3	7.8 ± 2.8	126	7.3 ± 3.8	54	– –	0	– –	0	11.9 ± 2.4	70	7.9 ± 1.8	30	– –	0	– –	0	11.9 ± 2.4	70
4	8.8 ± 2.4	124	4.8 ± 2.1	55	– –	0	– –	0	11.1 ± 1.8	75	7.8 ± 1.3	24	– –	0	– –	0	11.1 ± 1.8	75
5	8.4 ± 2.4	89	5.3 ± 2.2	70	6.6 ± 2.4	16	6.6 ± 4.2	5	10.9 ± 2.2	49	8.3 ± 2.8	38	4.8 ± 1.3	8	5.2 ± 1.4	3	10.0 ± 3.0	57
6	9.5 ± 2.7	54	5.4 ± 2.3	38	5.8 ± 1.8	67	5.8 ± 2.8	20	11.9 ± 3.0	35	7.8 ± 2.2	21	5.7 ± 1.9	35	5.7 ± 1.7	9	8.8 ± 4.0	70
7	10.5 ± 3.3	92	5.4 ± 1.5	43	3.3 ± 2.0	41	3.3 ± 0.3	4	12.8 ± 2.2	46	8.4 ± 1.8	24	5.5 ± 1.6	27	4.1 ± 0.1	2	10.1 ± 4.1	73
8	9.7 ± 3.0	50	5.6 ± 2.5	34	5.1 ± 1.7	89	5.1 ± 1.6	7	11.2 ± 2.1	26	8.1 ± 1.7	18	6.0 ± 2.1	51	3.9 ± 1.6	5	7.8 ± 3.3	77
9	8.2 ± 2.5	55	5.4 ± 2.0	44	4.4 ± 1.4	9	5.2 ± 1.0	4	11.6 ± 2.7	33	8.8 ± 1.8	22	5.6 ± 2.3	6	6.1 ± 2.2	3	10.7 ± 3.4	39
Overall	10.1 ± 2.0	768	6.2± 1.2	421	5.0 ± 1.0	364	5.4 ± 1.2	55	12.2 ± 1.0	447	8.4 ± 0.9	236	5.5 ± 0.3	203	5.6 ± 1.3	32	10.1 ± 3.8	650

Note: SD = standard deviation, dashes indicate no sample.

Table 5. Overstory stand structure characteristics for the primary plots of the International Crown Fire Modelling Experiment

	Basal area (m^2/ha)		Basal area by species and condition (%)				Density (no./ha)		Density by species and condition (%)				Average spacing between stems (m)		
			Jack pine		Black spruce				Jack pine		Black spruce				
Plot	Live stems	Dead stems	Live	Dead	Live	Dead	Live stems	Dead stems	Live	Dead	Live	Dead	Live stems	Dead stems	Live and dead stems
A	36.7	4.4	93.7	100.0	6.3	0.0	3268	1089	71.1	100.0	28.9	0.0	1.7	3.0	1.5
1	29.9	6.5	86.0	84.6	14.0	15.4	4372	1372	48.9	81.4	51.1	18.6	1.5	2.7	1.3
2	22.0	3.9	90.0	92.3	10.0	7.7	2343	679	57.2	82.5	42.8	17.5	2.1	3.8	1.8
3	24.2	10.1	100.0	100.0	0.0	0.0	4460	1912	100.0	100.0	0.0	0.0	1.5	2.3	1.3
4	29.6	4.2	100.0	100.0	0.0	0.0	4492	1992	100.0	100.0	0.0	0.0	1.5	2.2	1.2
5	21.7	7.6	92.6	88.2	7.4	11.8	3981	2844	84.8	93.3	15.2	6.7	1.6	1.9	1.2
6	22.7	6.5	71.4	61.5	28.6	38.5	4738	2253	45.1	65.5	54.9	34.5	1.5	2.1	1.2
7	35.7	4.0	89.9	97.5	10.1	2.5	4779	1689	69.2	92.5	30.8	8.5	1.4	2.4	1.2
8	21.9	4.3	67.1	86.0	32.9	14.0	5068	1494	36.0	82.9	64.0	17.1	1.4	2.6	1.2
9	19.0	6.9	95.8	92.8	4.2	7.2	3647	2735	85.9	91.7	14.1	8.3	1.7	1.9	1.3
All plots															
Mean	26.3	5.8	88.7	90.3	11.4	9.7	4115	1806	69.8	89.0	30.2	11.1	1.6	2.5	1.3
SD	6.2	2.0	11.2	11.7	11.2	11.7	827	689	22.8	11.0	18.4	11.0	0.2	0.6	0.2

Note: SD = standard deviation.

Table 6. Percentage of inorganic materials found in forest floor samples and forest floor load for the main study area of the International Crown Fire Modelling Experiment

Depth class[a] (cm)	Sample size (n)	Inorganic materials (%)				Forest floor weight per unit area (kg/m^2)					
						Total			Organic		
		Mean	±	SD	Range	Mean	±	SD	Mean	±	SD
0–2	99[b]	2.3	±	10.5	0–61.5	1.710	±	0.400	1.654	±	0.385
2–4	38	13.7	±	21.8	0–69.3	1.790	±	0.530	1.506	±	0.555
4–6	13	13.2	±	18.1	0–40.8	2.090	±	0.590	1.729	±	0.531
6–8	3	10.0	±	17.3	0–30.0	2.420	±	0.690	2.100	±	0.272

[a]These class limits should be mutually exclusive.
[b]One sample was discarded because of misclassification of measurement.
Note: SD = standard deviation.

Table 7. Preburn depth, load, and bulk density of the forest floor layer for the primary plots of the International Crown Fire Modelling Experiment[a]

Plot	Preburn depth (cm)				Total load (kg/m^2)	Bulk density (kg/m^3)	
	Mean	±	SD	n		Total	Organic
A	4.6	±	1.4	98	3.705	88.8	80.0
1	7.0	±	3.9	155	5.939	95.6	84.8
2	6.0	±	2.5	101	4.863	91.4	81.5
3	6.0	±	3.8	157	4.921	91.6	81.6
4	4.6	±	1.7	150	3.635	88.6	79.9
5	5.3	±	2.1	156	4.249	90.2	80.8
6	7.5	±	3.0	152	6.422	97.2	86.1
7	5.2	±	2.4	158	4.154	90.0	80.7
8	5.6	±	2.1	160	4.569	90.8	81.1
9	5.8	±	2.9	76	4.725	91.1	81.3
All plots							
Mean	5.8				4.718	91.5	81.8
SD	0.9				0.895	2.8	2.0

[a]The fuel loads pertain to organic matter only.
Note: SD = standard deviation, n = number of samples.

reported in Table 7 because the latter quantity is an input in various ground and subsurface fire models (Frandsen 1997; Lawson et al. 1997; Anderson 2000). The forest floor bulk densities were similar to those reported for other regions of the Canadian boreal forest (e.g., Stocks et al. 1990; McAlpine 1995; Miyhanishi and Johnson 2002). (According to McAlpine [1995, page 150, Table 2] the forest floor bulk density for the 10 jack pine slash plots burned during the Frontier Lake experimental burning study in eastern Ontario varied from 47 to 171 kg/m^3 [mean 108 kg/m^3]. However, according to Weber et al. [1995, page 160, Table 1] the bulk density for the same set of plots was a constant 167 kg/m^3, a value that was also apparently used by Duchesne and McAlpine [1993] in their publication on the Frontier Lake study. The reason for this difference is unknown [M.G. Weber, Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, Ontario, personal communication, e-mail, 2002].)

Although the forest floor of the main ICFME forest was similar in depth to the immature and mature jack pine stands studied by Stocks (1987a, 1989), the forest floor fuel loads in the primary plots of the ICFME were about 3 to 4 times greater (Table 1). The forest floor layer at the ICFME site is accordingly much more compacted (Table 1). Note that in the heading of Table 2 in Stocks (1989) the forest floor depth and load labels were mistakenly reversed. Furthermore, in Stocks and Hartley (1995) the data for fuel loads presented for the forest floor in the mature and immature jack pine stands were actually the mean forest floor depths. The mean fuel loads for the mature and immature jack pine stands were 1.7 and 1.3 kg/m^2, respectively, and, in turn, the total fuel loads were 4.1 and 4.9 kg/m^2, respectively.

Characteristics of Dead-down Woody Surface Fuel

All of the woody debris on 2880 m of LIM transects was tallied. The woody surface fuel loads by the various roundwood diameter size classes for the primary ICFME plots are presented in Tables 8 and 9. Interestingly, there were on average nearly equal amounts of fuel (i.e., approximately 0.7 kg/m^2) for the fine and medium-size diameters (<7.0 cm) and the larger pieces (≥7.0 cm). There were nearly equal proportions of sound and rotten material in the largest size class (representing dead and downed logs averaging approximately 10 cm in diameter). These results contrast with those of Singh (1987), who found that 83% of the large downed woody debris in jack pine stands in Alberta was rotten or punky.

The general consistency in the average piece diameter between plots (Table 9) suggests that the ICFME forest originated from a single-age class stand. The woody surface fuel loads of the main ICFME forest were comparable to those of the mature jack pine stand studied by Stocks (1989). However, there were differences between the ICFME forest and the immature jack pine stand studied by the same author (Stocks 1987a): in the earlier study there was only half as much of the smaller woody fuel (pieces <7.0 cm in diameter) but more than double the amount of larger log material on the ground (Table 1).

Regression Estimation of Weights of Crown Fuel Components

A total of 106 stems were destructively sampled (Table 10), covering the main range in stem DBHOB and height encountered in the understory and overstory canopy inventories (Appendix 2). This total consisted of 33 live jack pine, 31 dead jack pine, 34 live black spruce greater than 1.3 m in height, and 8 live black spruce less than or equal to 1.3 m in height.

The coefficients and associated statistics derived from the regression analyses are presented in Table 11. As has been reported by many authors (e.g., Walker and Stocks 1975; Green and Grigal 1978; Stocks 1980; Grigal and Kernik 1984), the correlations between DBHOB (or DGLOB) and the dry weight of the various crown fuel components were in general very high (Fig. 11, Table 11). The present study complements the work of Woodard and Delisle (1987) and that of Johnson et al. (1990), who also used the roundwood diameter size classes established by the CFS fire research group (McRae et al. 1979; Van Wagner 1982) in their individual biomass studies. It also constitutes a contribution to the growing list of tree crown biomass studies undertaken in North America (Ter-Mikaelian and Korzukhin 1997).

