A PATH TOWARD IMPROVED MANAGEMENT OF THE NORTHERN FORESTS OF ALASKA: FOREST INVENTORY, BARK THICKNESS, AND STEM VOLUME

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A

THESIS

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Abstract

This thesis provides three essential forest management tools that resource managers and researchers can use to improve management the northern forests of Alaska.

The Cooperative Alaska Forest Inventory (CAFI) is a comprehensive database of northern forest conditions and dynamics. The basis for the CAFI database is a system of permanent sample plots located throughout interior and south-central Alaska. This information can be used to develop forest growth models and track long-term forest changes.

The bark thickness model was developed because there was no published white spruce bark thickness model for Alaska. The data used to develop this and volume models were taken from stands located throughout interior and south-central Alaska. Analysis shows that this Alaska statewide bark thickness model accuracy estimates white spruce bark thickness when compared to other bark thickness models.

Cubic-foot volume models were developed to estimate total stem and merchantable volume of white spruce in Alaska. These multiple-entry (diameter and height) models estimate volume both outside and inside bark. Analysis shows that these volume models were more accurate for Alaska when compared to published and unpublished white spruce models. These models can be used to estimate individual stem volume, volume per unit area, and to develop biomass models.

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Chapter 1 General Introduction

Alaska is the largest state in the United States with approximately 129 million acres of forest land (van Hees 1999). The coastal forest account for 14 million acres and the northern forest cover approximately 115 million acres (van Hees 1999) (fig. 1.1). This land base is managed by numerous private and public agencies. Approximately 59 percent of Alaska is managed by the federal government, 28 percent is managed by the State of Alaska and municipalities, and the remainder is owned by private individuals or corporations (Hull and Leask 2000; Irwin et al. 2010).

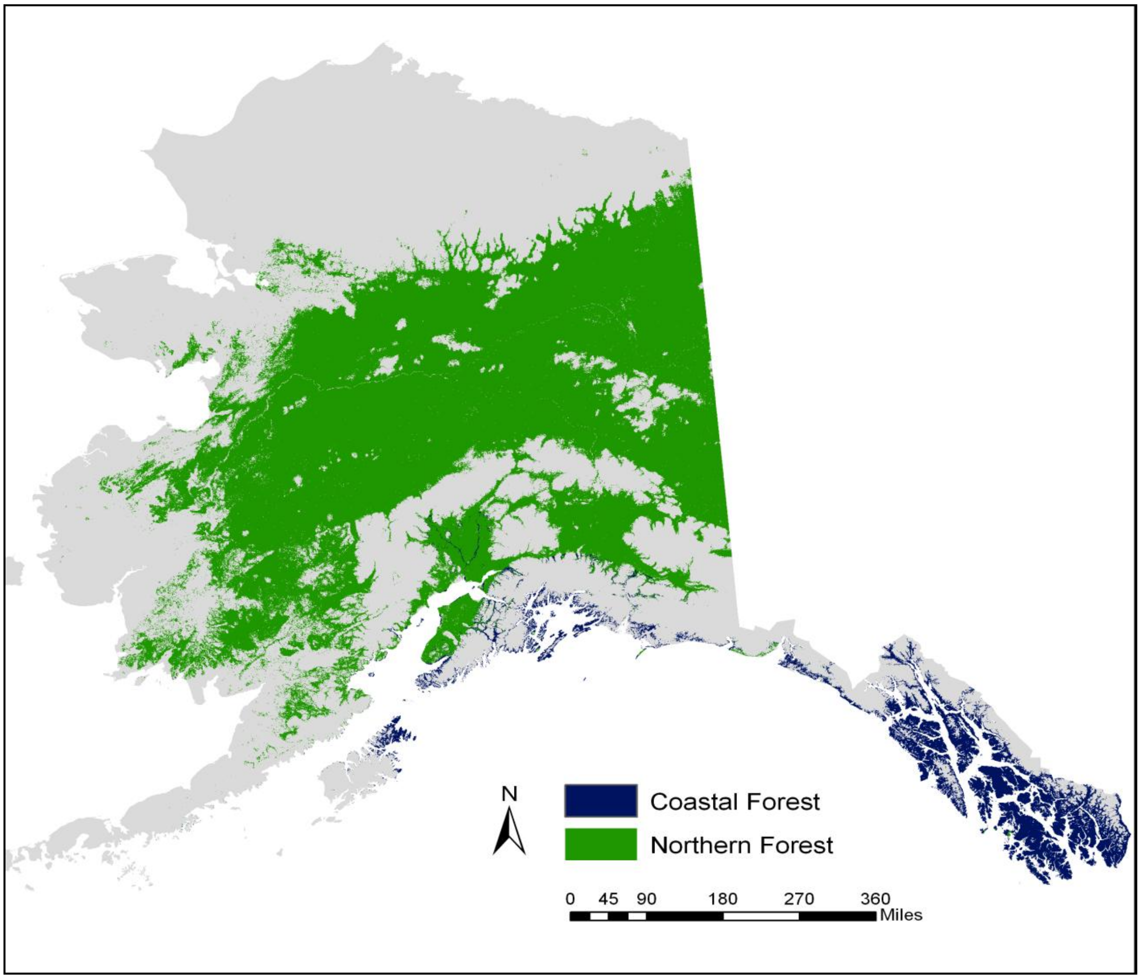

Figure 1.1 Vegetation map of Alaska (Ruefenacht et al. 2008).

The area of study of these research projects are the northern forests of interior and south-central Alaska. The northern forests of Alaska cover the boreal forests of northern Alaska and the transition forests of the Matanuska and Susitna Valleys, the west side of the Kenai Peninsula, and the Bristol Bay area. These transition areas are characterized by a combination of vegetation from both the boreal forest and the coastal forests. For example, the tree species are boreal such as white spruce (*Picea glauca* (Moench) Voss) and black spruce (*Picea mariana* ((Mill.) B.S.P.) while some of the understory vegetation are coastal species such as false azalea (*Menziesia ferruginea* Sm.) and five-leaf bramble (*Rubus pedatus* Sm.). The study area which does not cover the entire range of forest classified land in northern Alaska, due to budget restriction, does encompass most of the commercial forestry activity in the northern forests of Alaska.

