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THE UNIVERSITY OF ALBERTA

EQUATIONS FOR ESTIMATING STANDING LIVE WHITE SPRUCE AND LODGEPOLE PINE FUELS IN ALBERTA

by

ALLEN F. JOHNSON

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF FOREST SCIENCE

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THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled EQUATIONS FOR ESTIMATING STANDING LIVE WHITE SPRUCE AND LODGEPOLE PINE FUELS IN ALBERTA submitted by ALLEN F. JOHNSON in partial fulfilment of the requirements for the degree of Master of Science in Forest Science.

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ABSTRACT

Equations were developed to predict the oven-dried weight of the total crown; live crown; foliage; and roundwood diameter classes: 0.0-0.5, 0.5-1.0, 1.0-3.0, 3.0-5.0, 5.0-7.0 and 7.0-10.0 cm for lodgepole pine (n=27) and white spruce (n=24). Sampling occurred throughout Alberta, Canada. Sampled tree diameters ranged from 5 cm to 50 cm for lodgepole pine and from 5 cm to 65 cm for white spruce. The non-linear allometric equation ($Y = a X^b$) best modeled the relationships when diameter at breast height (1.3m height;DBH) was used as the independent variable (X). Most values for the standard error of the estimate were calculated to be less than 40 percent of the mean. For the total crown, live crown and roundwood diameters from 0.0-3.0 cm, most empirical r^2 values were greater than 0.80.

If large scale aerial photographs are available and accurately interpreted, these dependent weights can be predicted using the equation: $\text{WEIGHT} = a\ \text{HEIGHT}^b \times$ approximate CROWN WIDTH^c. The approximate crown width (aCW) was measured by summing the length of the branch which had the longest horizontal projection as seen from below, the stem diameter and the length of the opposite branch at the same whorl. Based on SEE and R^2 values, this model performs nearly as well as the DBH-based model; suggesting the feasibility of using large scale aerial photographs to predict biomass by most of these roundwood diameter classes.

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The work of my very capable field assistant Mr. Dave Roth is greatfully acknowledged.

Finally I thank my wife, Lee Anne, for her patience.

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1. GENERAL INTRODUCTION

Fire management decisions are based on information of how fuel, weather and topography for specific land units will affect plant growth and biomass accumulation. Live and dead plant biomass in forest stands are commonly referred to as forest fuel. Both fuel conditions will contribute to the spread and intensity of a forest fire, although dead fuel usually requires less energy to maintain flaming combustion.

Fuel is usually stratified by its vertical position (ground, surface or aerial) and by its condition (live or dead) (Brown and Davis 1973). The vertical arrangement directly affects crown fire potential (Pyne 1984), and would be of immense value in assessing fire hazard (Brown and Davis 1973) or evaluating fuel management alternatives (Alexander 1987). Regardless of its position in the fuel strata, plant biomass is flammable and will contribute to the spread and intensity of an ongoing fire.

Fire behavior models have been developed which enable foresters to predict how fires will behave under various conditions of fuel, wind, and slope (Rothermel 1983; Lawson et al. 1985). Yet, only the fuel variable can be manipulated or managed before a forest fire begins. Hence, a large amount of research has been dedicated to finding ways of quantifying the weight of this material.

Mathematical models (equations) exist for estimating the weight of ground fuels, commonly referred to as duff (McRae et al. 1979; Woodard and Martin 1980). These models are usually based on regression relationships between duff depth and weight. Standard procedures are available in Canada for field sampling downed and dead roundwood surface fuels (Van Wagner 1965, 1968, 1982). Also many models have also been developed which predict the amount of biomass in standing live trees (Kiil 1967, 1968; Johnstone and Peterson 1980; Singh 1982, 1986; Delisle 1986). These models are particularily valuable because they allow managers to easily predict fuel loadings when developing forest management plans. Knowledge of fuel loading is necessary for developing: pre-suppression preparedness plans, fuel manipulation plans, prediction of fire behavior and effects, assessment of fire potential within 'high values at risk' areas of a forest, and the evaluation of silvicultural options (Roussopoulos and Johnson 1975; Sackett 1979).

Once trees have been felled, surface fuel loadings will dramatically increase because of the deposition of once standing live fuels (Howard and Ward 1972). The weight of this slash by nationally recognized and accepted roundwood diameter classes can be measured using widely accepted procedures developed by Van Wagner (1965, 1968, 1982) and McRae et al. (1979). Yet, these procedures for estimating slash residue in cutblocks are extremely tedious and time consuming for inventory crews (McRae *et al*. 1979).

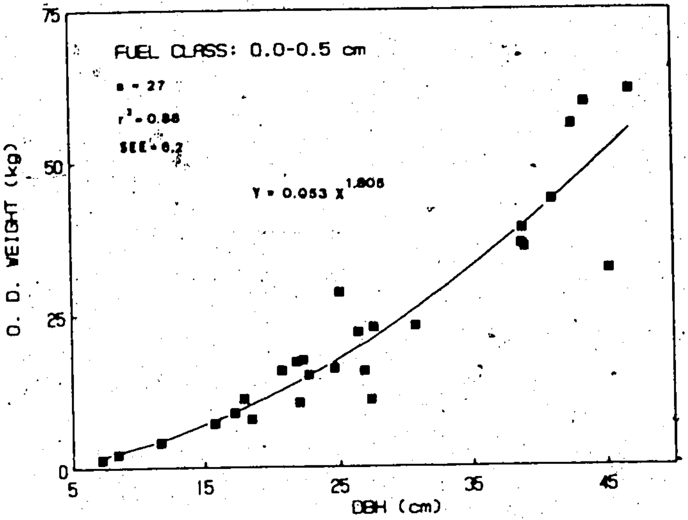
Therefore, the two objectives of this study were:

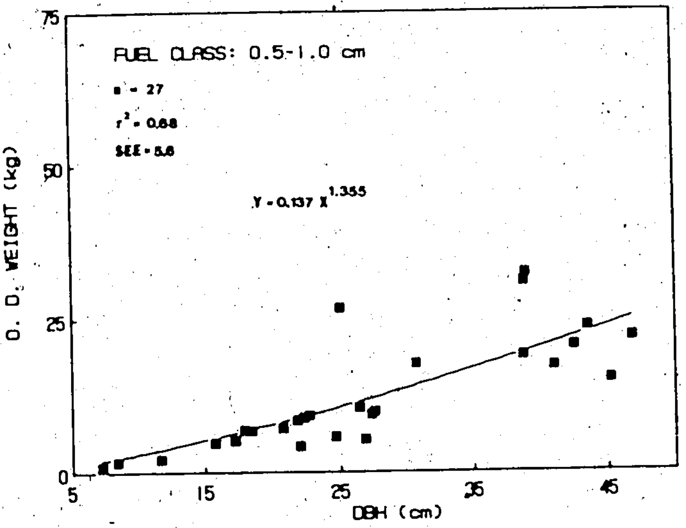
(1) To evaluate the relationship between the total crown fuel weight or individual roundwood diameter class fuel weights using tree stem characteristics such as diameter at breast height which is easily and commonly measured during ground field surveys.

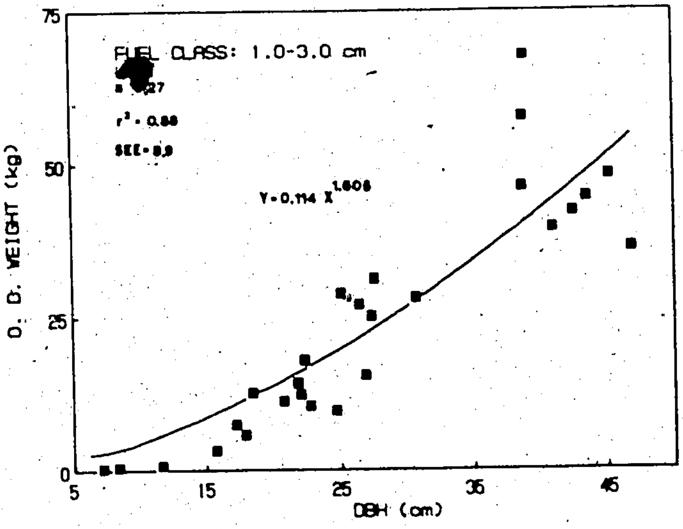
(2) To evaluate the relationship between the total crown fuel weight or individual roundwood diameter class fuel weights using tree stem characteristics such as total height and approximate crown width which can be interpreted from large-scale aerial photographs.

This thesis is composed of four chapters. Chapter 1 introduces the study area, describes the methods used in selecting sample trees, and outlines the field and lab procedures used. Chapters 2 and 3 pertain respectively, to the two objectives listed above. Chapter 4 is a summary of all the material presented and includes a section outlining future research needs.