Characteristics of Ladder and Crown Fuels

Most of the primary ICFME plots are distinctly two-storied in nature. In addition to an overstory dominated by jack pine and to a lesser extent black spruce, there is usually a well-developed understory of black spruce. The maximum height of any live black spruce stem exhibiting a DBHOB of less than 3.0 cm was less than 3.5 m. The immature jack pine fuel complex studied by Stocks (1987a) lacked any black spruce understory of note (Walker and Stocks

Table 8. Characteristics of preburn dead-down woody surface fuel, for pieces less than 7.0 cm in diameter, for the primary plots of the International Crown Fire Modelling Experiment

	Surface fuel loads (kg/m²) by roundwood diameter size class[b]										
	<0.5 cm		0.5–1.0 cm		1.0–3.0 cm		3.0–5.0 cm		5.0–7.0 cm		<7.0 cm
Plot[a]	Mean ± SD	%[c]	Mean ± SD	%[c]	Mean ± SD	%[c]	Mean ± SD	%[c]	Mean ± SD	%[c]	Mean ± SD[d]
A	0.045 ± 0.019	8.5	0.020 ± 0.011	3.8	0.119 ± 0.045	22.4	0.136 ± 0.074	25.6	0.211 ± 0.216	39.7	0.531 ± 0.272
1	0.022 ± 0.008	3.4	0.016 ± 0.008	2.5	0.091 ± 0.047	14.0	0.220 ± 0.131	33.9	0.300 ± 0.271	46.2	0.649 ± 0.381
2	0.041 ± 0.011	11.5	0.029 ± 0.013	8.1	0.065 ± 0.060	18.2	0.094 ± 0.097	26.3	0.128 ± 0.127	35.9	0.357 ± 0.193
3	0.037 ± 0.008	4.9	0.019 ± 0.005	2.5	0.221 ± 0.093	29.4	0.312 ± 0.143	41.5	0.162 ± 0.134	21.5	0.752 ± 0.242
4	0.041 ± 0.007	4.8	0.021 ± 0.005	2.4	0.216 ± 0.086	25.0	0.310 ± 0.132	35.9	0.276 ± 0.201	32.0	0.863 ± 0.219
5	0.042 ± 0.010	3.7	0.033 ± 0.014	2.9	0.266 ± 0.107	23.4	0.386 ± 0.137	34.0	0.408 ± 0.337	35.9	1.136 ± 0.464
6	0.035 ± 0.007	4.3	0.032 ± 0.010	3.9	0.180 ± 0.063	22.2	0.212 ± 0.108	26.1	0.354 ± 0.201	43.6	0.812 ± 0.246
7	0.040 ± 0.009	6.6	0.032 ± 0.014	5.3	0.172 ± 0.075	28.5	0.175 ± 0.100	29.0	0.186 ± 0.119	30.8	0.604 ± 0.206
8	0.039 ± 0.010	4.2	0.040 ± 0.015	4.3	0.172 ± 0.064	18.3	0.296 ± 0.087	31.6	0.390 ± 0.193	41.6	0.938 ± 0.230
9	0.049 ± 0.009	5.3	0.029 ± 0.007	3.1	0.204 ± 0.070	21.9	0.212 ± 0.095	22.7	0.437 ± 0.204	46.9	0.932 ± 0.278
All plots											
Mean	0.039	5.72	0.027	3.88	0.171	22.33	0.235	30.66	0.285	37.41	0.757
SD	0.007	2.5	0.008	1.75	0.062	4.7	0.090	5.76	0.110	7.882	0.228

[a]The number of line intersect method transects (i.e., sample size, *n*) for plots 1–8 was 16.For plots A and 9 it was 10 and 9, respectively.
[b]Actual size classes were <0.50, 0.50–0.99, 1.00–2.99, 3.00–4.99, and 5.00–6.99 cm.
[c]Percentage of total quantity < 7.0 cm in diameter.
[d]Discrepancies may be due to rounding.
Note: SD = standard deviation.

Table 9. Characteristics of preburn dead-down woody surface fuel, for pieces equal to or greater than 7.0 cm in diameter, for the primary plots of the International Crown Fire Modelling Experiment

	Surface fuel loads (kg/m^2) by wood quality					Roundwood piece diameter (cm)					
	>7.0 cm sound		>7.0 cm rotten		>7.0 cm total	>7.0 cm sound		>7.0 cm rotten		>7.0 cm total	
Plot [a]	Mean ± SD	%[b]	Mean ± SD	%[b]	Mean ± SD	Mean ± SD	*n*	Mean ± SD	*n*	Mean ± SD	*n*
A	0.290 ± 0.338	38.1	0.471 ± 0.276	61.9	0.761 ± 0.435	10.0 ± 2.2	11	11.0 ± 2.5	19	10.7 ± 2.4	30
1	0.201 ± 0.275	54.2	0.170 ± 0.123	45.8	0.371 ± 0.309	8.6 ± 1.6	15	9.2 ± 1.4	17	8.9 ± 1.5	32
2	0.176 ± 0.310	28.4	0.444 ± 0.315	71.6	0.620 ± 0.485	9.6 ± 1.9	6	9.7 ± 2.1	22	9.7 ± 2.1	28
3	0.410 ± 0.485	45.4	0.493 ± 0.684	54.6	0.903 ± 0.952	10.5 ± 2.8	20	10.4 ± 3.1	36	10.5 ± 3.0	56
4	0.325 ± 0.423	46.1	0.380 ± 0.386	53.9	0.705 ± 0.745	9.4 ± 2.1	19	10.9 ± 3.6	25	10.2 ± 3.1	44
5	1.119 ± 0.628	74.2	0.388 ± 0.422	25.7	1.508 ± 0.812	9.2 ± 2.5	68	11.0 ± 3.7	25	9.7 ± 2.9	93
6	0.335 ± 0.552	65.7	0.175 ± 0.286	34.3	0.510 ± 0.673	8.6 ± 1.3	14	10.8 ± 2.9	9	9.5 ± 2.3	23
7	0.206 ± 0.255	59.5	0.140 ± 0.331	40.5	0.346 ± 0.391	8.8 ± 1.5	18	10.2 ± 2.6	8	9.4 ± 2.1	26
8	0.400 ± 0.480	65.6	0.210 ± 0.294	34.4	0.610 ± 0.645	9.0 ± 1.4	38	9.3 ± 3.6	15	9.1 ± 2.2	47
9	0.557 ± 0.392	52.6	0.502 ± 0.330	47.4	1.059 ± 0.571	10.7 ± 2.3	17	9.6 ± 2.3	22	10.1 ± 2.4	39
All plots											
Mean	0.402	53	0.337	47	0.739	9.4	226	10.2	198	9.8	418
SD	0.277	13.9	0.147	13.9	0.349	0.8		0.7		0.6	

[a]The number of line intersect method transects (*n*) for plots 1–8 was 16. For plots A and 9 it was 10 and 9, respectively.
[b]Percentage of total quantity > 7.0 cm in diameter.
Note: SD = standard deviation, *n* = number of samples.

Table 10. Characteristics of the trees selected for crown biomass sampling in the main study area of the International Crown Fire Modelling Experiment

Characteristic[a]	Mean	±	SD	Range
DBHOB (cm)				
Live jack pine >1.3 m	11.0	±	5.2	1.7–19.8
Dead jack pine >1.3 m	7.1	±	2.5	3.9–10.7
Live black spruce >1.3 m	3.8	±	3.0	0.5–10.5
DGLOB (cm)				
Live jack pine >1.3 m	13.8	±	6.6	2.4–25.5
Dead jack pine >1.3 m	9.7	±	3.6	5.2–16.5
Live black spruce >1.3 m	6.2	±	3.7	2.2–14.1
Live black spruce <1.3 m	1.4	±	0.5	0.7–2.3
Height (m)				
Live jack pine >1.3 m	12.1	±	4.1	2.3–18.1
Dead jack pine >1.3 m	10.1	±	1.8	7.2–13.3
Live black spruce >1.3 m	4.4	±	3.0	1.4–11.4
Live black spruce <1.3 m	0.8	±	0.2	0.5–1.2
LCBH (m)				
Live jack pine >1.3 m	7.9	±	2.2	1.7–12.2
Live black spruce >1.3 m	0.9	±	1.1	0.0–4.2
Live black spruce <1.3 m	0.3	±	0.2	0.1–.45
Live crown length (m)				
Live jack pine >1.3 m	5.6	±	2.4	2.6–11.8
Live black spruce >1.3 m	3.6	±	2.5	0.9–9.4
Live black spruce <1.3 m	0.5	±	0.3	0.15–0.9
Live crown width (m)				
Live jack pine >1.3 m	1.6	±	1.2	0.5–7.2
Live black spruce >1.3 m	1.2	±	0.4	0.6–2
Live black spruce <1.3 m	0.5	±	0.3	0.1–1.2
Age at ground level (yr)				
Live jack pine >1.3 m	63.4	±	2.3	55–65
Live black spruce >1.3 m	61.2	±	4.2	46–65

[a]According to tree species, characterized by condition and stem height.
Note: DBHOB = diameter at breast height outside bark, DGLOB = diameter at ground level outside bark, LCBH = live crown base height.