The Forest Growth and Yield Program (FGYP) of the University of Alaska, School of Natural Resources and Agricultural Sciences, conducted an informal survey of resource managers to determine the tools they needed to better manage the northern forests of Alaska. Two of the tools that were high on the priority list were forest growth and yield models and improved volume models. For these reasons, FGYP research projects are supported by many land owners and land management agencies, both private and public (Appendix 1.A).

Three studies are combined in this thesis to provide forest managers with some of the tools necessary to properly manage the northern forests of Alaska. The first project is the development of Cooperative Alaska Forest Inventory (CAFI). The second study provides a white spruce bark thickness model which allows estimates of volume inside bark. The third study develops models to estimate cubic foot volume of white spruce in Alaska.

CAFI user's manual and database

To meet the needs of resource and land managers in Alaska the Forest Growth and Yield Program initiated a Cooperative Alaska Forest Inventory project; an ongoing long-term study. To develop this database, a system of permanent sample plots was established throughout interior and south-central Alaska starting in 1994. The plots are remeasured on a periodic basis. The database includes growth and visual health information of trees, presence of understory vegetation, and site characteristics. While each measurement of these plots is a snap-shot of the conditions of the site, the real value of these plots and the accompanying database come from repeated measurements which reveal the dynamics of sampled forests. Foresters and land managers must know how forest stands are changing to properly manage them (Gruell et al. 1999; Nyland 1996). Successive remeasurement of permanent plots increase the precision of statistical inferences and improves ability to make correct management decisions (Avery and Burkhart 2002).

Currently there are 603 plots at 201 sites throughout the study area (fig. 2.1). Ongoing plot establishment is described in chapter 2. At this time, 66 of the 603 plots have been remeasured 3 times.

Being the only comprehensive permanent sample plots system in northern Alaska CAFI can be used to monitor the impacts of environmental and climate change within the study area, to develop forest management tools, and to enhance numerous research projects. This database has been used to develop forest growth and dynamics models (Liang 2010; Liang and Zhou 2010). The Alaska State Division of Forestry is using the CAFI data to ground-truth their satellite imagery and the US Forest Service, Forest Management Service Center is using the CAFI data to develop an Alaska northern forest variant for the Forest Vegetation Simulator (Crookston and Dixon 2005). In addition, the forest succession work done by the US Forest Service and the University of Alaska Fairbanks can be expanded and validated by these plots (Viereck et al. 1983). Stand succession can be tracked over time throughout interior and south-central Alaska since trees are measured every 5 years once a tree reaches 0.51 in at diameter at breast height (dbh). Van Cleve et al (1996) stated that vegetation composition and structure are controlled in part by topography. The CAFI data will allow this hypothesis to be further tested throughout the northern forests of Alaska. Also fire researchers can use the bark thickness data and CAFI data to assess forest stands for burn frequency and severity

(Busing and Solomon 2006). The data contained in the CAFI database such as vegetation type, slope, amount of deadwood, and depth of organic soil can also help fire managers predict fire behavior and develop suppression and fuels management strategies (Rothermel 1972).

Most of the sites included in the CAFI database are located in forested stands or stands that are capable of supporting forests but do not contain trees at this time. Some sites have been burned and one site was affected by an avalanche. Numerous sites are located in taiga forest types which are characterized by sparse tree cover. From a forestry stand point, the taiga forests are not commercially viable at this time but they are a large and important part of the northern Alaska ecosystem (Van Cleve and Dyrness 1983).

White spruce bark thickness model

Prior to this research, there were no published bark thickness models for white spruce in Alaska. This bark thickness model compliments the other two research projects in this thesis. Bark thickness models are necessary to estimate wood volume (inside-bark) therefore this model has been used in the white spruce volume models (Chapter 4). The CAFI data can be used to estimate volume per unit area and biomass; these estimates are improved with an inside-bark volume model. Bark thickness models are also used in productivity studies, tree volume estimates, and forest economic analysis to estimate stumpage. Timber volume and value cannot be correctly estimated without knowing the thickness of bark (Meyer 1946).

White spruce covers a large portion of the northern forests of Alaska (fig. 1.2). The data collected for this bark thickness study and the volume study, were taken in the same geographic areas but not from the same white spruce trees.

White spruce volume models

Development of volume models for the tree species of northern Alaska was a priority of land managers (Packee, per. comm., University of Alaska Fairbanks, 1983). There are numerous white spruce cubic-foot volume models currently in use throughout interior and south-central Alaska. None of these models were developed from samples widely distributed throughout northern Alaska. To develop these Alaska statewide volume models, 2,016 trees were sampled from 43 stands located throughout interior and south-central Alaska (table 4.2). The objective of this white spruce volume project was to develop multiple-entry (diameter and height) models that would accurately estimate volume both outside and inside bark.

Eight models including total stem volume outside and inside bark and merchantable volume models outside and inside bark to a 2-in, 4-in and 6-in top were developed to estimate cubic-foot volume of white spruce in Alaska.

There are numerous questions and issues facing people interested in the northern forests of Alaska and some basic information necessary for proper decision making is missing or incomplete. Setting the allowable cut in managed forests, climate change, carbon sequestration, species diversity, and increased demand for biofuels are but a few of the issues. To improve forest management, basic inventory data including the volume of wood is essential information. The climate of the world is constantly changing and interior and south-central Alaska is no different. Climate change is a complex issue especially at high latitudes where models predict greater warming rates (ACIA 2005). Predictions are for increased fire frequency and severity and expansion of forested lands into current tundra landscapes (Calef et al. 2005). Data available through the CAFI project can add to the knowledge pool. With land management tools, presented in this thesis, managers and researches can help develop more informed strategies to address these and other land management issues on a path toward improved management of the northern forests of Alaska.