LODGEPOLE PINE







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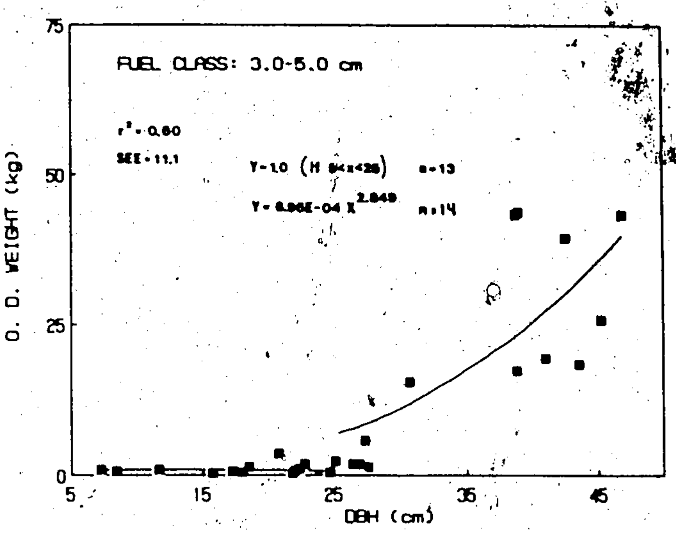
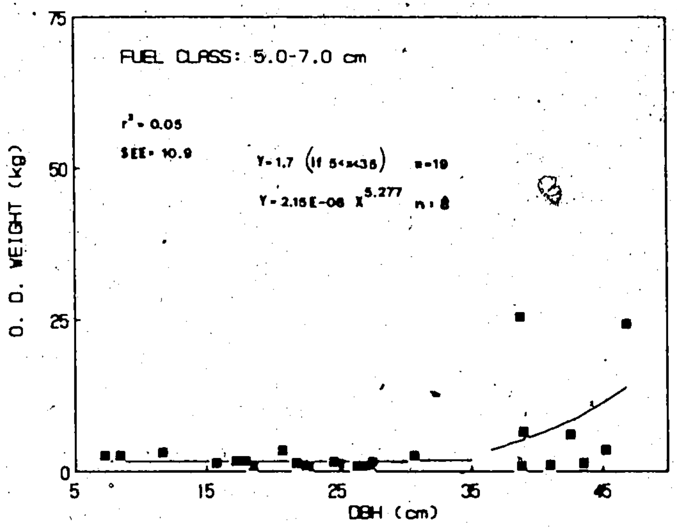
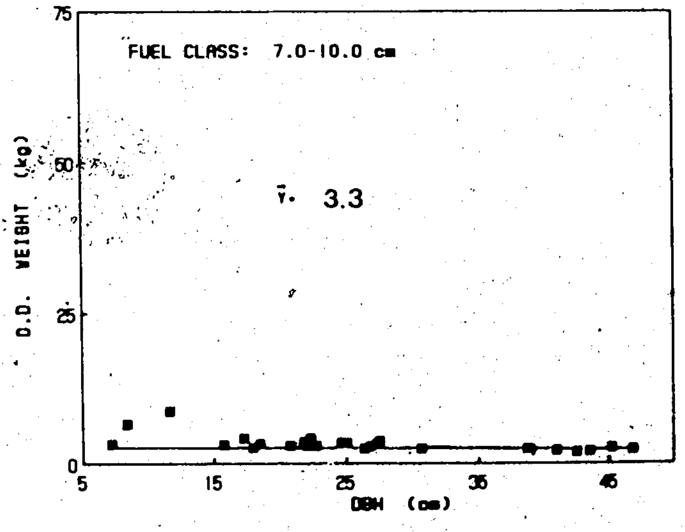


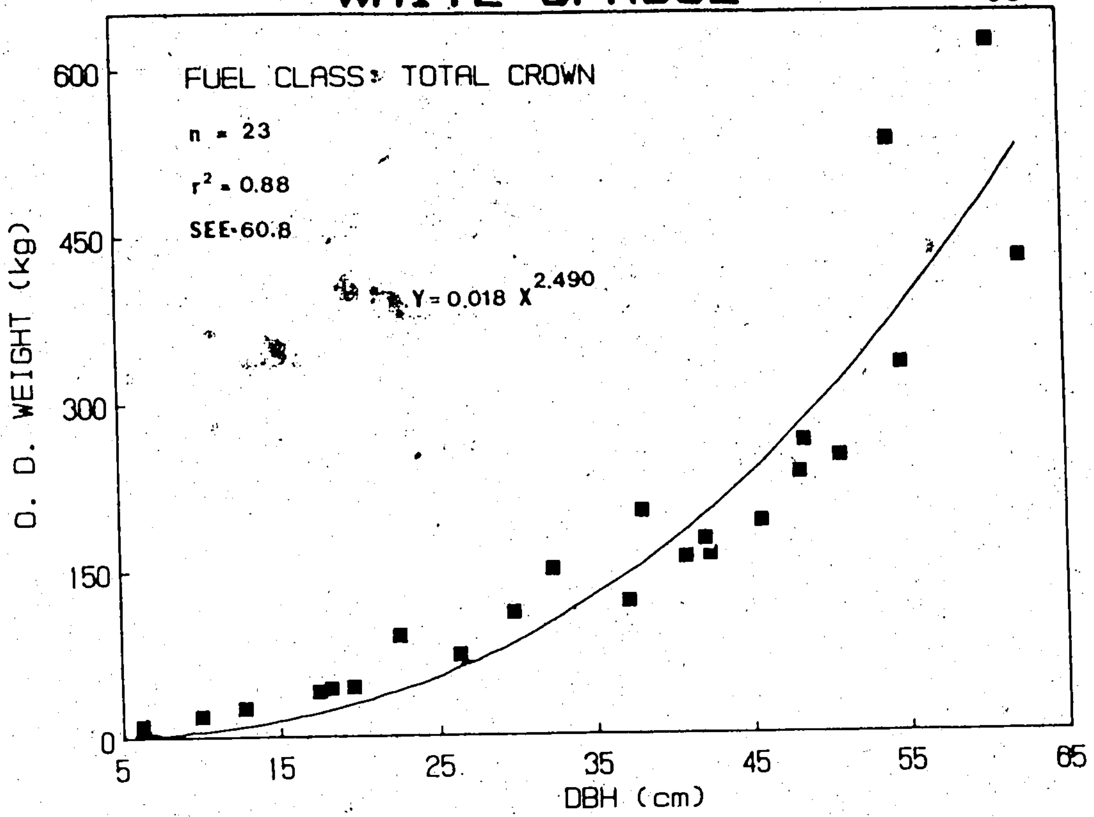


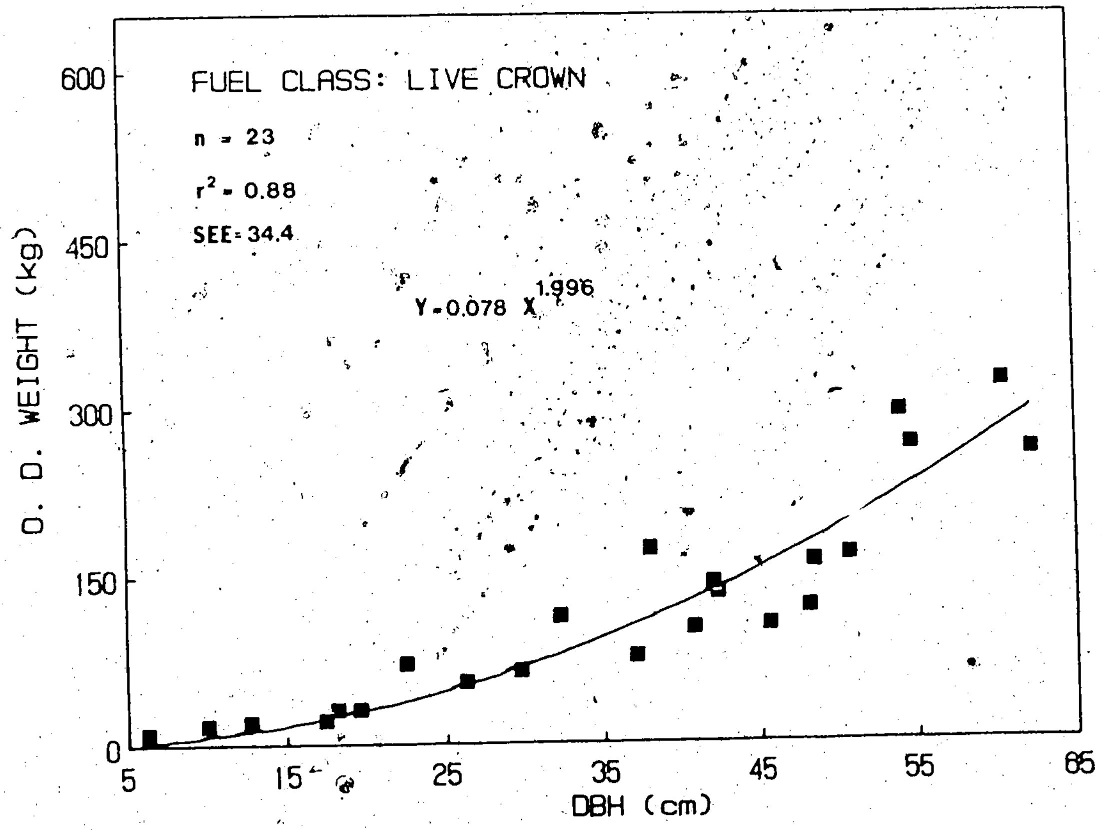


APPENDIX IV

WEIGHT EQUATIONS FOR WHITE SPRUCE FUELS BASED ON DBH.

WHITE SPRUCE





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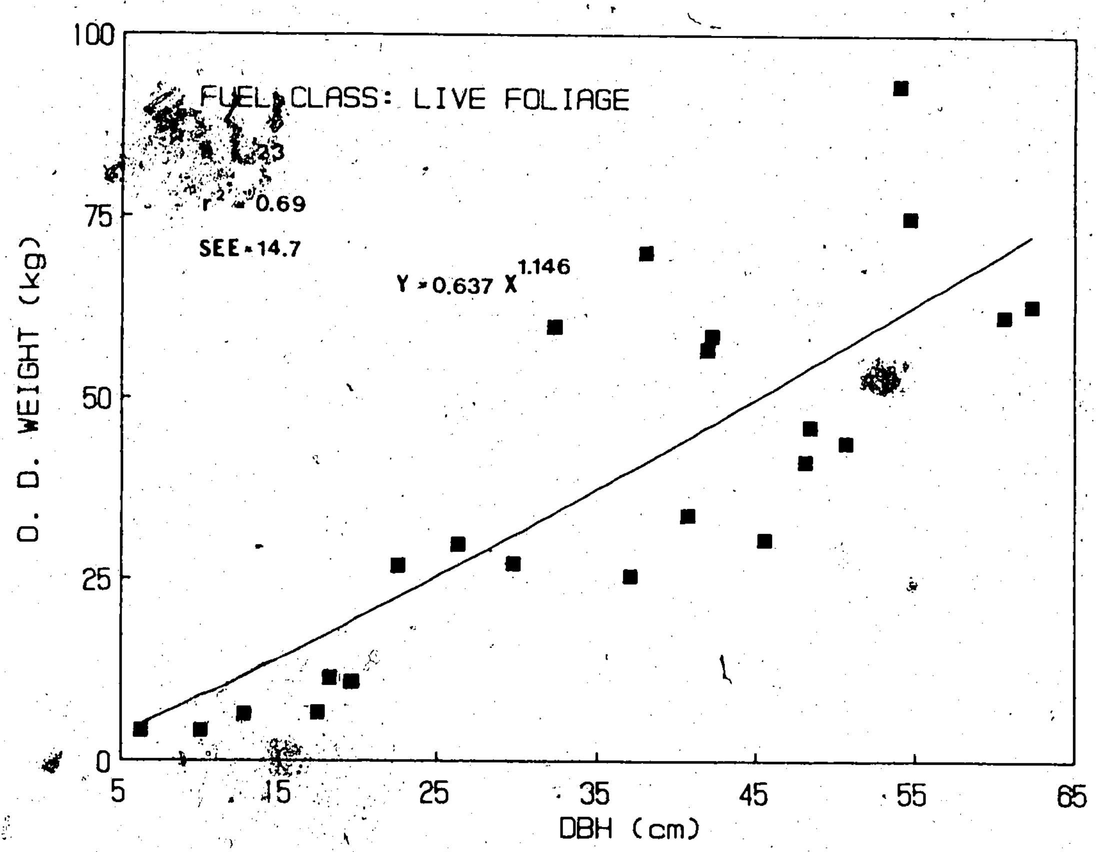