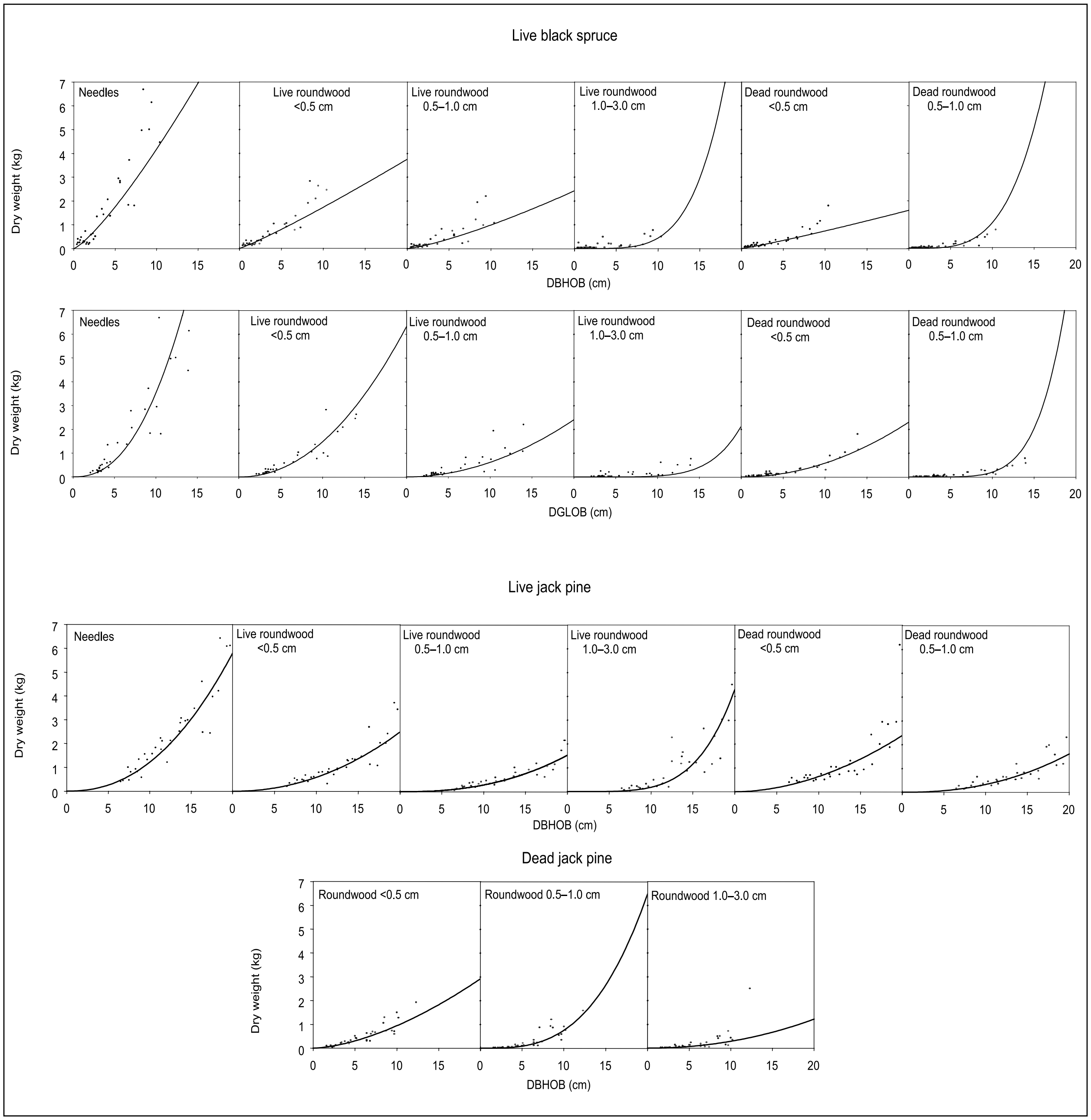

Figure 11. Scattergrams of the oven-dry weights of individual fuel components against stem diameter for tree crown biomass sampling in the International Crown Fire Modelling Experiment study area. DBHOB = diameter at breast height outside bark, DGLOB = diameter at ground level outside bark. Diameter size classes are actually <0.50, 0.50–0.99, and 1.00–2.99 cm (i.e., mutually exclusive).

Table 11. Elements of the crown fuel weight regression equations developed for the main study area of the International Crown Fire Modelling Experiment

	Crown fuel weight[a]				
	Regression coefficients		Statistics		
Crown fuel component	*a*	*b*	R^2	SE	df
Live jack pine >1.3 m in height					
Needles	0.00672	2.25699	0.88	0.27	31
Live roundwood <0.5 cm	0.00478	2.08881	0.84	0.31	31
Live roundwood 0.5–1.0 cm	0.00105	2.43234	0.80	0.40	31
Live roundwood 1.0–3.0 cm	5.18E-06	4.54745	0.57	1.30	31
Dead roundwood <0.5 cm	0.00824	1.88877	0.76	0.35	31
Dead roundwood 0.5–1.0 cm	0.00161	2.30592	0.82	0.36	31
Dead roundwood 1.0–3.0 cm	2.17E-10	7.84334	0.61	2.08	31
Dead jack pine >1.3 m in height					
Dead roundwood <0.5 cm	0.02188	1.63319	0.75	0.58	29
Dead roundwood 0.5–1.0 cm	0.00060	3.10118	0.68	3.55	29
Dead roundwood 1.0–3.0 cm	0.00233	2.08779	0.52	3.86	29
Live black spruce >1.3 m in height					
Needles	0.23317	1.25384	0.80	0.56	32
Live roundwood <0.5 cm	0.13267	1.11546	0.83	0.45	32
Live roundwood 0.5–1.0 cm	0.04995	1.29626	0.67	0.81	32
Live roundwood 1.0–3.0 cm	8.91E-06	4.69386	0.51	4.21	32
Dead roundwood <0.5 cm	0.05553	1.12281	0.82	0.48	32
Dead roundwood 0.5–1.0 cm	1.67E-04	3.81224	0.58	2.92	32
Dead roundwood 1.0–3.0 cm	6.30E-07	3.06767	0.38	3.52	32
Live black spruce <1.3 m in height					
Needles	0.01534	2.36069	0.95	0.43	42
Live roundwood <0.5 cm	0.01202	2.09296	0.95	0.39	42
Live roundwood 0.5–1.0 cm	0.00673	1.96155	0.79	0.80	42
Live roundwood 1.0–3.0 cm	7.91E-08	5.71104	0.60	3.73	42
Dead roundwood <0.5 cm	0.00588	1.99293	0.89	0.58	42
Dead roundwood 0.5–1.0 cm	4.39E-07	5.67014	0.68	3.14	42
Dead roundwood 1.0–3.0 cm	1.36E-07	3.05431	0.38	3.17	42

[a]As per equation $Y = aX^b$, where Y is oven-dry weight (kilograms) and X is diameter at breast height outside bark (centimeters) for
height.

Note: R^2 = coefficient of determination, SE = standard error, df = degrees of freedom.

1975). However, the mature jack pine fuel complex described by Stocks (1989) did exhibit an appreciable black spruce understory, although not nearly as well developed as that found in most of the primary ICFME plots. According to Walker and Stocks (1975, page 7, Fig. 7), approximately 77% of the black spruce stems in the mature jack pine stand had a DBHOB of less than 2.8 cm and there were about 842 stems/ha.

The fuel characteristics associated with the understory and overstory canopies are presented in Tables 12–14 and Figures 12 and 13. The presentation of crown or canopy bulk densities in Table 14 simply reflects the current uncertainty in specifying precisely what proportion of woody material is consumed during flaming combustion in this stratum of the fuel complex. Fuel consumption data obtained as a result of the ICFME project indicate that nearly all of the roundwood fuel less than 0.5 cm in diameter is consumed in a crown fire, as well as a large percentage of the 0.5–1.0 cm diameter material (Stocks et al. 2004) depending on flame front residence time.

The three coefficients and associated statistics derived from the analysis based on Equation 6, used in constructing the vertical fuel profiles (Figs. 12 and 13), are presented in Table 15. Graphs of the fraction of cumulative dry weight for the various crown fuel components against fraction of cumulative height for the jack pine and black spruce trees that were destructively sampled as part of the crown biomass study are presented in Appendix 3. In contrast to other vertical fuel profiles (e.g., Sando and Wick 1972; Kilgore and Sando 1975; Roussopoulos 1978; Scott and Reinhardt 2002), the manner in which Figures 12 and 13 have been constructed allows simultaneous display of the crown or canopy fuel load and bulk density.

The vertical fuel distributions attributed to the overstory tree canopies of the primary ICFME plots are generally similar (Fig. 12). The principal difference among the plots is the variation in the amount of fuel contributed by both the live and dead black spruce stems in the overstory and understory canopies within the first 3 to 4 m above the ground surface (Fig. 12). Plots 3 and 4 appear to lack a black spruce understory component, according to the fuel quantities in the first couple of meters above the ground surface (Fig. 12). In fact, this appearance is principally a reflection of the complete lack of any black spruce in the overstory canopy (Tables 4 and 5). The overstory black spruce stems are shorter and have lower LCBH than the jack pine (Table 4).

The LCBH is the major determinant of susceptibility of a conifer forest stand to crown fire development (Van Wagner 1977; Alexander 1988, 1998; Cruz 1999; Cruz et al. 2003b, 2003c). One simple model for assessing the potential for crown fire initiation is that offered by Van Wagner (1977):

$$I_o = [0.01\, z\, (460 + 26\, m)]^{1.5} \qquad (7)$$

where I_o = the critical surface fire intensity needed for initial crown combustion (kilowatts per meter), z = crown or canopy base height (meters), and m = foliar moisture content (percent). In many but not all conifer stands, LCBH can be equated to z in Equation 7.

The LCBH for the primary ICFME plots, based on the overstory canopy, varied from 3.6 to 8.2 m and averaged 6.6 m for the ICFME forest as a whole (Table 12). The mean LCBHs of the immature (4.0 m) and mature (12.0 m) jack pine overstories of Stocks's (1987a, 1989) plots were slightly less and considerably greater, respectively, than that of the ICFME fuel complex (Table 1).

The "combined" model of McAlpine and Hobbs (1994) for predicting LCBH from stand height and stem density for plantations of boreal conifer (i.e., jack pine, black spruce, and white spruce) in eastern Ontario consistently underpredicted the LCBH by about 2 to 3.5 times. For example, at the forest level, the McAlpine and Hobbs (1994) model predicted an LCBH of 2.8 m for an average combined live jack pine and black spruce stand height of 10.1 m (Table 4) and stand density of 4115 stems/ha (Table 5). The model predictions for plots A and 1–9, based on combined live jack pine and black spruce stem height from Table 4 and live stem density from Table 5 were as follows: 6.5, 7.1, 6.1, 8.2, 7.0, 8.0, 6.9, 5.8, 3.6, and 7.2 m, respectively.

Several fire researchers have made subjective estimates about the minimum amount of fuel necessary to propagate fire vertically through the crown or canopy stratum in terms of defining the effective crown or canopy base height with respect to potential for crown fire initiation (Muraro 1971; Sando and Wick 1972; Williams 1977; Roussopoulos 1978; Scott and Reinhardt 2001). These estimates have ranged from a low of 0.011 kg/m^3 (Scott and Reinhardt 2001) through 0.037 kg/m^3 (Sando and Wick 1972) to a high of 0.067 kg/m^3 (Williams 1977). To the authors' knowledge, no published theory, model, or empirical data of any kind concerning wildland fire fuels currently exists to support any of these estimates. As Sando and Wick (1972) stated over 30 years ago, "little is known about the amount of fuel required to support combustion vertically."