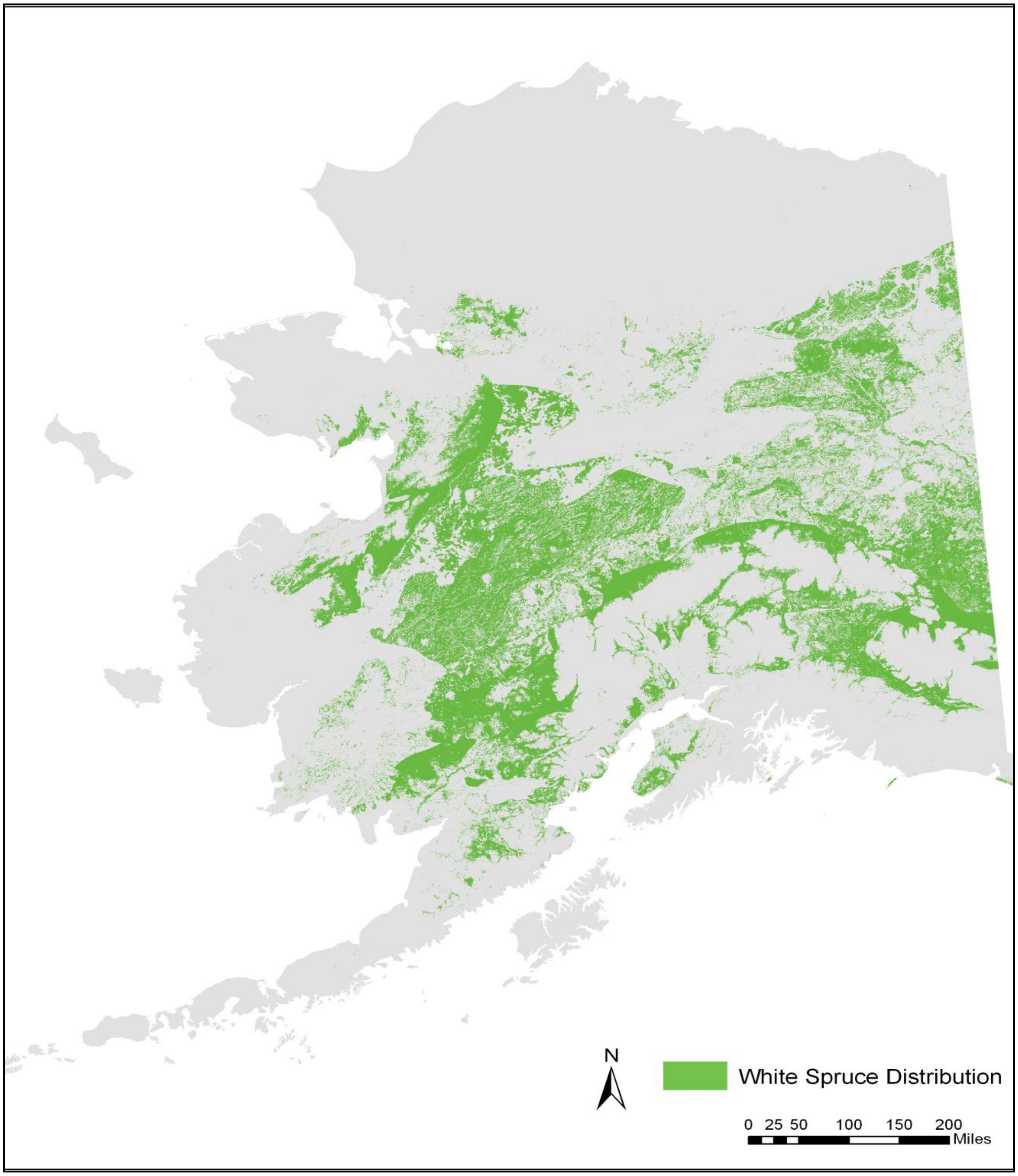

Figure 1.2. Distribution of white spruce in Alaska (Ruefenacht et al. 2008).

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Chapter 2 Cooperative Alaska Forest Inventory: CAFI[1]

Abstract

The Cooperative Alaska Forest Inventory (CAFI) is a comprehensive database of boreal forest conditions and dynamics in Alaska. The CAFI consists of field-gathered information from numerous permanent sample plots distributed across interior and south-central Alaska including the Kenai Peninsula. The CAFI currently has 603 permanent sample plots on 201 sites representing a wide variety of growing conditions. New plots are being added to the inventory annually. To date, over 60 percent of the permanent sample plots have been remeasured and approximately 20 percent have been remeasured three times. Repeated periodic inventories on CAFI permanent sample plots provide valuable long-term information for modeling of forest dynamics such as growth and yield. Periodic remeasurements can also be used to test and monitor large-scale environmental and climate change.

This guide documents sampling and estimation procedures of CAFI v.1.0, and provides details of the database, including attribute description and summary statistics. To help researchers and land managers successfully initiate or expand a permanent sample site program in Alaska, this guide offers a comprehensive tutorial to establish, maintain, and process permanent sample plots in Alaska's boreal forests.

The database can be found at: http://www.faculty.uaf.edu/ffjl2/CAFI.html.

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[1] Malone, T., J. Liang, and E.C. Packee. 2009. Cooperative Alaska Forest Inventory. USDA Forest Service General Technical Report PNW-GTR-785. 42 p. Minor revisions were made from the publication.

Introduction and Background

The boreal forest, the largest forest component of the Alaskan landscape, occupies 60 to 70 percent of Alaska's land area (Van Cleve and Dyrness 1983). The forest consists of eight species dependent upon the taxonomic treatment of the genus *Populus*: three conifers --- white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) B.S.P.), tamarack (*Larix laricina* (DuRoi) K. Koch) --- and five hardwoods --- Kenai birch (*Betul*a *kenaica* W.H. Evans), Alaska birch (*Betula neoalaskana* Sarg.), quaking aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L. spp. *balsamifera*), and western black cottonwood (*Populus balsamifera* L. spp. *trichocarpa* (Torr. & Gray). Of these, white spruce, Alaska birch, Kenai birch, and quaking aspen are currently of significant commercial importance.