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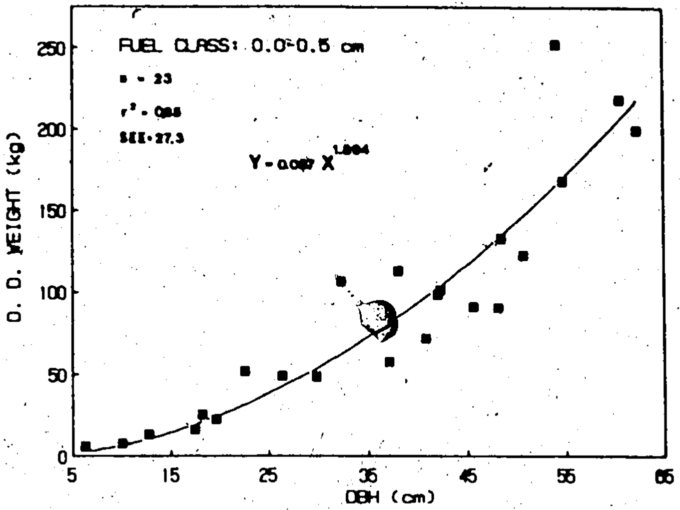
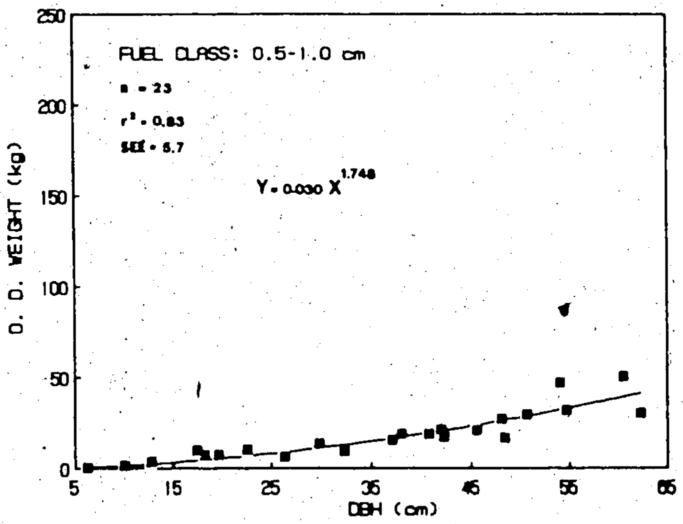
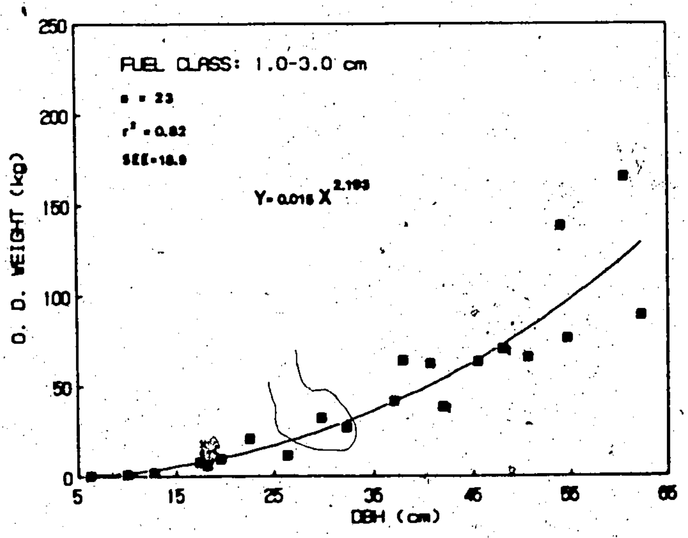
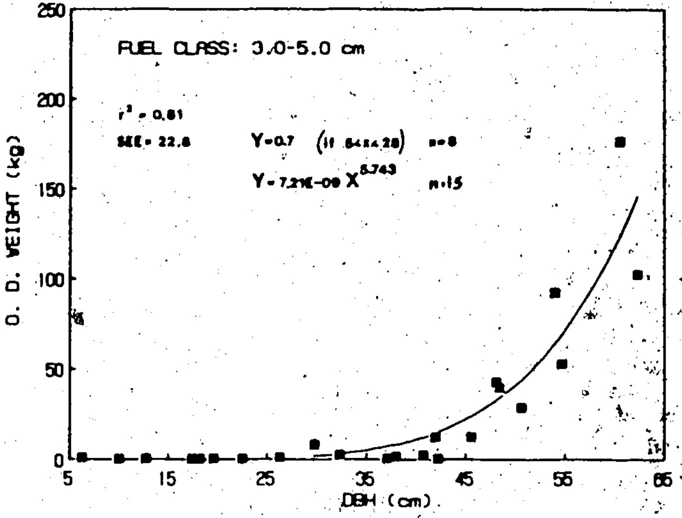
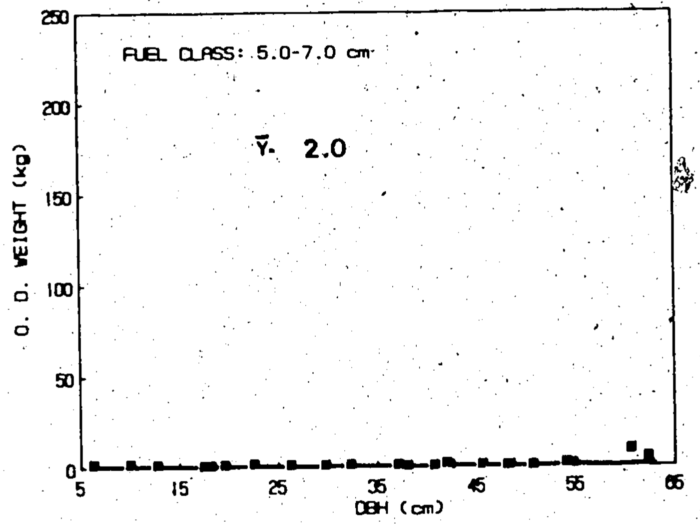