In terms of the ICFME primary plots, the effective crown or canopy base height would essentially range from zero according to Scott and Reinhardt's (2001) criteria to 1.0 m according to Williams's (1977)

Table 12. Characteristics of understory ladder and overstory crown fuel for the primary plots of the International Crown Fire Modelling Experiment

	Understory black spruce							Overstory canopy					
	Live stems			Dead stems, height (m)		Density (no./ha)[a]		LCBH (m)[b]			Live crown depth (m)[b]		
	Height (m)	LCBH (m)				Live stems	Dead stems	Jack pine	Black spruce	Combined	Jack pine	Black spruce	Combined
Plot	Mean ± SD	Mean ± SD	*n*	Mean ± SD	*n*	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
A	1.4 ± 0.6	0.4 ± 0.3	71	1.5 ± 0.8	4	3767 ± 2892	212 ± 472	8.9 ± 1.4	0.9 ± 0.6	6.5 ± 3.9	4.3 ± 1.7	4.4 ± 2.4	4.3 ± 1.9
1	1.8 ± 0.9	0.6 ± 0.5	177	1.2 ± 0.8	20	5634 ± 4134	637 ± 859	8.1 ± 2.4	2.4 ± 2.6	7.1 ± 3.2	4.2 ± 1.9	3.8 ± 1.5	4.0 ± 1.7
2	1.7 ± 0.7	0.6 ± 0.4	66	1.9 ± 1.5	15	2101 ± 1822	477 ± 975	8.6 ± 1.5	1.8 ± 1.1	6.1 ± 3.6	5.2 ± 2.0	4.0 ± 2.0	4.7 ± 2.1
3	1.0 ± 0.5	0.2 ± 0.2	80	4.0 ± 1.7	3	2546 ± 3065	95 ± 264	8.2 ± 1.7	–	8.2 ± 1.7	3.6 ± 1.9	–	3.6 ± 1.9
4	1.0 ± 0.5	0.3 ± 0.1	42	2.5 ± 1.6	3	1453 ± 1621	104 ± 274	7.0 ± 1.6	–	7.0 ± 1.6	4.2 ± 1.4	–	4.2 ± 1.4
5	1.4 ± 0.7	0.4 ± 0.2	229	2.6 ± 2.0	8	7289 ± 5792	255 ± 994	5.2 ± 1.4	10.0 ± 3.0	8.0 ± 2.8	3.0 ± 1.0	4.1 ± 1.3	3.1 ± 1.1
6	1.8 ± 0.9	0.7 ± 0.6	213	1.9 ± 1.5	26	6780 ± 3960	828 ± 933	7.9 ± 1.8	0.7 ± 0.5	6.9 ± 3.0	3.3 ± 1.6	4.0 ± 1.5	3.6 ± 1.6
7	1.9 ± 0.9	0.7 ± 0.4	121	2.2 ± 1.6	24	3852 ± 4800	764 ± 1901	8.5 ± 1.7	1.3 ± 0.9	5.8 ± 3.8	4.3 ± 1.5	4.3 ± 1.6	4.7 ± 1.5
8	1.8 ± 1.0	0.8 ± 0.5	152	1.3 ± 1.2	61	4838 ± 3124	1942 ± 3184	7.4 ± 2.2	1.7 ± 0.7	3.6 ± 3.0	4.1 ± 1.8	4.3 ± 2.0	4.2 ± 1.9
9	1.6 ± 0.7	0.5 ± 0.3	140	3.2 ± 2.2	5	7427 ± 6132	265 ± 576	8.1 ± 2.4	2.4 ± 2.6	7.2 ± 3.2	3.6 ± 1.6	3.2 ± 0.5	3.5 ± 1.5
All plots	1.5 ± 0.3	0.5 ± 0.2	1291	2.2 ± 0.9	169	4569 ± 2178	558 ± 554	7.8 ± 1.1	2.7 ± 3.0	6.6 ± 1.3	4.0 ± 0.6	4.0 ± 0.4	4.0 ± 0.5

[a] For plots 1 to 8, black spruce density is based on a sample size (*n*) of 25; for plots A and 9, it is based on a sample size of 15 and 16, respectively.
[b] Sample sizes for LCBH and live crown depth for the overstory canopy are the same as reported for live stem heights in Table 4.
Note: LCBH = live crown base height, SD = standard deviation, *n* = number of samples.

Table 13. Preburn understory and overstory canopy fuel loads for the primary plots of the International Crown Fire Modelling Experiment as estimated from elevated vertical fuel profiles and tree measurements

	Fuel load in understory canopy (kg/m^2)				Fuel load in overstory canopy (kg/m^2)[a]			
		Roundwood, by diameter size class (cm)[b]				Roundwood, by diameter size class (cm)[b]		
Plot	Needles only	<0.5	0.5–1.0	1.0–3.0	Needles only	<0.5	0.5–1.0	1.0–3.0
A	0.101	0.151	0.049	0.0001	0.754 (77)	0.686 (84)	0.402 (84)	0.355 (97)
1	0.124	0.185	0.083	0.0001	0.796 (54)	0.709 (65)	0.380 (72)	0.243 (98)
2	0.068	0.103	0.034	0.0003	0.515 (66)	0.476 (74)	0.290 (77)	0.320 (100)
3	0.028	0.052	0.027	0.0001	0.426 (100)	0.514 (100)	0.294 (100)	0.104 (100)
4	0.013	0.023	0.006	0.0007	0.459 (99)	0.524 (99)	0.257 (99)	0.102 (100)
5	0.159	1.006	0.072	0.0010	0.424 (72)	0.459 (81)	0.235 (80)	0.086 (93)
6	0.220	0.269	0.087	0.0006	0.762 (33)	0.635 (48)	0.320 (49)	0.087 (84)
7	0.125	0.176	0.057	0.0008	0.792 (65)	0.735 (75)	0.381 (75)	0.221 (98)
8	0.146	0.173	0.057	0.0005	0.822 (28)	0.673 (44)	0.336 (44)	0.097 (84)
9	0.199	0.385	0.133	0.0019	0.354 (78)	0.443(84)	0.209 (86)	0.072 (99)
All plots								
Mean	0.118	0.252	0.061	0.001	0.610 (67)	0.585 (75)	0.310 (77)	0.168 (95)
SD	0.068	0.284	0.036	0.001	0.189	0.113	0.065	0.107

[a]Values in parentheses represent the percentage contributed by jack pine.
[b]Actual diameter size classes were <0.50, 0.50–0.99, and 1.00–2.99 cm.
Note: SD = standard deviation.

Table 14. Preburn understory and overstory canopy bulk densities (kg/m^3) for the primary plots of the International Crown Fire Modelling Experiment as estimated from elevated vertical fuel profiles and tree measurements

	Understory canopy			Overstory canopy			Midcanopy space			Total profile		
		Needles and twigs			Needles and twigs			Needles and twigs			Needles and twigs	
Plot	Needles only	<0.5 cm	<1.0 cm	Needles only	<0.5 cm	<1.0 cm	Needles only	<0.5 cm	<1.0 cm	Needles only	<0.5 cm	<1.0 cm
A	0.03	0.07	0.12	0.13	0.22	0.28	0.04	0.07	0.12	0.07	0.13	0.18
1	0.07	0.14	0.22	0.10	0.17	0.22	0.08	0.13	0.18	0.10	0.18	0.24
2	0.03	0.06	0.10	0.08	0.13	0.17	0.04	0.06	0.10	0.05	0.09	0.13
3	0.03	0.05	0.11	0.10	0.17	0.20	0.01	0.02	0.06	0.04	0.06	0.11
4	0.01	0.03	0.08	0.10	0.17	0.20	<0.01	0.01	0.05	0.04	0.07	0.11
5	0.05	0.11	0.16	0.09	0.15	0.18	0.03	0.06	0.10	0.06	0.10	0.15
6	0.08	0.17	0.25	0.07	0.13	0.15	0.11	0.18	0.22	0.11	0.19	0.24
7	0.10	0.21	0.31	0.10	0.17	0.22	0.12	0.20	0.26	0.11	0.19	0.25
8	0.07	0.13	0.18	0.08	0.13	0.20	0.06	0.10	0.15	0.07	0.13	0.19
9	0.06	0.11	0.16	0.08	0.14	0.18	0.03	0.05	0.10	0.05	0.09	0.14
All plots												
Mean	0.05	0.11	0.17	0.09	0.16	0.20	0.06	0.09	0.13	0.07	0.12	0.17
SD	0.03	0.06	0.07	0.02	0.03	0.04	0.04	0.06	0.07	0.03	0.05	0.05

Note: SD = standard deviation.

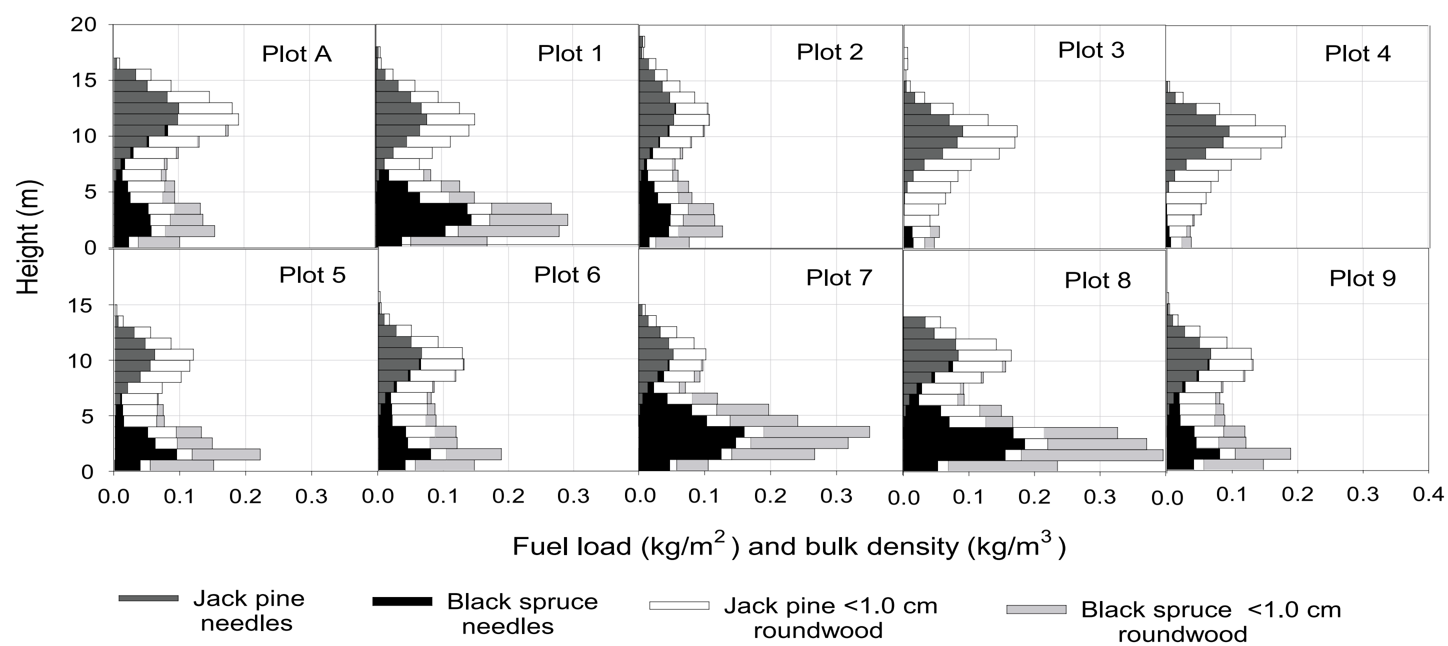

Figure 12. Composite vertical fuel profile for each of the primary plots of the International Crown Fire Modelling Experiment. The forest floor and dead-down woody surface fuel loads are not included.