The Alaskan boreal forest exists in an environment of extreme climatic conditions that differ considerably across Alaska. For example, in interior Alaska, the difference in temperatures can be as much as 160 ºF between summer and winter, and precipitation rarely exceeds 20 in per year. In contrast, in south-central Alaska, the temperature differential between summer and winter is not as extreme, and the heavier snowfall and more rain in south-central Alaska causes different tree growth. Across the full range of the boreal forest in Alaska, the growing season is relatively short compared to other biomes (Van Cleve et al. 1983). However, the long days of the growing season provide more light for photosynthetic activity and thus mitigate, in part, the effect of the short growing season. Despite an increased interest in the resources from these forests, the forest industry in the boreal forest region of Alaska continues to be limited to small mills and cottage industries.

The Cooperative Alaska Forest Inventory (CAFI) is a comprehensive database consisting of field-gathered information on boreal forest conditions and dynamics in Alaska. The overall program was initiated in 1984 by E.C. Packee. Data are collected from sites distributed across interior and south-central Alaska including the Kenai Peninsula (fig. 2.1).

Permanent sample plots (PSPs) are a valuable tool for resource managers, in part because they provide managers with a wide variety of data and are remeasured periodically. An established PSP database becomes more valuable as the plots are remeasured and maintained over time. A measurement gives a snapshot of the site, but repeated periodic site visits provide much more valuable long-term information on forest growth and yield that aids in the modeling of future forest dynamics. In addition, periodic remeasurement of PSPs across a large area over time can be used to test and monitor large-scale environmental and climate change.

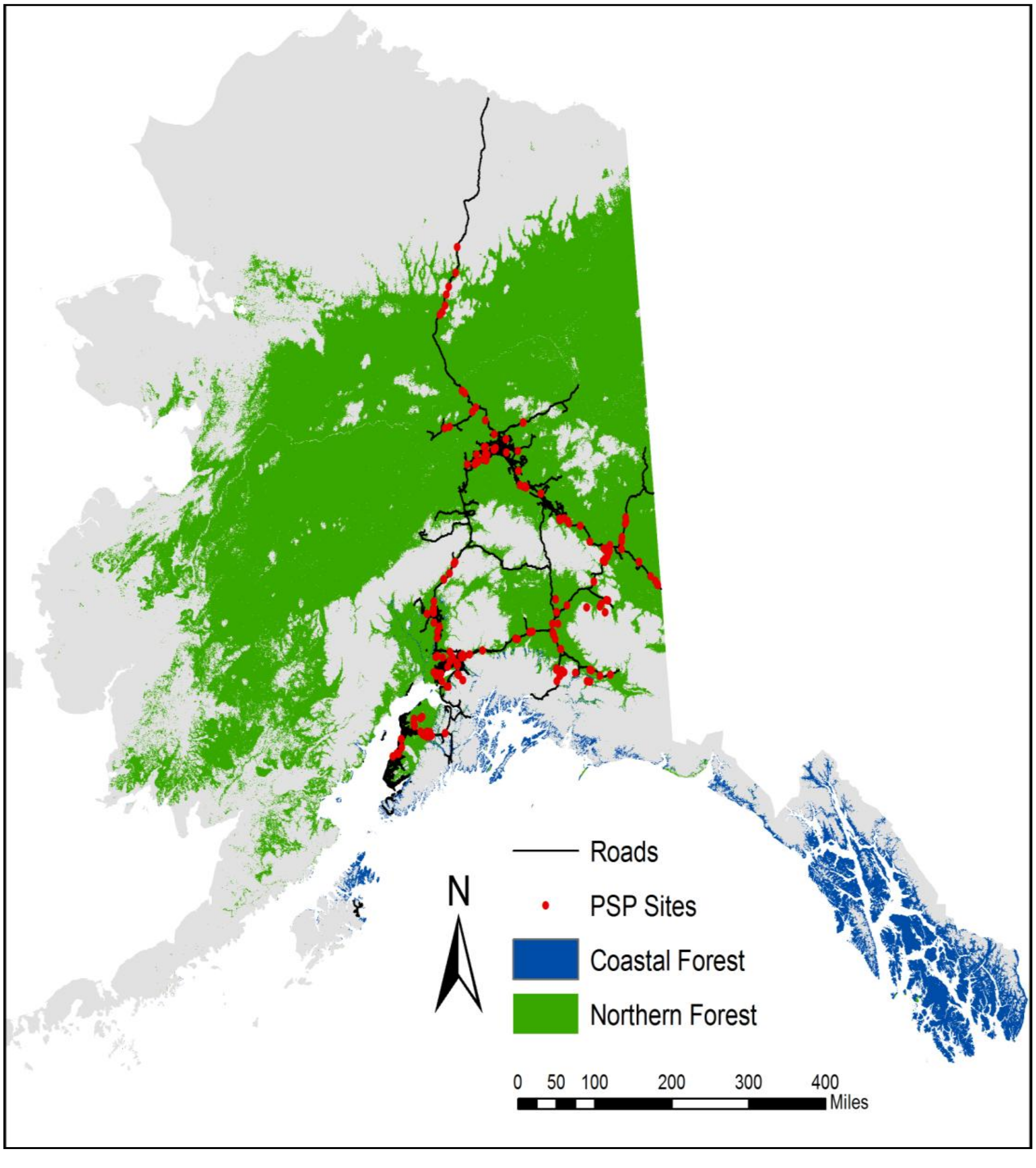


Figure 2.1 Geographic distribution of the 201 permanent sample plot sites (in dots) and their relative location within Alaska. Solid lines represent highways.

This user's guide describes version 1.0 of the CAFI. New data are being continually added to the database; the user's guide will be updated periodically to accommodate future changes. The next sections summarize sampling and estimation procedures for CAFI and provide details of the database, including attribute descriptions and summary statistics. The appendixes (2.A and 2. B) provide a list of equipment and supplies used to establish PSPs. The guide also provides detailed procedures to establish, maintain, and process PSPs in Alaska's boreal forests.

For more information on the CAFI, or to request a copy, please visit http://www.faculty.uaf.edu/ffjl2/CAFI.html.