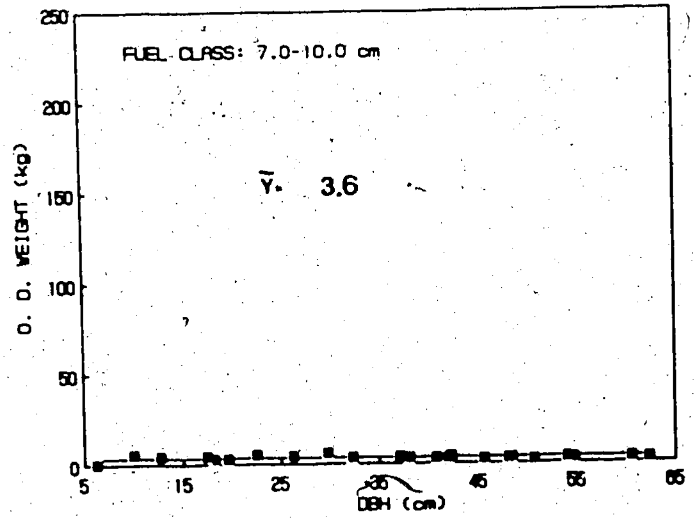




WHITE SPRUCE





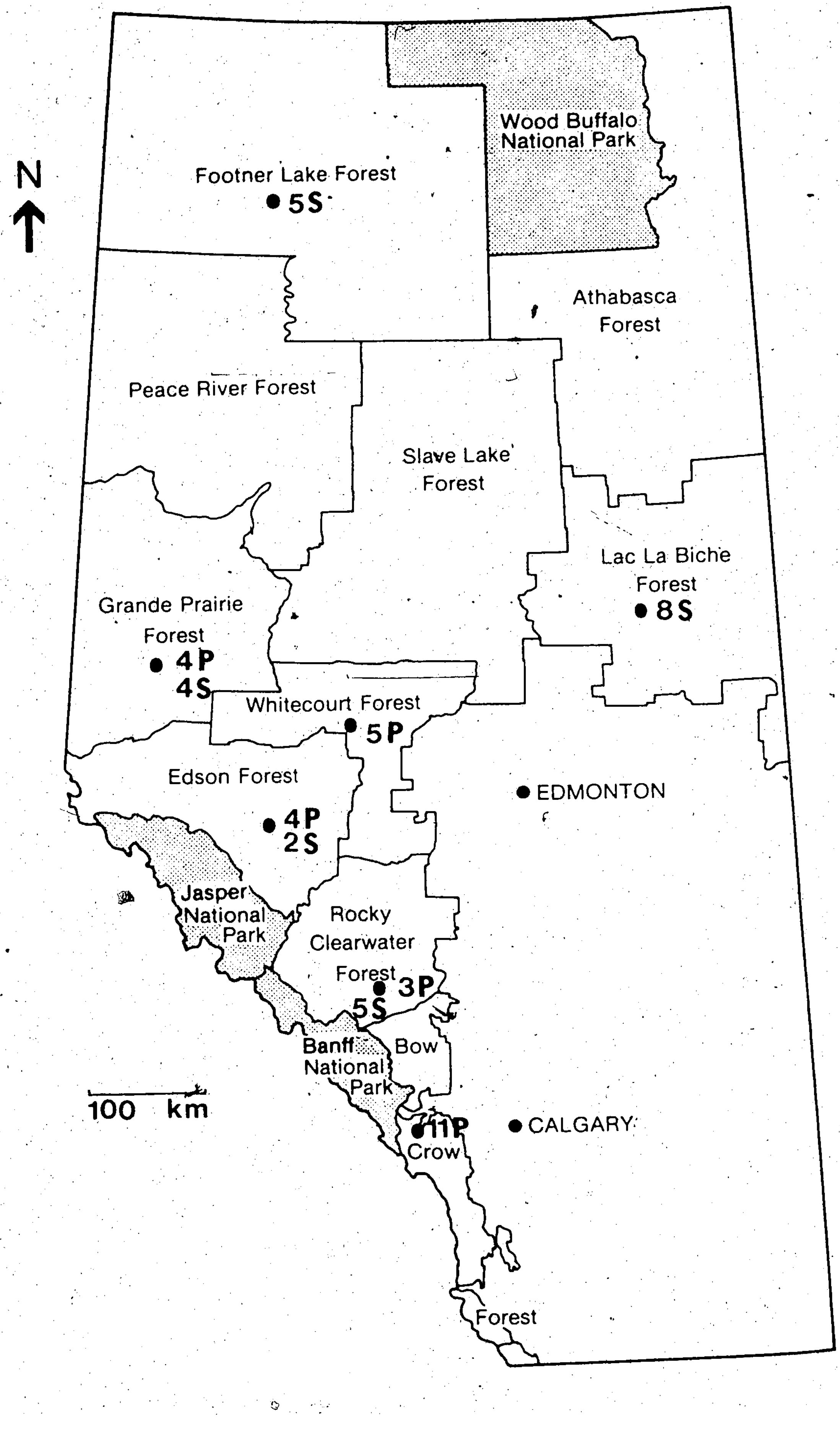


1.1 STUDY AREA

Sampling occurred within the 'Mixedwood section' and the 'Foothills section' of the Boreal Forest Region, and within the Subalpine Forest Region (Rowe 1972). Sample trees were selected from within the following provincial forests: Footner Lake, Grande Prairie, Lac La Biche, Whitecourt, Edson, Rocky Clearwater and Bow-Crow. The number of trees sampled by species and location are shown in Figure 1.

The physiography, soils and climate of the study area have been summarized in the Atlas of Alberta (Government of Alberta and the University of Alberta 1969). Soils are generally Grey Luvisols (Rowe 1972). The annual precipitation ranges from 360 mm to 610 mm (Stashko 1971a). Temperatures throughout the sample area vary from 11 °C to 17 °C during July and information pertaining to other mean monthly temperatures between May to September have been summarized by Stashko (1971b). Trees within the sampled area typically experienced fewer than 120 frost-free days per year. The ecological conditions for the ecoregions where sampling was conducted have been described by Strong and Leggat (1981).

Figure 1.1.1 Location of number of trees sampled by species in Alberta, Canada.
(P=lodgepole pine, S=white spruce).


N
Wood Buffalo National Park
Footner Lake Forest
5S
Athabasca Forest
Peace River Forest
Slave Lake Forest
Lac La Biche Forest
8S
Grande Prairie Forest
4P
4S
Whitecourt Forest
5P
Edson Forest
4P
2S
EDMONTON
Jasper National Park
Rocky Clearwater Forest
3P
5S
Banff National Park
Bow
100 km
11P
Crow
CALGARY
Forest

1.2 METHODS

1.2a SAMPLING DESIGN

No attempt was made to continuously sample all DBH classes throughout the complete range of diameters common to both species in Alberta. The time required to replicate samples within all classes across the complete range of dbh's found in Alberta prohibited such an approach. Singh (1986) reported that variation even among Prairie provinces was not large and that data from different provinces can be used to develop one predictive equation for entire regions. Instead, samples were taken within each of five diameter classes (5-15 cm, 15-25 cm, 25-35 cm, 35-50 cm, and 50-65 cm) (Table 1.2.1). The distribution of the data used in this study was greatly affected by sample time constraints. White spruce trees larger than 30 cm required more than one day to measure fresh weight by roundwood diameter class. Smaller trees were sampled when the field time remaining in any one forest was insufficient to completely process a large tree. Hence, the number of trees within the five DBH ranges are not equal and a rigorous test of variation among five different forests within the province were samples were collected for each species is unavailable.

Table 1.2.1 Distribution of samples by dbh class.

	DBH Classes (cm)					
	5-15	15-25	25-35	35-50	50-65	Total
LODGEPOLE PINE	3	10	6	8	0	27
WHITE SPRUCE	3	4	3	8	5	23

Selecting Stands

Sample stands with 'Good' site indices as identified on Alberta Phase 3 Forest Inventory maps [S.I.= 18 metres (reference age 50 years at breast height) (Anon 1985)] were the only stands selected in this study . However, after felling and processing, five lodgepole pine and one white spruce clearly did not grow at this rate. These six samples may have contributed to the magnitude of variation within a DBH class but each is part of the population of inference and should not be removed from the data set.

Selecting Trees

An individual tree with approximately average stand DBH was selected for sampling if it: (1) was dominant or codominant in crown position; (2) was not open grown or a 'wolf' tree; (3) was uniform in the crown shape; and (4) showed no visible signs of deformity as a result of disease, defoliation, past fire scar or broken top (Brown 1976). Only one or two trees were selected from within any one stand.

This selection criteria provides forest managers with the 'worst case' crown fuel weight condition to be experienced in a forested area. No attempt was made to randomly sample trees for the purpose of understanding the magnitude of variation within the total population. The population of inference would therefore be dominant crown class trees, without deformities, growing in 'good' stands.

A purely random sampling would provide average fuel weight conditions of the crown and would therefore underestimate the crown fuel hazard on good sites which generally accumulate more biomass on the same size tree. Forest managers using average weights may predict a surface fire with some torching of tree crowns (when in fact the fire behavior may be a sustained crown fire on more productive sites). Conversely, forest managers using 'worst case' weights may predict a sustained crown fire (when in fact the fire behavior may be a surface fire with some torching of tree crowns on less productive sites). I believe the latter scenario would be preferred by most forest managers. Therefore, the scope of this study was directed toward satisifying the need for 'worst case' crown fuel weights, by roundwood diameter classes of interest to the provincial forest fire agency.

1.2b FIELD PROCEDURES

Tree Measurements

Sample trees were selected and the following measurements were recorded for each tree prior to felling: (1) diameter at breast height (DBH ±0.1 cm), (2) diameter at base of live crown (±0.1 cm), and (3) approximate crown width [by measuring the length of the branch which had the longest horizontal projection as seen from below + the length of branch opposite to it on the same whorl + the stem diameter at this height] (±0.1 m). While these branches were not always horizontal, each did not deviate greatly from being perpendicular to the stem, and I believe that this procedure is an approximate measure of crown width as would be seen from above on an aerial photograph.

After felling, the following measurements were recorded: (4) stump diameter at 0.3 m above mean ground level (±0.1 cm), (5) height to live crown (±0.1 m), and (6) total tree height (±0.1 m).

Weight Measurements

Sample trees less than 15 cm DBH were felled directly onto tarps, then delimbed. Larger trees were climbed and delimbed to a 10 cm top before felling (Brown 1976). Beginning at the base of the sample tree, all live and dead branches were cut using a hand saw. One out of every fourth branch in sequence was then placed on a separate tarp for further analysis. This subsample of both dead (not supporting live foliage) and live (supporting live foliage) roundwood was then stratified by the following roundwood diameter classes: 0.0-0.5 cm, 0.5-1.0 cm, 1.0-3.0 cm, 3.0-5.0 cm and 5.0-7.0 cm (Van Wagner 1982). In addition, roundwood between 7.0 and 10.0 cm diameter was also weighed. Both the stratified and remaining unstratified sample of roundwood was weighed (± 0.1 kg) using a portable spring scale. Results of this sampling procedure and the efficiency of this method are discussed in Appendix I.

For each tree five randomly selected, fresh biomass samples within each roundwood diameter class for both live and dead wood were collected in sealed plastic bags of known weight. The remaining tree biomass greater than 10 cm diameter was not weighed. In a logging operation, this material would be utilized and hence would not be left as residue on the cutover site. Left standing, this material would not be consumed during the torching of individual crowns in a crown fire.

1.2c LABORATORY PROCEDURES:

The five fresh moisture content samples for each diameter class were weighed (± 0.01 g) using a top-loading balance, placed in paper bags of known weight, and oven-dried at 70 °C in a portable oven to a constant weight (Moir and Francis 1972). Fresh roundwood samples with live foliage attached were also oven-dried using these procedures. After drying, the foliage was separated from the twigs by hand and the separate weights of foliage and branchwood were recorded. Oven-dried weights were determined using the following two formulas:

$$MC = (FW-ODW) / ODW * 100 \qquad [1]$$

$$ODW = FW / (1+MC/100) \qquad [2]$$

where: MC = moisture content (percent)

FW = fresh weight (kg)

ODW = oven-dried weight (kg)

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2. LODGEPOLE PINE AND WHITE SPRUCE CROWN FUEL WEIGHTS PREDICTED FROM FROM DIAMETER AT BREAST HEIGHT

2.1 INTRODUCTION

Standing live biomass is recognized as potential fuel in forest stands (Brown and Davis 1973). Many authors have presented equations or tables which predict standing biomass for most tree species in Alberta (Kiil 1967, 1968; Stanek and State 1978; Johnstone and Peterson 1980; Singh 1982, 1986; Delisle 1986). A variety of independent variables have been used for this purpose; typically: basal stem diameter, diameter at breast height (DBH), and total height. Unfortunately, except for Delisle (1986), most of these authors have not attempted to predict fuel weights by the roundwood diameter classes now desired by forest fire agencies in Canada, and Delisle's equations only pertain to juvenile trees ≤ 3 m in height.