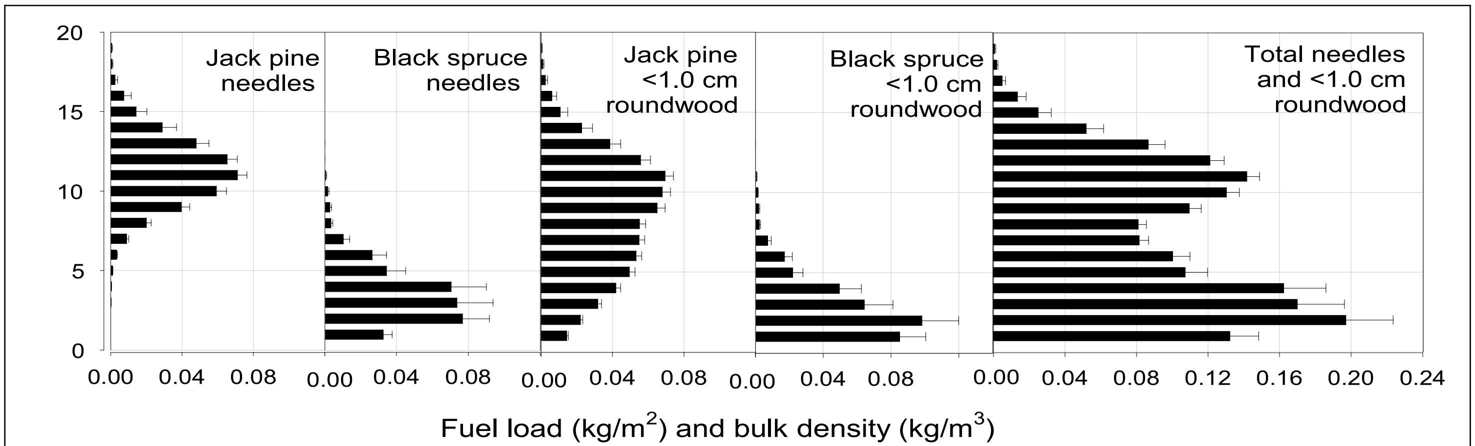

Figure 13. Vertical fuel profiles of the individual crown fuel components for the International Crown Fire Modelling Experiment, with standard error bars.

Table 15. Statistical analysis for constructing the elevated vertical fuel profiles for the primary plots of the International Crown Fire Modelling Experiment

Tree component[a]	*n*	MSE	R^2_{adj}	Parameter[b]	Estimated value	ASE	Confidence interval (95%)
Live jack pine > 1.3 m in height							
Needles	443	0.008	0.886	*a*	0.996	0.006	± 0.011
				b	2.403	0.110	± 0.217
				c	13.086	0.558	± 1.097
Live roundwood							
<0.5cm	443	0.009	0.893	*a*	0.996	0.006	± 0.012
				b	2.936	0.135	± 0.265
				c	14.112	0.623	± 1.225
0.5–1.0 cm	443	0.009	0.879	*a*	0.997	0.006	± 0.012
				b	2.538	0.121	± 0.238
				c	13.46	0.603	± 1.185
Dead roundwood							
<0.5cm	443	0.008	0.939	*a*	1.025	0.016	± 0.032
				b	3.840	0.118	± 0.232
				c	6.945	0.263	± 0.516
0.5–1.0 cm	443	0.014	0.903	*a*	1.059	0.027	± 0.053
				b	4.079	0.160	± 0.314
				c	6.706	0.340	± 0.669
Dead jack pine > 1.3 m in height							
Dead roundwood							
<0.5cm	279	0.009	0.914	*a*	1.053	0.024	± 0.049
				b	2.625	0.100	± 0.197
				c	5.358	0.280	± 0.551
0.5–1.0 cm	261	0.019	0.825	*a*	1.090	0.042	± 0.083
				b	2.282	0.124	± 0.244
				c	4.769	0.386	± 0.759
Live black spruce > 1.3 m in height							
Needles	167	0.015	0.872	*a*	1.015	0.019	± 0.038
				b	2.755	0.200	± 0.394
				c	6.923	0.545	± 1.077
Live roundwood							
<0.5cm	167	0.020	0.830	*a*	1.032	0.028	± 0.056
				b	2.654	0.219	± 0.433
				c	6.113	0.584	± 1.155
0.5–1.0 cm	167	0.032	0.802	*a*	1.144	0.079	± 0.156
				b	3.386	0.302	± 0.595
				c	5.351	0.704	± 1.390
Dead roundwood							
<0.5cm	168	0.023	0.878	*a*	1.000	NA	NA
				b	9.790	0.861	± 1.700
				c	12.254	1.057	± 2.087

[a]Actual roundwood diameter size classes were <0.50 and 0.50–0.99 cm.
[b]Model form: $R_W = a/[1 + \exp(b - cR_H)]$, where R_H is the fraction of height and R_W is the fraction of cumulative fuel component.
Note: *n* = number of samples, MSE = mean square error, R^2_{adj} = adjusted coefficient of determination, ASE = asymptotic standard error, and NA = not applicable (the value was fixed to 1.000).

criteria because of the black spruce understory (Fig. 13). As a ladder or bridge fuel, the black spruce understory is certainly capable, under the right burning conditions (Van Wagner 1977), of initiating "subcanopy" crown fires (Methven 1973; Methven and Murray 1974; Burrows et al. 1989). However, this does not guarantee that a fully developed, active crown fire will ensue (Van Wagner 1977).

The available crown fuel contributes additional energy or heat release to the overall intensity of a spreading fire once crowning has occurred (Byram 1957, 1959). The needle fuel loads of the ICFME overstory averaged about 0.6 kg/m^2, which was just slightly less than that reported by Stocks (1987a, 1989). However, there was considerably more variation in the quantities of twig and branch material in the overstory canopy among the three studies (Table 1).

The crown or canopy bulk density (CBD, kilograms per cubic meter) dictates the likelihood for crown-to-crown fire spread and the potential rate of advance (Van Wagner 1977; Cruz 1999; Cruz et al. 2002). For example, Van Wagner (1977) has theorized that the critical minimum spread rate (meters per minute) for active crowning (R_o) can be calculated as follows (Alexander 1988):

$$R_o = 3.0/\text{CBD} \quad (8)$$

For the ICFME fuel complex, with understory and overstory canopy bulk densities of at least 0.15 kg/m^3 (Table 14), this yields an R_o of 20 m/min or 1.2 km/h, a rate of advance that is readily achieved by crowning forest fires, according to experimental and operational evidence (Stocks 1987a, 1989; Alexander 1998). The ICFME fuel complex and the immature jack pine stand of Stocks (1987a) exhibited nearly identical overstory canopy bulk densities, largely because of the similarities in stand height, but differed from the mature jack pine stand (Stocks 1989) (Table 1).

The bark flakes on the lower boles of the overstory jack pines were an effective ladder or bridge fuel in the ICFME experimental fires. Bark fuel loads were not studied as part of the 1995–1996 preburn fuel sampling in the ICFME study area but were the subject of a follow-up investigation undertaken in 1999, to be reported later as part of a PhD thesis project (N. Lavoie, unpublished data). Nevertheless, assuming that the ratio of needle to bark fuel load is roughly 1.3:1 (Walker and Stocks 1975), then it is reasonable to assume that the bark fuel load for the fuel complex at the ICFME forest is approximately 0.5 kg/m^2.

Evaluation of Sampling Methodology

The techniques used to sample the various elements of the ICFME fuel complex were considered efficient and reliable. To judge the adequacy of the sampling intensity, percent errors (i.e., [standard error of mean/mean] x 100) were computed. The percent errors calculated for the forest floor weight per unit area samples at 0–2, 2–4, 4–6, and 6–8 cm depth were 2.3, 6.0, 8.5, and 7.5, respectively. The percent errors for the other fuels that were sampled are summarized in Table 16. With a few exceptions, the percent errors were generally what was expected according to the original sampling intensity established in the experimental design (i.e., up to 15%).

General Comments on Interplot and Intraplot Variation

The percent errors in Table 16 give some indication of the within-plot variation at the ICFME site. The standard deviations presented in Tables 4, 5, 7, 8, 9, and 12 do the same. With some exceptions (e.g., large dead-down woody surface fuels), the sample means were generally greater than the standard deviations.

In most cases, the ICFME forest-level standard deviations determined from the 10 primary plots were less than the standard deviation of any of the individual plots. This suggests that, in general terms, the primary ICFME plots were basically not very different from one another. In other words, it would be reasonable to pool the primary ICFME plot data to characterize the various attributes of the jack pine – black spruce fuel complex at the ICFME site.