Methods

The CAFI ground plots are a system of fixed-size PSPs, established to monitor growth, yield, and health of boreal forests in Alaska. They cover a large geographic area and multiple ownerships to represent various stand conditions. They have a fixed location and fixed size and are remeasured periodically. Many of the data collection procedures and codes used in this research are taken from General Technical Report PNW-155, *Procedures for establishing and maintaining permanent plots for silvicultural and yield research* (Curtis 1983).

The geographic area includes forested regions dominated by pure or mixed stands of white and black spruce, tamarack, Alaska and Kenai birch, aspen, balsam poplar or, locally, western black cottonwood. Included within the boreal forest are two vegetation types: closed spruce-hardwood forests and open spruce forests (Viereck and Little 1972). On the Kenai Peninsula and in southern south-central Alaska, scattered mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) may be present as scattered individuals or stands in the transition zone between the boreal forest and the Sitka spruce-western hemlock coastal forest. The boreal forest region is bounded on the north and west by tundra (moist and wet), and shrub land types and on the south by the coastal Sitka spruce-hemlock forests (Viereck and Little 1972).

Site description, tree, and understory vegetation data are collected to quantify site characteristics. Physical site attributes collected include location, slope, aspect, landform, and soils information. Tree data include diameter, height, health, and quality and quantity of regeneration. Presence of understory vegetation, both vascular and nonvascular, is recorded as percentage of cover.

It is important to establish PSPs not only in current forested areas, but also in recently disturbed areas in which forests will become established. In this way, post disturbance growth rates can be compared to the growth and yield of mature forest stands, and stand development patterns can be observed. Because funding is limited, the only means of transportation for the crews are motor vehicles and walking. To ensure the crews' safety, no PSP site is selected farther than 10 mi from a road. Therefore, all CAFI PSPs are located within 20-mile corridors surrounding established roads.

The procedure for establishing PSPs is as follows:

1. Prior to sampling at a given location, sites are visually assessed for suitability; this is usually done in spring or summer. To be suitable, a potential PSP site must be in a single forest stand and minimally 5 ac.
2. If the site is deemed suitable, the site location information is brought back to the office for processing a PSP land use permit.
3. Land ownership for each site is determined, and the landowners are contacted to obtain permission to establish a PSP.
4. If the land use is compatible with PSP objectives and will remain that way, and the owner plans to retain the land, a letter is submitted to the landowner requesting permission to establish a PSP. The landowner must grant written permission for a permanent plot to be established and allow the field crew to reenter the land for periodic remeasurement; the landowner will need to be contacted every 5 years. If a public agency manages the land, an appropriate land use permit is necessary; otherwise, a formal letter of permission is adequate.

Field sampling

Each site consists of three PSPs. Each PSP is located at least 100 ft into a forest stand or potential stand. The closest corner of any of the three PSPs must be at least 100 ft away from openings such as roads, trails, power lines, meadows, or stand openings to avoid an edge effect. The first of the three PSPs is randomly located using the following method: one person stands facing away from the stand, takes a corner post, and throws it back over his head into the stand. The point where the post lands is the first corner of the first PSP from which the rest of the site is established. At each corner and at the PSP center, a 1-ft-long metal post is driven into the ground; thus five posts mark each PSP. Flagging is tied around each corner and the center post so that they can be easily seen. Flagging is also hung in a tree near each post with the PSP number written on it.

The normal layout of the three PSPs at a site is triangular. The second and third PSPs are located 100 ft from the nearest corner of the initial PSP (fig.2.2). The second PSP is located on the left side of the initial PSP and the third PSP on the right side at angles of 45° going through the center and either the right or left corner points of the initial PSP. In a rare situation where PSPs cannot be established in the standard triangular layout, other layouts can be employed (fig.2.3). In alternate site layouts, the distance between each PSP is still 100 ft.

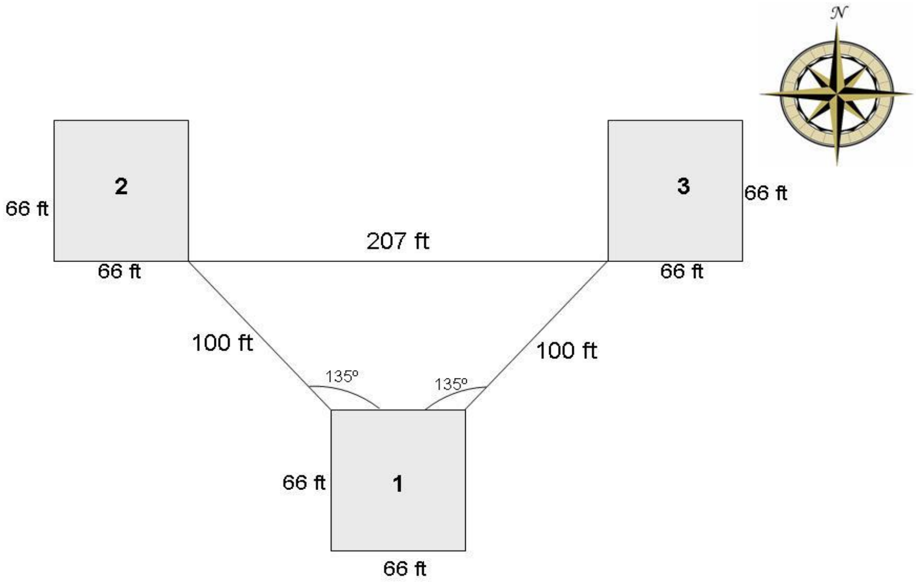


Figure 2.2 Typical CAFI plot layout within a site.