The objective of this study was to develop equations that would predict: the total crown fuel weight, live crown fuel weight, foliage weight, or individual roundwood diameter class fuel weights for mature lodgepole pine (*Pinus contorta* Loudon var. *latifolia* Engelm.) and white spruce (*Picea glauca* (Moench) Voss var. *albertiana* (S. Brown) Sarg.)[1].

---

[1] Moss (1983) is the botanical authority for this work.

2.2 METHODS

Oven-dried weight of the total crown, live crown, live foliage and individual roundwood diameter class components of the total crown were the dependent variables evaluated. An initial screening of the correlation between all these weights and all the independent variables measured was completed using an SPSSx package (Nie 1983).

DBH was selected as the primary variable because: (1) it had reasonable correlation with the dependent variables determined in this study and historically DBH accounts for most of the total variation in many biomass studies of different species (Stanek and State 1978), (2) it is easily and accurately measured in the field, and (3) it is [illegible] variable consistently sampled in many forest inventories (Anon 1985). Multiple linear regression equations describing the relationship of total crown weight, live crown weight or individual roundwood class weights were developed and tested for a variety of independent variables including DBH, DBH^2, and DBH^3. Non-linear models were also evaluated using BMDP interative non-linear least squares packages (Dixon and Brown 1979) to derive predictive allometric ($Y = a X^b$) equations, and two DBH-based growth functions .. An empirical r^2 value [1-(SSresidual/SStotal)] (Steel and Torrie 1980), was calculated to indirectly measure the 'quality' of each non-linear equation. The standard error of the estimate and a residuals plot were used directly.

2.3 RESULTS

The strong relationship between total crown fuel weight, live crown fuel weight or fuel weight by roundwood diameter class and DBH has been reviewed by Stanek and State (1978). Strong linear correlation between roundwood diameter class fuel weights has also been demonstrated for stem diameter at the base of the live crown, total height and crown width. This matrix is displayed in Appendix II. The curvilinear allometric model $Y = a\,DBH^{b}$ was selected as the model that best fit the distribution of the data for total crown weight, live crown weight, foliage weight, and fuel weight by roundwood diameter classes.

The equation, the r^2 value, the standard error of the estimate (SEE), the mean of predicted Y, and the SEE as percent of that mean (SEE%) for each allometric relationship are presented in Table 2.3.1 for lodgepole pine, and in Table 2.3.2 for white spruce crown weights.

The r^2 values for each of the DBH to dependent weight relationship evaluated ranged from 0.88 to 0.05 for lodgepole pine and from 0.88 to 0.69 for white spruce. Most equations have r^2 values greater than 0.80 and the poorer linear relationships between predicted and observed values are usually associated with larger roundwood diameter classes. Corresponding SEE values were about 30 percent of each mean. Predictive weight regression curves for total crown, total live crown, foliage, and individual roundwood diameter classes 0.0-0.5 cm, 0.5-1.0 cm, 1.0-3.0 cm, 3.0-5.0 cm, and 5.0-7.0 cm are presented in Appendix

III for lodgepole pine, and Appendix IV for white spruce. The 7.0-10.0 cm class roundwood was composed of only stemwood and a mean of 3.3 kg for lodgepole pine or 3.6 kg for white spruce is presented as the best estimate of this material because of the lack of observations which consisted of both stemwood and branchwood and no curvilinear distribution of the data was therefore evident.

TABLE 2.3.1 Lodgepole pine equations for estimating the oven-dried crown weight components (kg) from diameter at breast height (DBH; cm).

WEIGHT	allometric coefficients(*) a	b	n	r^2	SEE	$\bar{Y}$	SEE%
TOTAL CROWN	0.1744	1.8127	27	0.88	20.8	77.1	27.0
LIVE CROWN	0.1669	1.7020	27	0.82	15.8	50.6	31.2
FOLIAGE	0.0525	1.6057	27	0.83	3.3	11.4	28.8
0.0-0.5 cm	0.0533	1.8052	27	0.88	6.2	23.0	27.0
0.5-1.0 cm	0.1369	1.3553	27	0.68	5.6	12.3	45.6
1.0-3.0 cm	0.1140	1.6047	27	0.88	8.9	23.9	37.3
3.0-5.0 cm	use the mean value if DBH < 25 cm:					1.0	
	6.95E-04	2.8488	14	0.60	11.1	20.0	55.4
5.0-7.0 cm	use the mean value if DBH < 35 cm:					1.7	
	2.15E-08	5.2771	8	0.05	10.9	8.7	125.5
7.0-10.0 cm	use the mean value:					3.3	

Where:

(*)	Equation in the form: $WEIGHT = a\ DBH^b$
SEE	Standard error of the estimate (kg).
$\bar{Y}$	Mean of the estimated and observed weight (kg).
SEE%	SEE expressed as percent of the mean.

TABLE 2.3.2 White spruce equations for estimating the oven-dried crown weight components (kg) from diameter at breast height (DBH; cm).

	allometric coefficients(*)						
WEIGHT	a	b	n	r^2	SEE	$\bar{Y}$	SEE%
TOTAL CROWN	0.0181	2.4896	23	0.88	60.8	186.4	32.7
LIVE CROWN	0.0782	1.9961	23	0.88	34.4	120.0	28.7
FOLIAGE	0.6373	1.1457	23	0.69	14.7	38.5	38.2
0.0-0.5 cm	0.0869	1.8938	23	0.85	27.3	89.6	30.4
0.5-1.0 cm	0.0304	1.7481	23	0.83	5.7	18.1	31.3
1.0-3.0 cm	0.0150	2.1929	23	0.82	18.9	47.9	39.5
3.0-5.0 cm	use the mean value if DBH < 28 cm:					0.7	
	7.21E-09	5.7425	15	0.81	22.8	38.3	59.4
5.0-7.0 cm	use the mean value:					2.0	
7.0-10.0 cm	use the mean value:					3.6	

Where:

(*)	Equation in the form: $WEIGHT = a\ DBH^{b}$
SEE	Standard error of the estimate (kg).
$\bar{Y}$	Mean of the estimated and observed weight (kg).

2.4 DISCUSSION

A nonlinear model with untransformed, unweighted data was used to determine the coefficients for each equation. Some equations presented had increasing error variance, or a few observations on a residuals plot (differences between the actual and the predicted values) were more isolated from their predicted values. However, a weighting scheme to make the variance less unequal was not performed because a weighting technique may reduce a model's ability to be used for accurate predictive purposes for its entire DBH range (Comerford and Leaff 1982a, 1982b), and may result in only a slight reduction in the standard error of estimate (Alban and Laidly 1982). A weighted least-squares method of regression analysis has been shown to be useful for reducing heteroscedasticity (inequality of variances among samples) in forest tree biomass studies (Schreuder and Swank 1971, 1973). This procedure has a tendency to provide a better fit for the smaller, less variable sized trees and to 'force' a poorer fit for larger, more variable sized trees. Comerford and Leaff (1982a, 1982b) suggested this characteristic would produce undesirable equation coefficients if accurate predictions of larger trees are also required. In studies of juvenile trees, a weighted predictive equation will generally estimate smaller tree biomass with higher accuracy than the unweighted regression equation (Smith _et_ al. 1986); however, they predicted negative weights for unmerchantable (< 10 cm) boles of spruce trees >25 cm DBH with a weighted equation, and demonstrated that an unweighted equation provided much greater predictive accuracy of foliage and roundwood in the class 2.5 to 7.6 cm for trees >18 cm DBH.

The allometric model ($Y = a\ DBH^{b}$) was selected because each equation for total crown weight, live crown weight, foliage weight, or roundwood class weight provided logical predicted values over the entire range of DBH studied and the plots of residuals and SEE were reasonable. As with all non-linear systems, an exact significance test of each coefficient can not be completed in the same manor as linear systems. A log/log transformation was not completed because the statistics generated from these coefficients are unique to the linear transformed equation and can not be applied to the non-linear system, and (2) logarithmic bias is created during retransforming back to arithmetic units which results in a systematic under-estimation of weight (Zar 1968) unless efforts are made to correct for this error (Baskerville 1972).

Every model evaluated failed to provide reasonable predictions for the roundwood diameter classes: 3.0-5.0 cm, 5.0-7.0 cm and 7.0-10.0 cm. This is perhaps because only the largest trees of each species had any branchwood in these classes. Therefore, the allometric equations could not be used to adequately predict the weight of fuels in these diameter classes. The observed weights were not distributed in a curvilinear pattern for the entire range of tree sizes. For smaller trees, biomass in these classes came only from small amounts of bole or stem material. The mean weight of each roundwood class should therefore be used as the best available estimate of weight. For example, the 13 lodgepole pine trees <25 cm DBH had only stem material in the 3.0-5.0 cm roundwood class and a constant of 1.0 kg was the mean observed weight. However, for the 14 pine trees ≥25 cm DBH, the 3.0-5.0 cm roundwood class was composed of stemwood and branchwood and a separate allometric equation was used to predict the curvilinear relationship of the observed roundwood diameter class weight for these larger trees.

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3. LODGEPOLE PINE AND WHITE SPRUCE CROWN FUEL WEIGHTS PREDICTED FROM HEIGHT AND APPROXIMATE CROWN WIDTH

3.1 INTRODUCTION

Foliage weight, individual roundwood diameter size class weights, and live crown weight are components of interest in the total crown weight of individual standing live trees. Knowledge of these components is essential in forest fire research and in developing fuel and fire behavior prediction models in forestry. Tree species, height, diameter, stocking, volume and biomass information of stands delineated on aerial photographs during the course of typical forest inventories have generally been acquired from ground plots. Equations or models to estimate biomass of forest trees and undergrowth shrubs are proliferating (Stanek and State 1978). Some equations derived from single locations are used for interpreting intensive stand dynamics (Barney _et al._ 1978) while other equations derived from broader data bases are used in strategic studies of extensive areas (Alban and Laidly 1982).