Table 16. Percent errors in sampling of selected preburn fuel and stand characteristics for the primary plots of the International Crown Fire Modelling Experiment

	Forest floor	Surface fuel loads by roundwood diameter size class (cm)[a]							Black spruce stem density		LCBH		LCD		DBHOB				Stem height			
															Jack pine		Black spruce		Jack pine		Black spruce	
Plot	depth	<0.5	0.5–1.0	1.0–3.0	3.0–5.0	5.0–7.0	<7.0	>7.0	Live	Dead	Jack pine	Black spruce	Jack pine	Black spruce	Live	Dead	Live	Dead	Live	Dead	Live	Dead
A	3.0	17.2	22.5	15.4	28.2	41.8	20.9	23.3	19.8	57.5	2.8	18.5	7.0	15.1	4.2	10.4	15.0	–	2.0	8.0	14.1	–
1	4.5	9.1	12.5	12.9	14.9	22.6	14.7	20.8	14.7	27.0	5.1	18.3	7.8	6.7	3.6	6.9	3.1	10.4	3.0	4.4	4.2	14.1
2	4.2	6.7	11.2	23.1	25.8	24.8	13.5	19.6	17.3	40.9	2.5	11.5	5.6	9.4	3.5	7.0	6.2	18.1	2.3	5.3	8.6	20.4
3	5.1	5.4	6.6	10.5	11.5	20.7	8.0	26.4	24.1	55.6	2.5	–	6.3	–	3.2	7.1	–	–	2.4	4.2	–	–
4	3.0	4.3	6.0	10.0	10.6	18.2	6.3	26.4	22.3	52.7	2.6	–	3.8	–	2.4	5.9	–	–	1.8	3.4	–	–
5	3.1	6.0	10.6	10.1	8.9	20.6	10.2	13.5	15.9	78.0	3.8	10.6	4.8	11.2	3.0	5.0	9.1	28.5	2.9	5.5	9.6	15.5
6	3.3	5.0	7.8	8.8	12.7	14.2	8.1	33.0	11.7	22.5	3.9	12.1	8.2	6.3	3.9	6.9	3.8	10.8	4.3	6.2	5.6	9.9
7	3.7	5.6	10.9	10.9	14.3	16.0	8.5	28.3	24.9	49.8	2.9	13.3	5.1	7.2	3.3	4.2	9.5	4.5	2.5	4.4	5.6	1.7
8	2.9	6.4	9.4	9.3	7.3	12.4	6.1	26.4	12.9	32.8	5.8	5.8	8.6	6.5	4.4	7.7	3.5	11.9	3.7	4.9	4.9	18.3
9	5.7	5.8	7.6	10.9	14.2	14.8	9.4	17.1	20.6	54.3	5.2	44.2	7.7	6.4	4.1	5.6	10.6	9.6	4.1	4.4	16.8	20.8
Mean	3.8	7.2	10.5	12.2	14.8	20.6	10.6	23.5	18.4	47.1	3.7	16.8	6.5	8.6	3.6	6.7	7.6	13.4	2.9	5.1	8.7	14.4

[a]Actual size classes were <0.50, 0.50–0.99, 1.00–2.99, 3.00–4.99, and 5.00–6.99 cm.

Note: LCBH = live crown base height, LCD = live crown depth, DBHOB = diameter at breast height outside bark.

CONCLUSIONS

The 10 primary plots of the ICFME project were located in a ca. 1931 fire origin stand comprising an overstory dominated by jack pine and, to a lesser extent, black spruce with a well-developed black spruce understory. Although the forest generally appeared uniform, there was a certain degree of spatial variation, as is inherent in any natural forest stand (Sackett 1979; Brown and See 1981). Nevertheless, it was possible to characterize the ICFME fuel complex as follows.

The overstory canopy averaged about 12 m in height with about 4100 stems/ha, with a much shorter (<3 m) and equally dense (approximately 4600 stems/ha) understory of black spruce. The forest floor layer averaged 5.75 cm in depth and was relatively well compacted, exhibiting a mean fuel load of approximately 4.7 kg/m^2 and a corresponding bulk density of 81.8 kg/m^3. Shrubs and herbaceous vegetation were relatively scarce, but there were significant quantities of dead-down woody fuels. Quantities of dead-down woody surface fuels less than 7.0 and equal to or greater than 7.0 cm in diameter averaged 0.757 and 0.739 kg/m^2, respectively; rotten and punky material accounted for half of the latter category and had a mean piece diameter of almost 10 cm.

Although bark flakes on jack pine boles contribute to the ease of crown fire development in this fuel type, the principal ladder or bridge fuel is the black spruce understory, which in this study amounted to about 0.4 kg/m^2 of readily available fuel for an advancing surface or crown fire. Assuming that the surface litter, including the mosses and lichens (the uppermost centimeter of the forest floor), and the dead-down woody surface fuels less than 1.0 cm in diameter are similarly available to a spreading surface fire, the total fuel load is 1.334 kg/m^2, even without the contribution of 0.6–1.5 kg/m^2 from the overstory canopy in the event of a crown fire. Wendel et al. (1962) concluded that the probability of blowup fires decreased rapidly when available fuel loads were less than 1.345 kg/m^2 (i.e., 6 tons/acre).

The height from the ground surface to the live crown base of the overstory canopy averaged 6.6 m. However, there was no distinct separation between the surface and crown fuel layers as a result of the black spruce understory. The bulk density for the overstory canopy and for the entire stand profile was about 0.20 and 0.17 kg/m^3, respectively, which would readily support the propagation of active crown fires (Van Wagner 1977, 1993; Alexander 1988; Johnson 1992).

The methods used here to sample and describe the ICFME fuel complex are not new or unique, but the data gathered do represent the first complete characterization of a closed-canopy fuel type in the boreal forest region of western and northern Canada, going well beyond some limited forest floor load sampling previously reported (Nalder and Wein 1999). In this regard, the present study complements two existing fire-fuel characterizations in open-canopy fuel types in the Northwest Territories (Sylvester and Wein 1981; Alexander et al. 1991). There is in Canada a general paucity of comprehensive descriptions of fuel complexes in natural forest stands, especially in the far northern boreal forests, although a few examples exist for southern forest regions (e.g., Kiil 1968; Muraro 1971; Lawson 1972; Walker and Stocks 1975; White 1985; Stocks et al. 1990).

The characterization of the ICFME jack pine – black spruce forest fuel complex as documented in this report will prove useful in future efforts to model carbon release from biomass burning in the northern boreal forest (e.g., Kasischke et al. 1995; Amiro et al. 2001) and for many other environmental and ecological applications (e.g., nutrient cycling, wildlife habitat).

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APPENDIX 1

Ground Vegetation Characteristics for the Primary Plots of the International Crown Fire Modelling Experiment (ICFME) Study Area[a]

		Frequency (%) by ICFME plot										Cover (%) by ICFME plot										Prominence value by ICFME plot[b]									
Species[a]	Common name	A	1	2	3	4	5	6	7	8	9	A	1	2	3	4	5	6	7	8	9	A	1	2	3	4	5	6	7	8	9
Trees and shrubs																															
Arctostaphylos uva-ursi	Kinnikinnick	71	75	65	90	78	77	48	57	47	32	10.0	10.0	12.5	17.0	10.8	12.5	3.9	11.9	3.4	2.9	84.3	86.6	100.8	161.3	95.4	109.7	27.0	89.8	23.3	16.4
Arctostaphylos rubra	Bearberry	–	3	–	–	3	0	2	–	5	0	–	0.2	–	–	0.0	3.7	0.2	–	2.5	0.0	–	0.4	–	–	0.0	0.0	0.3	–	5.6	0.0
Picea mariana	Black spruce	–	–	–	–	–	–	7	2	–	–	–	–	–	–	–	–	0.2	0.0	–	–	–	–	–	–	–	–	0.5	0.0	–	–
Potentilla spp.	Cinquefoil	29	22	37	17	25	27	13	10	7	15	2.0	3.0	2.9	1.2	1.7	0.7	0.4	0.4	0.2	0.3	10.7	14.1	17.6	4.9	12.9	3.6	1.4	1.3	0.5	1.2
Rosa acicularis	Prickly rose	54	43	33	78	58	18	13	38	27	22	4.0	3.0	1.5	2.8	0.8	0.7	0.2	3.5	0.5	0.5	29.3	19.6	8.6	24.7	4.0	3.0	0.7	21.6	2.6	2.3
Salix spp.	Willow	21	42	15	17	20	17	15	5	13	15	9.0	3.0	2.4	1.7	3.2	2.1	1.8	0.2	0.8	1.2	41.2	19.4	9.3	7.0	14.3	8.6	7.0	0.4	2.9	4.6
Shepherdia canadensis	Canada buffaloberry	–	8	5	–	0	–	3	13	3	–	–	0.1	0.1	–	0.0	–	0.1	1.7	0.1	–	–	0.3	0.2	–	0.0	–	0.1	6.1	0.2	–
Herbaceous plants																															
Anemone mutifida	Cut-leaved anemone	–	–	–	–	3	–	3	–	–	–	–	–	–	–	0.0	–	0.1	–	–	–	–	–	–	–	0.0	–	0.2	–	–	–
Aster sibiricus	Arctic aster	17	–	–	–	–	3	–	–	2	2	0.0	–	–	–	–	0.1	–	–	0.3	0.3	0.0	–	–	–	–	0.2	–	–	0.4	0.0
Calamagrostis canadensis	Marsh reed grass	46	47	65	37	27	32	67	42	45	12	1.9	5.0	10.5	0.6	0.3	0.4	12.3	2.5	0.7	0.3	12.9	34.5	84.6	3.6	1.6	2.3	100.7	16.2	4.7	1.0
Coptis trifolia	Goldenthread	–	2	–	–	–	–	–	–	–	–	–	0.0	–	–	–	–	–	–	–	–	–	0.0	–	–	–	–	–	–	–	–
Cornus canadensis	Blunchberry	8	18	20	25	23	5	8	8	8	10	0.2	0.5	0.6	0.7	0.6	1.2	1.0	0.1	0.1	0.2	0.6	2.1	2.7	3.5	2.9	2.7	2.8	0.3	0.3	0.6
Primula incana	Mealy primrose	–	8	12	2	12	12	12	10	12	3	–	0.2	0.3	0.2	0.1	0.3	0.2	0.3	0.2	0.1	–	0.6	1.0	0.3	0.3	1.0	0.7	0.9	0.7	0.2
Pyrola virens	Wintergreen	–	27	8	18	38	25	32	25	23	28	–	2.0	1.3	0.6	2.0	0.6	0.8	2.3	0.8	1.1	–	10.4	3.7	10.8	12.3	3.0	4.5	11.5	3.8	5.8
Stellaria media	Common chickweed	17	10	–	17	18	20	8	23	12	3	0.2	0.2	0.3	–	0.2	0.4	0.2	0.4	0.3	0.1	0.8	0.6	–	1.2	0.8	1.8	0.5	1.9	1.0	0.2
Mosses and lichens																															
Cladina mitis	Reindeer lichen	42	55	25	57	42	80	53	42	52	38	11.0	15.0	3.6	11.5	6.0	10.9	5.3	4.5	5.6	9.4	71.3	111.2	18.0	30.4	38.9	97.5	38.6	29.2	40.4	57.9
Cladonia borealis	Red pixie-cup	92	82	38	87	80	93	97	55	97	62	10.0	6.0	5.3	15.7	5.3	7.9	9.6	3.9	9.0	7.1	95.9	54.3	32.7	146.4	47.4	76.2	94.5	28.9	88.6	55.9
Dicranum scoparium	Broom moss	71	78	33	37	21	52	78	47	72	38	15.0	8.0	5.2	3.1	5.5	2.9	9.5	5.4	3.6	3.2	126.3	70.6	29.9	18.8	25.2	20.9	83.9	37.0	30.5	19.7
Peltigera apthosa	Freckle pelt	12	25	15	33	25	15	38	12	33	8	1.0	2.0	2.0	6.6	2.4	0.7	2.3	1.9	2.5	0.8	3.5	10.0	7.7	37.9	12.0	2.7	14.2	6.6	14.4	2.3
Pleurozium schreberi	Feather moss	62	78	78	87	73	87	93	63	90	53	9.0	26.0	29.6	11.6	14.6	17.9	23.9	19.1	18.7	11.3	70.9	229.6	261.4	108.2	124.7	167.0	230.5	151.6	177.4	82.3