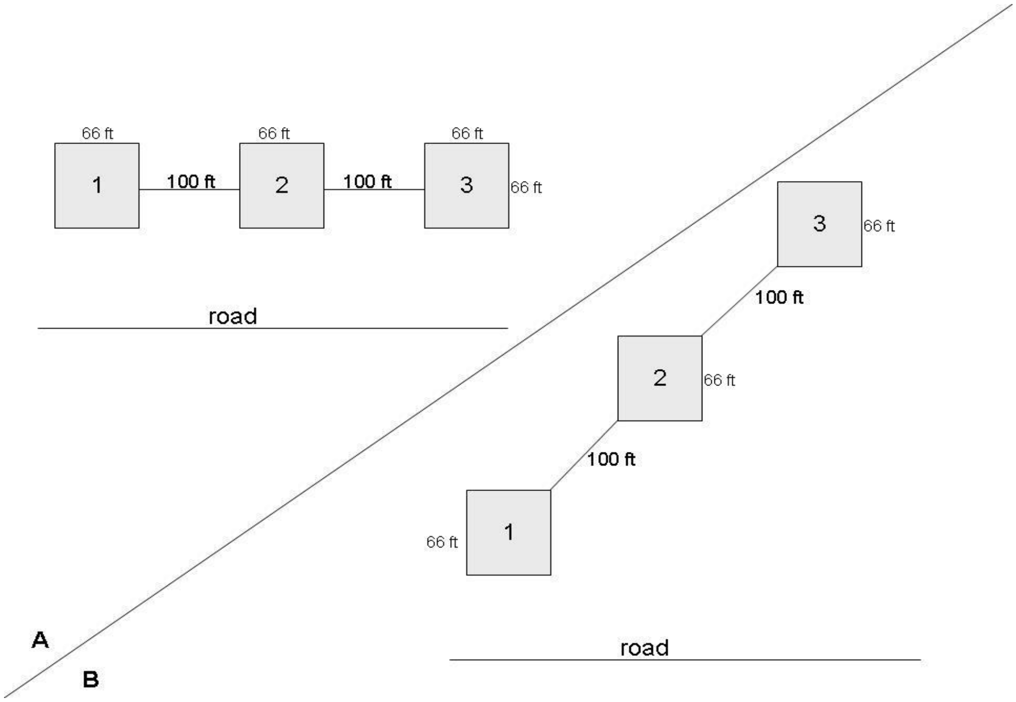


Figure 2.3 Two alternate CAFI plot layouts.

All PSPs are 0.1 ac and square with 66-ft sides (without regard to slope) (fig.2.2). The plots are laid out in the cardinal directions (north, south, east, and west). It is important to ensure that the PSPs are set up as square as possible by using a hand-held compass and tape measure. To improve accuracy, the diagonal is measured and should fall between 91.3 and 95.3 ft.

When revisiting a previously established site, the crew uses a site map and global positioning system (GPS) coordinates to bring the crew to the site and the approximate PSP centers; the previous flagging and corner stakes are used to reestablish plot boundaries. Once all PSPs are relocated, all corners and the center posts and the nearby tree are re-flagged before remeasurement.

Site data collection

Land ownership is determined from federal or state status plat maps (U.S. Department of the Interior or State of Alaska); because these are updated periodically, an office visit to the appropriate agency is necessary before remeasurement. The exact legal description of the site is determined and entered into the database after the crew comes back from the field.

The U. S. Public Land Survey System (USPLSS) is used to describe the general location of a PSP site. Data to be entered for each PSP are meridian, township, range, section, and quarter section of the site; this information is obtained from the appropriate U.S. Geological Survey (USGS) quadrant maps. Occasionally, a site is too close to a section line or township line to record the exact legal description from a map. Thus, on site, GPS coordinates are obtained for each PSP and retained in the GPS unit's memory.

The exact center of each PSP is recorded with a GPS unit. The GPS unit is set on the ground on top of the center post to acquire points. A point feature is selected and at least 100 readings are collected to accurately locate the site center. If the satellite signal is weak, it could take up to an hour to acquire at least 100 readings. These readings are then averaged to get accurate coordinates of the PSP center: the latitude, longitude, and elevation. These coordinates are also used to locate the plots for remeasurement.

The GPS coordinates for each of the three PSPs at a site are entered into a mapping program that provides the exact location and the USPLSS description of the PSPs. All the GPS coordinates in CAFI have been rounded to the nearest 0.01 degree for the purposes of security and privacy.

The following data are collected to complete the site sheet: date; crew; aspect; slope; presence of permafrost; slope position; contour; bedrock type; landform; soil texture, depth by horizon, color, and moisture; and percentage cover of deadwood, charcoal, mineral soil, litter, snags, trees, and understory vegetation by species.

Aspect identifies the direction of the slope of the PSP, basically which way water runs off the slope. The crew member holds the compass level, points it down slope and records the aspect. If the PSP is flat, aspect is recorded as “0.”

Percentage of slope is measured with a clinometer along the same compass bearing as for aspect. A crew person ties flagging, at eye level, to a tree at the lowest point on the PSP boundary and then moves to the highest point and sights on the lower flagging and records the percentage of slope. On variable slopes or where the slope appears flat, several measurements may be needed to get the average slope.

Permafrost is earth material that has had a temperature below 32 °F for 2 years or more. The presence of permafrost can be determined by observation of a soil pit, landscape position and/or using vegetation as an indicator. Three basic classes of permafrost exist across the Alaska boreal forest landscape: continuous permafrost occurs north of the Brooks Range and in western interior Alaska, discontinuous permafrost occurs in central and eastern interior Alaska and in the Copper River basin, and sporadic permafrost occurs in south-central Alaska. Permafrost on the Kenai Peninsula is extremely rare or lacking.

Slope position is the position of the PSP in relation to the surrounding topography as determined by observation.

Contour is the general form of the land surface within the PSP; determined by observation.

To determine bedrock types, we observe parent material on or below the surface either in or near the site. A USGS soil survey can be used to determine bedrock type.

Landform: is the name for the physical process that formed the topographic features within the PSP. Soil types and formation observed in a soil pit can assist in determining landform. Local soil survey maps and surface deposit maps and reports can also assist in determining landform.

Soil characteristics (Schoeneberger et al. 2002) are recorded for each PSP and are derived from a soil pit dug outside the PSP near the northwest corner. Soil pits are dug to the depth of 39 in or to parent material, whichever comes first. In most cases, mineral soil is found below the surface organic horizons. In some cases, this organic horizon can extend much deeper than 39 in.