Tree diameter at breast height (DBH), or stem basal area are often used as the primary independent variables when crown fuel weight equations are developed from ground plot data. For linear or non-linear equations, DBH will usually account for more sampling variation than any other stem variable measured. Brown (1976) had some success with using height as a single independent variable in predicting live crown weights of lodgepole pine. Young and Carpenter (1967) also had success with using height in fitting component weights of red spruce trees in Maine. However, Gary (1976) had poor success in predicting needle and branchwood weights of lodgepole pine when height or crown width was used as the independent variable. Equations not dependent on DBH as the primary independent variable seem best suited to juvenile trees or understory species.

The measurement of independent variables during ground field surveys have become increasingly expensive. A method or regression equation using conventional photo interpreted independent variables which could provide crown fuel weight estimates would be of immense value. For example, Sayn-Wittgenstein and Aldred (1967) constructed tree volume tables from conventional variables measured on large-scale aerial photographs (LSP). Large-scale aerial photography used in Canada especially for inventorying tree volume has developed quickly since first reported in 1961 (Hall <u>et al.</u> 1985). This method has been used extensively in forest inventory programs (Lowe, 1980). The interpretation of large-scale 1:1200 black and white aerial photographs provided data which was successfully used as a subsample and enhanced broad-based strategic planning (Alberta 1985). If scale and tilt are measured when photographing, large-scale photo measurements of tree height are no more and no less accurate than conventional field measurements of standing live trees (Titus and Morgan 1985). Parker et al. (1988) also suggested photo-measured tree height at a scale of 1:1250 may be substituted for ground-measured values with no loss of accuracy, but horizontal crown radius measured in the field corresponded less successfully to the same lengths measured on photographs. Morton et al. (1988) observed that the accuracy of photo-measured tree crown areas viewed from above is very difficult to test because, the crown area can not be as easily defined or measured from beneath the same tree. However, Aldred and Sayn-Wittgenstein (1972) concluded that the inaccuracies between photo-measured and ground-measured crown dimensions were not serious provided photo measurements were replicated.

Aldred and Sayn-Wittgenstein [illegible]972) and Aldred and Lowe (1978) determined that tree height was the single most powerful and easily measured primary independent variable on LSP for estimating stem diameter and stem volume. They also suggested that estimates may be improved by including a measure of horizontal crown size (crown radius, crown width or crown area) or a crowding factor. Height and crown width have been used in some models for predicting stem volume or DBH in British Columbia (Bradatsch 1980).

Apart from timber-inventory purposes, LSP's with controlled scale have been employed in surveys of logging residue and surface fuels measurements (Kirby and Hall

1979), regeneration appraisal (Butler 1983, Hall 1984), tree damage assessment (Murtha 1983), forestry engineering, and development of growth simulation models (Befort 1986) all without reference to ground measurement (Nielson et al. 1979, Bradatsch et al. 1981). Alemdag (1986) had reasonable success using measurements from aerial photographs with an average scale of 1:1150 to estimate weights of the whole-tree, the stem component, and the total live crown of individual white birch and trembling aspen trees.

Given the success of these previous studies and with accurate interpretation of individual tree dimensions or stand characteristics using available large-scale photographs, the objective of this study was to determine if ground-measured live crown length, approximate crown width, total height, and stand density would predict total crown fuel weights, foliage weights, and the weights of individual roundwood diameter classes for mature lodgepole pine (Pinus contorta Loundon var. latifolia Engelm.) and white spruce (Picea glauca (Moench) Voss var. albertiana (S. Brown) Sarg.)[1].

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[1] Moss (1983) is the botanical authority used.

3.2 METHODS

The total crown, live crown, foliage, and roundwood diameter class components of the total crown [0.0-0.5 cm, 0.5-1.0 cm, 1.0-3.0 cm, 3.0-5.0 cm, 5.0-7.0 cm (Van Wagner 1982), and 7.0-10.0 cm] were the oven-dried [70 ^{o}C (Moir and Francis 1972)] dependent fuel weights evaluated in this study. The data source is the same set evaluated in the previous DBH relationship [lodgepole pine (n=27) and white spruce (n=23)]. These weights were regressed against independent variables of: (1) approximate crown width, (2) live crown length, and (3) total height. Multiple linear regression SPSSx packages (Nie 1983), were used to evaluate logical combinations of these variables in models reviewed by Stanek and State (1978). Non-linear BMDP regression packages (Dixon and Brown 1979) were used to derive predictive allometric equations in the form:

$$\text{WEIGHT} = a\ \text{HEIGHT}^{b} \quad \text{and,}$$

$$\text{WEIGHT} = a\ \text{HEIGHT}^{b} \times \text{approximate CROWN WIDTH}^{c}.$$

The empirical R^2 value [1-(SSresidual/SStotal)] (Steel and Torrie 1980) was calculated to estimate the 'quality' of each non-linear equation. The standard error of the estimate was calculated directly from the non-linear regression and therefore, provides a more direct measurement of 'quality' in non-linear regression procedures. A residuals plot was also used to evaluate the different equations.

3.3 RESULTS

The equation, the empirical R^2, the standard error of the estimate (SEE), the mean of the predicted weight (Y), and the SEE as a percent of each mean (SEE%) for the relationship of the various component weights to independent variables selected are presented in Table 3.3.1. to Table 3.3.4.

The non-linear allometric model with height as a single independent variable (WEIGHT= a HEIGHT^b) was regressed against total crown weight, live crown weight and roundwood class component weights. The different equations had R^2 values that ranged from 0.14 to 0.70 for lodgepole pine and from 0.27 to 0.62 for white spruce. The corresponding SEE% ranged from 41.7 to 159.1 for lodgepole pine and from 41.7 to 152.4 for white spruce.

The non-linear allometric model with both height and crown width as independent variables (WEIGHT= a HEIGHT^b x CROWN WIDTH^c) was also regressed against crown component weights. Total crown and live crown regressions provided higher R^2 values for both lodgepole pine and white spruce than R^2 values of the weights of individual roundwood diameter classes when using multiple linear equations or non-linear equations. The different equations had R^2 values that ranged from 0.30 to 0.85 for lodgepole pine and from 0.66 to 0.90 for white spruce. The corresponding SEE% ranged from 29.6 to 144.3 for the pine and from 30.0 to 58.7 for the spruce.

TABLE 3.3.1 Lodgepole pine equations for estimating the oven-dried crown weight components (kg) from height (H; m) (n=27).

WEIGHT	allometric coefficients(*) a	b	r^2	SEE	$\bar{Y}$	SEE%
TOTAL CROWN	0.2489	1.8921	0.65	35.4	77.1	45.9
LIVE CROWN	0.3216	1.6723	0.54	25.1	50.6	49.6
FOLIAGE	0.0672	1.6939	0.59	5.1	11.4	44.9
0.0-0.5 cm	0.0551	1.9870	0.70	9.6	23.0	41.7
0.5-1.0 cm	0.1407	1.4847	0.48	6.6	12.3	54.1
1.0-3.0 cm	0.0869	1.8571	0.65	11.4	23.9	47.8
3.0-5.0 cm	0.0035	2.6422	0.42	11.8	10.8	109.1
5.0-7.0 cm	0.0059	2.1136	0.14	6.0	3.7	159.1
7.0-10.0 cm	use the observed mean weight value:				3.3	

Where:

(*) Equation in the form: $\text{WEIGHT} = a\ \text{HEIGHT}^b$

SEE Standard error of the estimate (kg).

$\bar{Y}$ Mean of the predicted and observed weights (kg).

SEE% SEE expressed as a percent of the mean Y.

TABLE 3.3.2 White spruce equations for estimating the oven-dried crown weight components (kg) from height (H; m) (n=23).

WEIGHT	allometric coefficients(*) a	 b	r^2	SEE	$\bar{Y}$	SEE%
TOTAL CROWN	0.0759	2.3958	0.52	115.8	186.4	62.1
LIVE CROWN	0.0883	2.2185	0.60	60.2	120.0	50.2
FOLIAGE	0.2400	1.5799	0.62	16.0	38.5	41.7
0.0-0.5 cm	0.0960	2.1078	0.60	44.8	89.6	50.0
0.5-1.0 cm	0.0134	2.2124	0.62	8.3	18.1	46.0
1.0-3.0 cm	0.0234	2.3457	0.53	30.2	47.9	63.0
3.0-5.0 cm	0.00002	4.2657	0.27	38.5	25.2	152.4
5.0-7.0 cm	use the observed mean weight value:				2.0	
7.0-10.0 cm	use the observed mean weight value:				3.6	

Where:

(*) Equation in the form: $\text{WEIGHT} = a\ \text{HEIGHT}^{b}$

SEE Standard error of the estimate (kg).

$\bar{Y}$ Mean of the predicted and observed weights (kg).

SEE% SEE expressed as a percent of the mean Y.

TABLE 3.3.3 Lodgepole pine equations for estimating the oven-dried crown weight components (kg) from height (H; m) and approximate crown width (aCW; m) (n=27).

WEIGHT	allometric coefficients(*) a	b	c	R^2	SEE	$\bar{Y}$	SEE%
TOTAL CROWN	0.4589	1.2371	0.9536	0.85	24.0	77.1	31.1
LIVE CROWN	0.8473	0.8015	1.1615	0.84	15.0	50.6	29.6
FOLIAGE	0.1537	1.0263	0.8461	0.78	3.8	11.4	33.4
0.0-0.5 cm	0.0754	1.5752	0.6507	0.80	7.9	23.0	34.5
0.5-1.0 cm	0.3135	0.8873	0.7183	0.59	6.0	12.3	48.9
1.0-3.0 cm	0.1476	1.4209	0.5644	0.71	10.5	23.9	44.0
3.0-5.0 cm	0.0110	1.2667	2.0331	0.78	7.5	10.8	69.3
5.0-7.0 cm	3.2077	-0.5419	0.8817	0.30	5.3	3.7	144.3
7.0-10.0 cm	use the observed mean weight value:					3.3	

Where:

(*) Equation in the form:

$$\text{WEIGHT} = a\ \text{HEIGHT}^{b} \times \text{approximate CROWN WIDTH}^{c}$$

SEE Standard error of the estimate (kg).