[a]Plant nomenclature follows Johnson et al. (1995).
[b]A value of 0 or 0.0 indicates a value of less than 0.05. A dash indicates no data entry.
[c]Prominence values range from 0 to 1000.

APPENDIX 2

Stem Diameter-at-Breast Height (DBHOB) and Height Distributions (stems/ha) of the Understory and Overstory Tree Canopies for the Primary Plots of the International Crown Fire Modelling Experiment (ICFME)

Stem DBHOB (cm)	ICFME Plot A				ICFME Plot 1				ICFME Plot 2[a]				ICFME Plot 3				ICFME Plot 4			
	Jack pine		Black spruce		Jack pine		Black spruce		Jack pine		Black spruce		Jack pine		Black spruce		Jack pine		Black spruce	
	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead
0	0	0	1590	106	0	32	2226	477	0	95	668	223	0	32	1844	32	0	127	1081	95
0.1–1.0	0	0	1007	53	0	32	731	32	0	0	413	95	0	0	382	0	0	95	159	0
1.1–2.0	0	53	583	0	0	95	1049	64	32	32	699	95	0	64	318	0	0	286	64	0
2.1–3.0	0	0	583	53	0	0	1622	95	0	95	318	64	0	223	0	32	32	254	32	0
3.1–4.0	0	218	436	0	0	128	925	32	0	17	458	68	106	566	0	0	36	978	36	0
4.1–5.0	0	145	218	0	96	160	542	32	17	102	255	17	248	637	0	0	290	507	0	0
5.1–6.0	73	145	145	0	0	128	383	0	17	85	102	0	389	283	0	0	290	145	0	0
6.1–7.0	0	73	73	0	96	287	223	96	17	34	85	0	496	177	0	0	543	181	0	0
7.1–8.0	0	218	0	0	32	32	160	0	51	68	34	17	814	71	0	0	616	36	0	0
8.1–9.0	73	145	0	0	255	64	0	64	85	0	17	17	708	35	0	0	688	0	0	0
9.1–10.0	218	73	0	0	223	160	0	32	119	119	17	0	496	71	0	0	616	36	0	0
10.1–11.0	290	0	0	0	191	64	0	0	136	17	0	0	354	0	0	0	471	36	0	0
11.1–12.0	218	0	0	0	223	32	0	0	187	34	0	0	460	0	0	0	580	36	0	0
12.1–13.0	218	0	73	0	128	0	0	0	136	17	17	0	248	0	0	0	217	36	0	0
13.1–14.0	363	73	0	0	319	32	0	0	102	34	0	0	71	0	0	0	72	0	0	0
14.1–15.0	218	0	0	0	160	0	0	0	85	0	17	0	71	0	0	0	36	0	0	0
15.1–16.0	145	0	0	0	223	0	0	0	102	17	0	0	0	0	0	0	36	0	0	0
16.1–17.0	218	0	0	0	96	0	0	0	102	17	0	0	0	0	0	0	0	0	0	0
17.1–18.0	218	0	0	0	64	0	0	0	51	0	0	0	0	0	0	0	0	0	0	0
18.1–19.0	0	0	0	0	0	32	0	0	34	0	0	0	0	0	0	0	0	0	0	0
19.1–20.0	73	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>20.1	0	0	0	0	32	0	0	0	102	0	0	0	0	71	0	0	0	0	0	0

[a]Plot 2 also includes a minor component of trembling aspen amounting to 17 stems/ha in both the 7.1–8.0 and 11.1–12.0 cm DBHOB classes.

APPENDIX 2 (continued)

Stem DBHOB (cm)	ICFME Plot 5				ICFME Plot 6				ICFME Plot 7				ICFME Plot 8				ICFME Plot 9			
	Jack pine		Black spruce		Jack pine		Black spruce		Jack pine		Black spruce		Jack pine		Black spruce		Jack pine		Black spruce	
	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead
0	0	286	3625	254	0	159	2448	636	0	159	1335	477	0	64	1876	1653	0	265	2968	159
0.1–1.0	0	0	1304	0	0	0	1176	95	0	0	636	32	0	0	954	64	0	53	1219	0
1.1–2.0	0	159	1749	0	0	95	1622	64	0	191	1017	191	0	64	986	32	0	265	2120	0
2.1–3.0	0	509	604	0	0	254	1494	32	32	382	827	64	0	159	1017	191	0	742	1113	106
3.1–4.0	76	758	227	38	39	466	660	621	72	323	503	144	36	292	984	36	114	627	228	0
4.1–5.0	152	720	190	76	117	388	738	427	36	359	288	0	0	292	1057	146	228	627	228	114
5.1–6.0	303	644	38	0	39	272	388	78	180	323	359	0	146	182	583	0	342	627	0	57
6.1–7.0	493	265	38	38	194	78	388	78	216	288	108	0	146	292	146	0	570	285	0	57
7.1–8.0	493	114	38	0	311	117	233	78	144	216	36	0	219	0	219	73	171	171	57	0
8.1–9.0	607	0	0	0	194	78	78	0	431	0	72	0	328	73	146	0	513	0	0	0
9.1–10.0	417	38	38	0	350	0	78	0	503	0	72	0	109	36	73	0	228	57	0	0
10.1–11.0	455	38	0	0	388	0	39	78	431	36	36	0	219	0	36	0	684	57	0	0
11.1–12.0	152	38	38	0	155	39	0	0	288	0	0	0	255	36	0	0	114	0	0	0
12.1–13.0	76	0	0	0	155	0	0	39	252	0	0	0	109	0	0	0	57	57	0	0
13.1–14.0	114	0	0	38	78	39	0	0	288	0	0	0	146	36	0	0	57	0	0	0
14.1–15.0	0	0	0	0	39	0	0	0	144	0	0	0	73	0	0	0	57	0	0	0
15.1–16.0	38	0	0	0	78	0	0	0	108	0	0	0	0	0	0	0	0	0	0	0
16.1–17.0	0	0	0	0	0	0	0	0	108	0	0	0	0	0	0	0	0	0	0	0
17.1–18.0	0	38	0	0	0	0	0	0	72	0	0	0	0	0	0	0	0	0	0	0
18.1–19.0	0	0	0	0	0	0	0	0	0	0	0	0	36	0	0	0	0	0	0	0
19.1–20.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>20.1	0	0	0	0	0	0	0	0	36	0	0	0	0	0	0	0	0	0	0	0

APPENDIX 2 (continued)

Stem height (m)	ICFME Plot A				ICFME Plot 1				ICFME Plot 2[a]				ICFME Plot 3				ICFME Plot 4			
	Jack pine		Black spruce		Jack pine		Black spruce		Jack pine		Black spruce		Jack pine		Black spruce		Jack pine		Black spruce	
	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead
≤1.0	0	0	1219	106	0	32	1272	413	0	64	382	223	0	0	1717	0	0	127	795	64
1.1–2.0	0	0	2014	53	0	32	2289	191	32	95	1081	95	0	64	763	32	0	223	445	32
2.1–3.0	0	0	477	53	0	32	1494	32	0	0	509	95	0	32	64	0	0	127	95	0
3.1–4.0	0	198	416	0	0	32	732	38	0	32	306	32	0	64	0	0	0	32	0	0
4.1–5.0	0	73	218	0	0	46	925	38	0	0	429	71	0	255	0	0	32	304	0	0
5.1–6.0	0	145	145	0	0	46	447	0	0	58	179	0	64	255	0	32	0	231	0	0
6.1–7.0	0	0	145	0	0	46	383	32	0	53	36	0	0	159	0	0	120	245	0	0
7.1–8.0	0	363	0	0	63	110	128	70	0	80	72	40	255	382	0	0	120	652	0	0
8.1–9.0	0	145	0	0	0	229	191	0	57	80	0	40	319	701	0	0	599	571	0	0
9.1–10.0	73	218	0	0	126	275	0	38	29	0	36	0	319	191	0	0	599	245	0	0
10.1–11.0	73	0	0	0	126	137	0	0	57	160	0	0	573	0	0	0	659	0	0	0
11.1–12.0	654	0	0	0	252	183	0	0	86	27	36	0	828	127	0	0	1198	0	0	0
12.1–13.0	363	0	0	0	566	46	0	38	314	80	36	0	573	0	0	0	779	0	0	0
13.1–14.0	581	0	73	0	314	0	0	0	342	27	0	0	701	0	0	0	359	0	0	0
14.1–15.0	436	0	0	0	252	0	0	0	114	27	0	0	446	0	0	0	60	0	0	0
15.1–16.0	145	0	0	0	252	0	0	0	200	0	0	0	255	0	0	0	0	0	0	0
16.1–17.0	0	0	0	0	126	0	0	0	86	0	0	0	64	0	0	0	0	0	0	0
17.1–18.0	0	0	0	0	0	0	0	0	29	0	0	0	64	0	0	0	0	0	0	0
18.1–19.0	0	0	0	0	63	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19.1–20.0	0	0	0	0	0	0	0	0	29	0	0	0	0	0	0	0	0	0	0	0
20.1–21.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
> 21.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