Soil Texture: is the size and quantity of particles in the mineral soil layer as detected by touch. Texture is an estimate of the relative proportions of sand, silt, and clay particles. Soil texture follows the NRCS definitions of soil particles.

Organic Depth: includes all surface organic horizons in the soil pit. The surface organic horizons consist of fresh and well-decayed plant and animal litter. Measurement is total thickness of organic matter from the bottom of the live/green vegetation to the top of the underlying mineral horizons. Organic depth ranges from 0 to more than 39 in.

The Oi horizon is the uppermost organic horizon, also referred to as the L horizon. The Oi horizon consists of undecayed to slightly decayed plant material; leaves, needles, twigs, and roots are still recognizable. Thickness is measured, in inches, from the top of the litter to the top of the Oe, Oa, or mineral horizon.

The Oe horizon if present, is below the Oi horizon. This horizon is referred to as the F horizon. The Oe horizon consists of partially decayed plant material with little if any in its original condition; 7 to 75 percent is still fibrous after being rubbed between the fingers. Thickness is measured, in inches, from the bottom of the Oi horizon to the top of the Oa or mineral horizon.

The Oa horizon if present, is below the Oe or Oi horizon. It is referred to as the H horizon. The Oa horizon consists of well-decayed plant material with little if any in its original or fibrous condition; it is <7 percent fibrous by volume and has a greasy feel and tends to stain fingers. Thickness is measured, in inches, from the bottom of the Oe or Oi horizon to the top of the mineral horizon.

The mineral layer is measured from the bottom of the organic horizon, if present, to parent material or 39 in, whichever comes first. For measurement purposes, parent material (bedrock) begins when the shovel hits mostly broken-up rock fragments with little fine-grained material.

Soil color is the color of mineral soil in the soil pit and can be determined from the same soil sample used to identify soil texture. The color must be determined immediately after the soil is excavated from the pit. There can be numerous color horizons within a single soil pit. Color identification consists of three notations: hue, value, and chroma as defined in the Munsell soil color chart (Macbeth 2000) and in the glossary.

Soil moisture reflects the general soil drainage conditions in each PSP as observed in the amount of water in the soil. Observation of other site conditions can help determine soil moisture, such as wet shoes while working on the site, or a south-facing sparse aspen stand.

Cover class is a measure used to quantify the remaining attributes in the site table. To determine the cover class, the recorder imagines that they are looking down on the PSP from above and estimates the percentage of the PSP that is covered by each attribute.

To ensure that all the attributes are accurately estimated, a crew member must walk through the 0.1ac PSP several times, and the most accurate and efficient way to walk through the PSP is in a systematic pattern. Start in the northwest corner and walk to the northeast corner and then to the southeast corner, then to the southwest corner and finally back to the northwest corner. The recorder then moves into the plot a few feet and repeats the forgoing square pattern spiraling inward to the center. At this time, the recorder has observed the PSP characteristics and can assign a cover class to the appropriate site attributes.

Dead wood includes branches and twigs larger than 1 in diameter lying on the ground, standing dead tree less than 4.5 ft high, and other dead woody plants such as alder.

Charcoal includes burned wood observed in the soil pit as well as burned wood remaining on surface of site.

Mineral soil exposed includes soil exposed on a steep slope, by uprooted trees, or by various disturbances such as fire or flood.

Litter includes nonliving vegetative material such as dead leaves, cones, stems, and twigs smaller than 1 in diameter.

Snags are dead standing trees at least 4.5 ft tall.

Tree cover is the percentage of plot covered by numbered trees in the PSP.

Understory vegetation: includes all tree regeneration, shrubs, herbs, moss, lichen, and grass. The first three letters of the genus and the first three letters of the species are recorded for each species along with the percentage cover class.

At least four pictures are taken from the northwest corner of each PSP during each site establishment and subsequent remeasurements. The first picture is taken of a paper with the PSP number and current year written on it. The second picture is taken with the camera pointed toward the northeast corner. The third picture is taken with the camera pointed at PSP center. The fourth picture is taken with the camera pointed at the southwest corner. Additional pictures can be taken of unique features within or near the PSP.

Tree data collection

The CAFI tree data collection follows the procedures below:

1. Number the trees in the PSP.
2. Measure diameter at breast height (dbh) and paint a dbh band on each tree.
3. Assess the health of that tree.
4. Measure tree height and length of live crown.

Trees are numbered in a boustrophedonic (alternating direction) order starting in the northwest corner and moving toward the northeast corner of each PSP (fig. 2.4). Number tags are pinned into the ground on the east side of each tree. Trees in a PSP should be consecutively numbered in the proper order to make it easier to locate them in the future, and no number should be repeated in a site. In CAFI, tall shrubs are not considered trees. Trees less than 4.5 ft in height or less than 0.51 in dbh are not tagged or measured.