$\bar{Y}$ Mean of the predicted and observed weights (kg).

SEE% SEE expressed as a percent of the mean Y.

TABLE 3.3.4 White spruce equations for estimating the oven-dried crown weight components (kg) from height (H; m) and approximate crown width (aCW; m) (n=23).

WEIGHT	allometric coefficients(*) a	b	c	R^2	SEE	$\bar{Y}$	SEE%
TOTAL CROWN	1.5301	0.3954	2.1983	0.87	62.9	186.4	33.8
LIVE CROWN	0.7440	0.8631	1.4554	0.84	39.6	120.0	33.0
FOLIAGE	0.4316	1.1686	0.4874	0.66	15.5	38.5	40.3
0.0-0.5 cm	0.6376	0.8300	1.4396	0.82	30.5	89.6	34.0
0.5-1.0 cm	0.1194	0.9312	1.2824	0.85	5.4	18.1	30.0
1.0-3.0 cm	0.4691	0.4741	1.9606	0.83	18.5	47.9	38.5
3.0-5.0 cm	0.0656	-3.0726	9.1345	0.90	14.8	25.2	58.7
5.0-7.0 cm	use the observed mean weight value:					2.0	
7.0-10.0 cm	use the observed mean weight value:					3.6	

Where:

(*) Equation in the form:

$$\text{WEIGHT} = a\ \text{HEIGHT}^{b} \times \text{approximate CROWN WIDTH}^{c}$$

SEE Standard error of the estimate (kg).

$\bar{Y}$ Mean of the predicted and observed weights (kg).

SEE% SEE expressed as a percent of the mean Y.

3.4 DISCUSSION

The results of this study show that variables such as height and approximate crown width, which can be interpreted from LSP, can provide estimates of total crown fuel weight, live crown fuel weight, and individual diameter roundwood class weights from 0.0 - 5.0 cm. Such estimates derived from these variables will provide information needed for broad fire hazard mapping of dominant trees especially in inaccessible areas.

Measurement of the live crown length is generally more difficult to interprete on aerial photos because it is often obscured by the maximum crown width which is above the point of the start of the live crown. This live crown length variable was therefore eliminated from analysis. The correlation of this and other independent variables to the dependent weights are listed in Appendix II.

The allometric model with height and approximate crown width as independent variables in the form:

$$\text{WEIGHT} = a\ \text{HEIGHT}^{b} \times \text{approximate CROWN WIDTH}^{c}$$

provided reasonable R^2 values when compared to the DBH-based model previously evaluated. Reasonable SEE values, and plotted residuals (difference between the actual and the predicted value) over this range of tree size for either species were also provided by this non-linear model.

The R^2 values and SEE values of the single variable model (WEIGHT= a $HEIGHT^b$) were inferior to the model which included an estimate of crown width. This conforms to suggestions made by Aldred and Sayn-Wittgenstein (1972) and Aldred and Lowe (1978) that estimates may be improved by including a measure of horizontal crown size or a crowding factor.

Prediction of roundwood component weights for the 5.0-7.0 cm class by the equations presented is not recommended for very large lodgepole pine trees with approximate crown widths greater than 7.4 metres. These predictive values underestimated the observed weight of roundwood in this diameter class on the few trees which had crown width measurements greater than 7.4 metres by as much as a factor of four. The reason for this is that a crown width greater than 7.4 metres would require unusually long, large and heavy branch stubs in this size class to support branches which may be longer than 3.5 metres. The R^2 values and SEE% values were also inferior to other roundwood diameter class equations.

The 7.0-10.0 cm class consists of a length of stemwood with a mean weight of 3.3 kg for lodgepole pine and 3.6 kg for white spruce for all trees studied. It was therefore extremely difficult to predict this 7.0-10.0 cm class weight with any combination of variables because of the lack of observations of woody material in the form of stemwood and branchwood.

The measurement standards for this project for height (±0.1 m) and approximate crown width (±0.1 m) exceed the abilities of photogrammetry personnel preparing 1:15,000 Phase III Forest Inventory Maps in Alberta (Alberta 1985). A large-scale photography system would be necessary for this precision. Spencer (1984) suggested crown width was a difficult variable to define and to measure with an LSP system because some forest tree species have irregular crown shapes. Crown area is a widely used alternative measure of horizontal crown size and can also be determined quickly and consistently on LSP's, but crown area can not be easily measured from the ground (Morton _et al_. 1988). Crown asymmetry tends to exaggerate an estimate of ground-measured crown radius as the distance from the centre of the bole to the maximum overhead projection of the base of the crown (Parker _et al_. 1988). Sayn-Wittgenstein (1978) describes the crown of white spruce as dense and symetrical, and the crown of lodgepole pine as short and narrow with regular branching. Theoretically, this observation of regular crown shape for both species and the criteria used to pre-select trees with uniform crown shape in this study suggests that a measurement of crown width, crown radius or crown area would provide reasonable estimates of horizontal crown size for these two species. However, for other species, crown area may be the only variable easily and accurately measured on large-scale photographs.

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4. CONCLUSIONS AND RECOMMENDATIONS

The ability to predict of crown fuel weights will provide forest managers with a tool for evaluating potential fire behavior and will serve as a preliminary estimate of surface slash fuel loadings created by logging. Fuel weight equations were developed for lodgepole pine and white spruce trees growing in a variety of ecoregions in Alberta.

Equations were developed so that field measurements of DBH for a single tree could be used to predict the weights of total crown, live crown, foliage, and six roundwood diameter classes (0.0-0.5 cm, 0.5-1.0 cm, 1.0-3.0 cm, 3.0-5.0 cm, 5.0-7.0 cm and 7.0-10.0 cm) which are of interest to most forest fire agencies in Canada. The simple allometric model of $WEIGHT = a\ DBH^b$ provided sensible; predictive values, SEE, and residual plots over the entire range of tree sizes sampled in real untransformed units. The empirical R^2 [1-SS residual/SS total] values for the models of most interest to forest managers ranged from 0.68 to 0.88 .

The ability of this DBH-based model to predict individual roundwood diameter fuel weights of 3.0-5.0 cm and 5.0-7.0 cm diminished because there was less number of trees with both branchwood and stemwood in these classes. Only the largest of the trees sampled had branchwood in those classes and all other less mature trees had only a single piece of stemwood in these classes. The weight of this material in smaller trees exhibits no curvilinear relationship to increasing DBH. Hence, it was determined that for trees with a DBH of less than 25 cm, the mean value for any one specific class should be used. For larger trees ($\geq$25 cm, dbh) the allometric equation: $Y = a\ DBH^{b}$ should be used.

Two non-linear models provided the predictive equations for total crown weights and component roundwood weights from individual tree measurements readily available on large-scale aerial photographs. A model based only on total height in the form: $Y = a\ H^{b}$ was inferior to a model which included an estimate of crown size. However, the accuracy of horizontal crown size measurements interpretated from aerial photographs has not be as fully tested as total height. Therefore, this model can provide weight estimates in situations were the accuracy of horizontal crown size is questionable.

The model of the form: $WEIGHT = a\ HEIGHT^{b} \times$ approximate $CROWN\ WIDTH^{c}$ had empirical R^{2} values from 0.59 to 0.87 for the roundwood diameter classes of most interest to forest managers. These predictive equations in real units provided similar R^{2} values and has performed nearly as well based on SEE values, when compared to the DBH-based model. These equations could be used for weight estimates if accessibility is limited or if large-scale aerial photographs of areas of interest are available to supplement some ground inventories.

The 'quality' of these models generally decreased when estimating the larger roundwood diameter fuel weights. The empirical R^2 values (for $Y = a\ DBH^b$ and $Y = a\ HEIGHT^b \times$ approximate $CROWN\text{-}WIDTH^c$) would decrease from greater than 0.80 for the 0.0-0.5 cm class down to values less than 0.50 for the 5.0-7.0 cm class, and corresponding SEE% values were much higher for the 3.0-5.0 cm and 5.0-7.0 cm diameter classes. Since standing live tree material larger than five cm in diameter would rarely be consumed during the torching of individual crowns in a crown fire, the prediction of the larger diameter class weights is of less importance than the accurate prediction of the smaller diameter flash fuels.

Future Research Needs

(1.) Results presented in this study provide the provincial forest fire agency with simple equations for predicting crown fuel weight components of standing live lodgepole pine and white spruce trees. Weight estimates within the same roundwood diameter classes for other timber types would provide knowledge for developing extensive fuel hazard mapping or predicting fire behavior and effects. A standing live inventory would also provide preliminary knowledge for silvicultural options or fuel manipulation plans prior to logging. The distribution of the weight in the smallest diameter class by position in the tree crown would also enhance modelling for fire behavior prediction because knowledge of crown bulk density (kg/m^3) is required to evaluate crowning potential. Intuitively, the bulk density of any crown is less near the ground and would increase towards a more dense tree top.

(2.) The slash fuel weight added to a site after logging can be extremely variable for various timber types, harvesting and processing types, or summer and winter harvesting periods. Stem breakage of juvenile trees and harvested mature trees will add to the post-harvest surface fuel loading. Knowledge of these interactions would improve fuel manipulation plans based on slash weight. However, weight and its distribution on a cutover is necessary in any fuel management plan which requires an estimate of fuel continuity.

(3.) Knowledge of moisture content variations by season, tree species, tree dimensions, or roundwood diameter classes could be applied to evaluating: (a) crowning potential and fuel hazard; or (b) fuel management alternatives. Also, over-sampling to determine the moisture content of fresh material is expensive and time-consuming. Field costs, equipment costs and lab time could be reduced if reasonable sampling intensities could be identified or lowered for any roundwood diameter class.