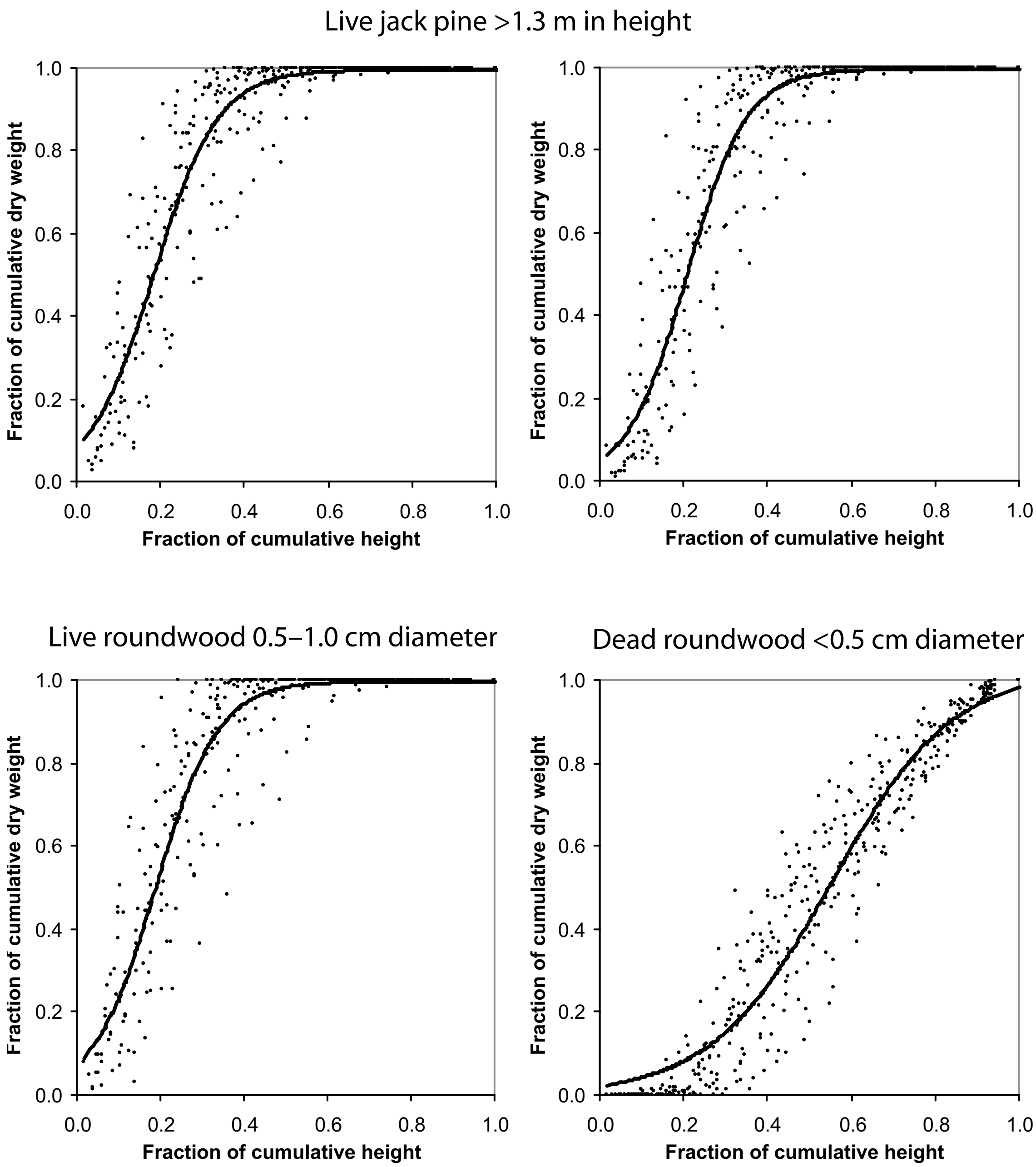
[a]Plot 2 also includes a minor component of trembling aspen amounting to 34 stems/ha in the 9.1–10.0 m height class.

APPENDIX 2 (concluded)

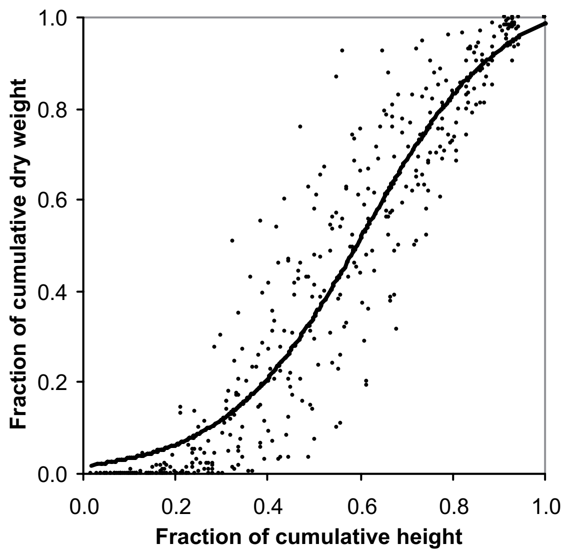
Stem height (m)	ICFME Plot 5				ICFME Plot 6				ICFME Plot 7				ICFME Plot 8				ICFME Plot 9			
	Jack pine		Black spruce		Jack pine		Black spruce		Jack pine		Black spruce		Jack pine		Black spruce		Jack pine		Black spruce	
	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead
≤1.0	0	254	2416	191	0	0	1431	445	0	95	572	477	0	64	1367	1463	0	265	2067	106
1.1–2.0	0	234	3847	64	0	127	3148	350	0	254	1971	159	0	32	1876	386	0	212	3603	106
2.1–3.0	0	127	827	0	0	95	1463	32	0	32	858	95	0	32	922	95	0	53	1431	53
3.1–4.0	0	101	418	114	0	95	901	155	0	127	686	72	0	32	859	105	0	106	403	85
4.1–5.0	0	291	152	0	0	68	913	78	32	256	327	104	0	101	1304	109	95	636	171	0
5.1–6.0	138	328	152	38	0	342	595	155	0	64	546	0	0	132	573	36	95	167	171	0
6.1–7.0	69	275	0	38	122	274	372	155	0	225	164	0	0	238	382	0	0	228	0	0
7.1–8.0	207	964	76	0	61	68	149	155	0	386	55	0	70	207	223	0	190	570	0	142
8.1–9.0	207	482	0	0	183	411	74	0	72	451	55	0	210	413	318	0	190	570	0	0
9.1–10.0	620	138	0	0	244	137	297	0	216	129	55	0	351	138	64	0	285	570	85	0
10.1–11.0	207	69	0	0	122	68	0	0	719	129	0	0	210	69	0	0	380	228	0	0
11.1–12.0	895	69	0	0	244	0	0	0	359	129	0	0	421	69	127	0	380	0	0	0
12.1–13.0	413	69	0	0	610	0	0	0	575	0	0	0	210	0	64	0	570	114	0	0
13.1–14.0	482	69	0	0	244	68	0	0	719	0	0	0	210	0	0	0	475	114	0	0
14.1–15.0	138	69	0	0	61	0	0	0	216	0	0	0	140	0	0	0	190	0	0	0
15.1–16.0	0	0	0	0	61	0	0	0	216	0	0	0	0	0	0	0	190	0	0	0
16.1–17.0	0	69	0	0	61	0	0	0	72	0	0	0	0	0	0	0	95	0	0	0
17.1–18.0	0	0	0	0	0	0	0	0	144	0	0	0	0	0	0	0	0	0	0	0
18.1–19.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19.1–20.0	0	0	0	0	61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20.1–21.0	0	0	0	0	61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>21.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX 3

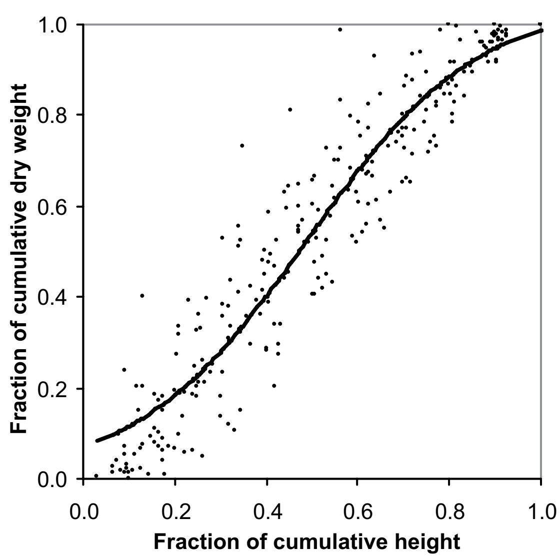
Fraction of Cumulative Dry Weight for the Various Crown Fuel Components against Fraction of Cumulative Height for Jack Pine and Black Spruce Trees Destructively Sampled in the Main Study Area of the International Crown Fire Modelling Experiment (diameter size classes are actually <0.50 and 0.50–0.99)

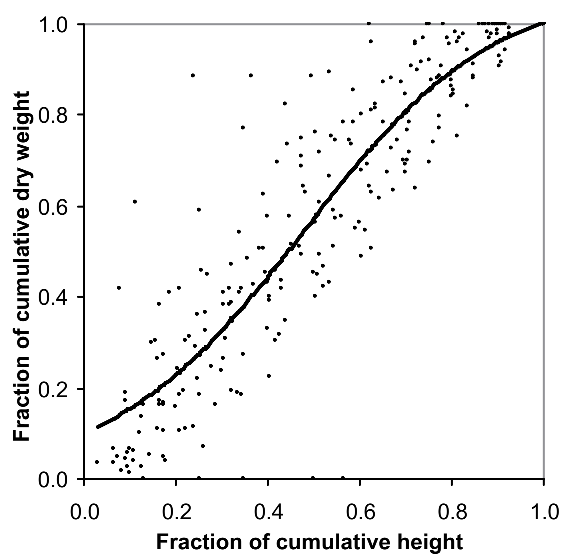


Dead roundwood 0.5–1.0 cm diameter



Dead jack pine >1.3 m in height





APPENDIX 3 (concluded)