APPENDIX I

FIELD SUBSAMPLING EVERY FOURTH BRANCH

Regression functions of tree biomass on independent variables are typically estimated from samples of trees selected from a forest population of interest. Once selected their biomass must be measured directly if possible, or estimated by subsampling otherwise. If the biomass is expressed as dry weight, direct measurement is extremely expensive and time consuming for large tree components. Subsampling for moisture content, has proven sufficiently precise to estimate the oven-dried biomass of any tree component and is a widely accepted practical procedure. Subsampling to evaluate the weight of each tree component or roundwood diameter class is less accepted. Some authors (Singh 1982) have stratified every branch into roundwood diameter classes. Other authors (Brown 1976) have visually divided crowns into two or three horizontal live sections and one dead section weighed each crown section, selected one or two branches which appeared average in size from each section, then stratified this subsample of branches into roundwood diameter classes. Two branches from four sections (or eight total branches) roughly equates to stratifying every fourth branch from immature trees. Subsampling every fourth branch was therefore selected as the standard procedure for all trees evaluated in this study.

A paired t-test derived from one-way analysis of variance was used to test the total fresh weight of every fourth branch (subsample of branches to be stratified into roundwood diameter classes), paired against one-quater of the total fresh weight from all branches from each tree studied. The calculated 't' statistic of 0.86 supports the conclusion of no significant differences between the subsample weight of every fourth branch and 1/4 of the total weight of all branches, at the probability level of 0.01 %.

This method of subsampling every fourth branch therefore seems appropriate in addition to being very cost efficient. There was no requirement to visually determine different sections of the live crown or to subjectively determine branches for stratifying from within each crown section. Subsampling every fourth branch allowed enough time for two people to process lodgepole pine trees as large [illegible] 50 cm DBH in just one day. The fresh total crown weight of a white spruce tree with an 85 cm DBH was determined to be over 2000 kg, subsampling every fourth branch allowed two people to process it in only four days. Without subsampling, this same tree would have taken about two weeks to completely stratify. More than 12 months time would have been required to duplicate the field portion of this study if subsampling was not undertaken, or far fewer observations would have been available to develop equations that would accurately predict: the total crown fuel weight, live crown fuel weight, foliage weight, or individual roundwood diameter class fuel weights.

APPENDIX II

CORRELATION OF INDEPENDENT AND DEPENDENT VARIABLES FOR LODGEPOLE PINE AND WHITE SPRUCE.

LEGEND

DEPENDENT VARIABLES

DST	Diameter (cm) at Stump Height (0.3 m)
DBH	Diameter (cm) at Breast Height (1.3 m)
DLC	Diameter (cm) at base of live crown
H	Total Height (m)
HLC	Total Height (m) to base of live crown
CW	Crown Width (m) [length of branch with maximum crown radius + length of opposite branch at same height + stem diameter at same height]
CL	Length of live crown (m)
AGE	Total age of tree (yr)
BA	Basal Area of stand (m2/ha)
DENSITY	Density of stand (#stems/ha)

CROWN COMPONENT WEIGHTS

TOTAL	Total weight of crown (kg)
LIVE	Total weight of live crown (kg)
FOLIAGE	Total weight of live foliage (kg)
TOH	Weight of 0.0-0.5 cm roundwood diameter class (kg)
TH1	Weight of 0.5-1.0 cm roundwood diameter class (kg)
T13	Weight of 1.0-3.0 cm roundwood diameter class (kg)
T35	Weight of 3.0-5.0 cm roundwood diameter class (kg)
T57	Weight of 5.0-7.0 cm roundwood diameter class (kg)
T710	Weight of 7.0-10.0 cm roundwood diameter class (kg)

LODGEPOLE PINE

Correlation

	DBT	DBH	DLC	H	HLC	CW	CL	AGE	BA	DENSITY	TOTAL	LIVE	FOLIAGE	T0H	TH1	T13	T35	T57	T710
DBT	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DBH	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DLC	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
H	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
HLC	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
CW	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
CL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AGE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DENSITY	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
LIVE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FOLIAGE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
T0H	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TH1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]
T13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]
T35	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]
T57	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]
T710	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000

WHITE SPRUCE

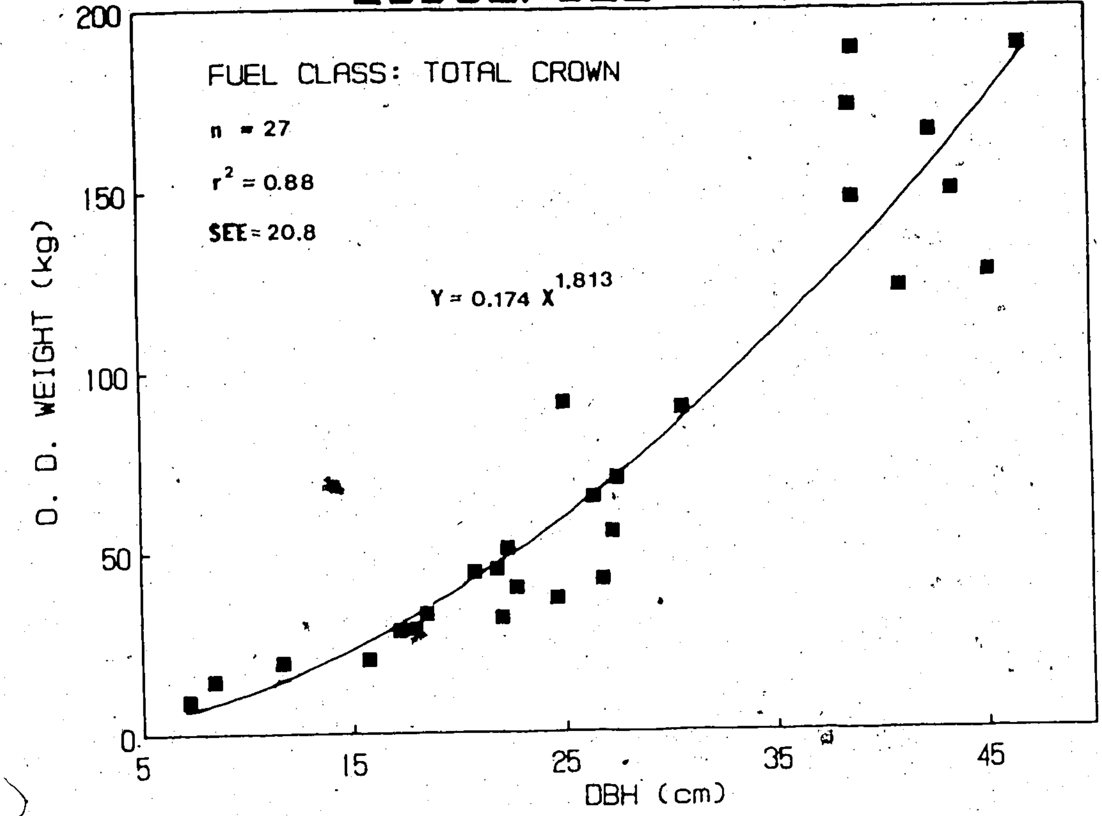
Correlation

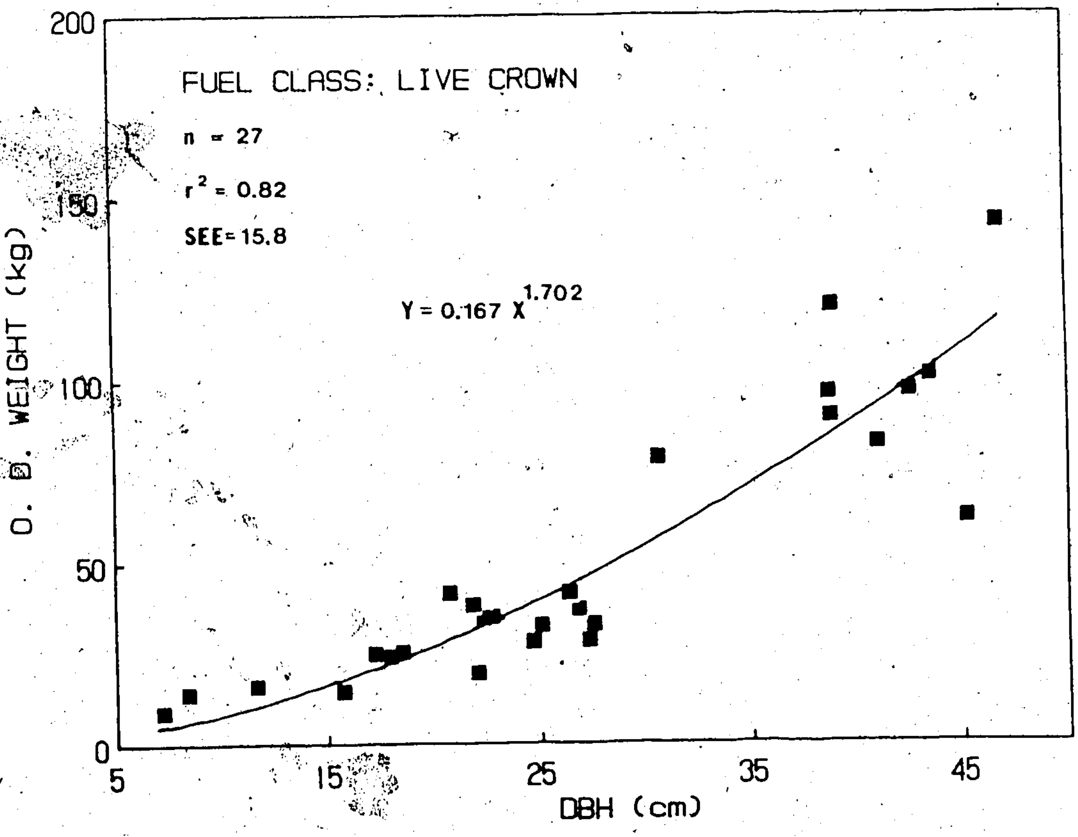
	DBT	DBH	DLC	H	HLC	CW	CL	AGE	BA	DENSITY	TOTAL	LIVE	FOLIAGE	T0H	TH1	T13	T35	T57	T710
DBT	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DBH	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DLC	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
H	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
HLC	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
CW	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
CL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AGE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DENSITY	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
LIVE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FOLIAGE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
T0H	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TH1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]	[illegible]
T13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]	[illegible]
T35	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]	[illegible]
T57	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000	[illegible]
T710	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.000

APPENDIX III

WEIGHT EQUATIONS FOR LODGEPOLE PINE FUELS BASED ON DBH.

LODGEPOLE PINE





LODGEPOLE PINE