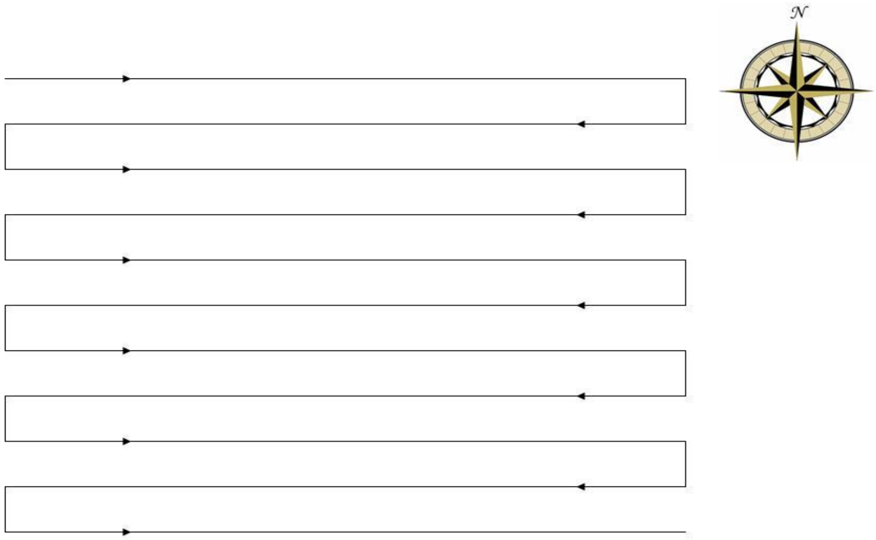
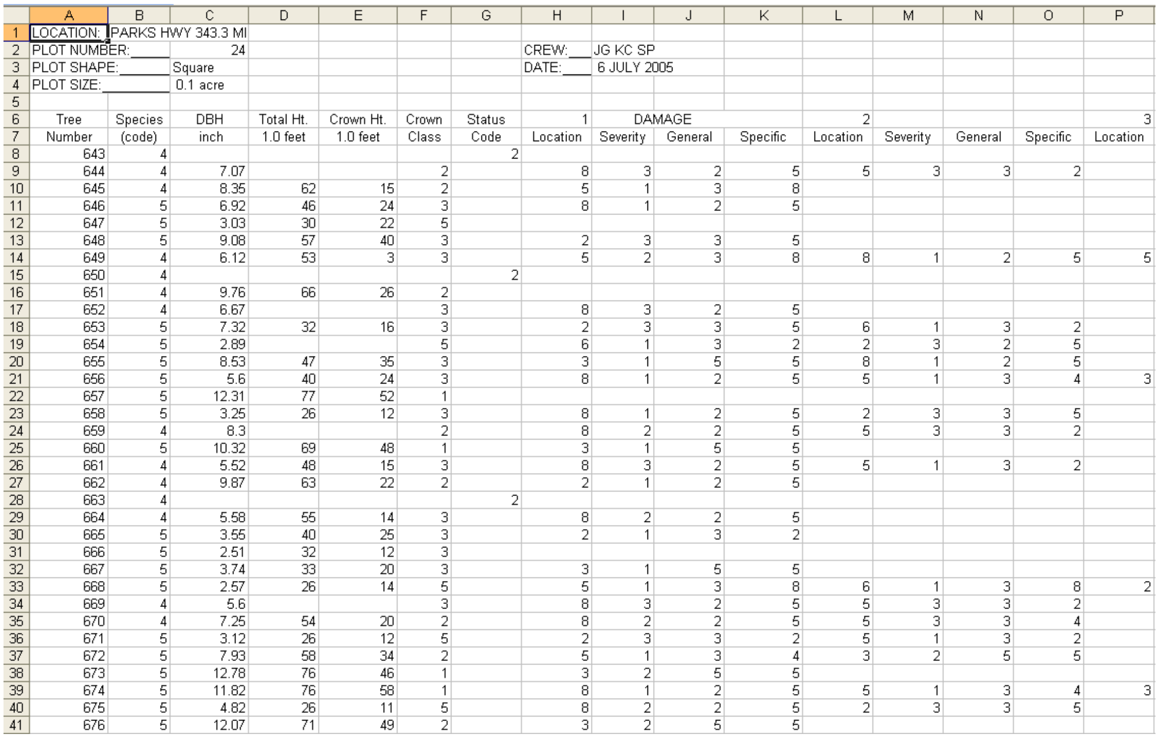


Figure 2.4 Order of tree numbering beginning in the northwest corner.

Trees on the line, either in or out of the PSP, need to be treated consistently. A borderline tree is determined based on the location of the center of the tree at ground level. Trees with their base more than halfway in the PSP are considered in the PSP. Trees that fall exactly halfway in and halfway out of the PSP are alternately counted as “in” or “out.”

In the field, tree data are also entered into a hand-held field computer. A tree data template is preloaded into a spreadsheet (fig. 2.5). All data recorded into the spreadsheet are in numeric codes or actual measurements. After returning from the field, all the data stored in the field computer are checked and transferred to the TREE_INVENTORY tables.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	LOCATION:	PARKS HWY 343.3 MI														
2	PLOT NUMBER:______		24					CREW:___	JG KC SP							
3	PLOT SHAPE:_______		Square					DATE:____	6 JULY 2005							
4	PLOT SIZE:_________		0.1 acre													
5																
6	Tree	Species	DBH	Total Ht.	Crown Ht.	Crown	Status	1	DAMAGE			2				3
7	Number	(code)	inch	1.0 feet	1.0 feet	Class	Code	Location	Severity	General	Specific	Location	Severity	General	Specific	Location
8	643	4					2									
9	644	4	7.07			2		8	3	2	5	5	3	3	2	
10	645	4	8.35	62	15	2		5	1	3	8					
11	646	5	6.92	46	24	3		8	1	2	5					
12	647	5	3.03	30	22	5										
13	648	5	9.08	57	40	3		2	3	3	5					
14	649	4	6.12	53	3	3		5	2	3	8	8	1	2	5	5
15	650	4					2									
16	651	4	9.76	66	26	2										
17	652	4	6.67			3		8	3	2	5					
18	653	5	7.32	32	16	3		2	3	3	5	6	1	3	2	
19	654	5	2.89			5		6	1	3	2	2	3	2	5	
20	655	5	8.53	47	35	3		3	1	5	5	8	1	2	5	
21	656	5	5.6	40	24	3		8	1	2	5	5	1	3	4	3
22	657	5	12.31	77	52	1										
23	658	5	3.25	26	12	3		8	1	2	5	2	3	3	5	
24	659	4	8.3			2		8	2	2	5	5	3	3	2	
25	660	5	10.32	69	48	1		3	1	5	5					
26	661	4	5.52	48	15	3		8	3	2	5	5	1	3	2	
27	662	4	9.87	63	22	2		2	1	2	5					
28	663	4					2									
29	664	4	5.58	55	14	3		8	2	2	5					
30	665	5	3.55	40	25	3		2	1	3	2					
31	666	5	2.51	32	12	3										
32	667	5	3.74	33	20	3		3	1	5	5					
33	668	5	2.57	26	14	5		5	1	3	8	6	1	3	8	2
34	669	4	5.6			3		8	3	2	5	5	3	3	2	
35	670	4	7.25	54	20	2		8	2	2	5	5	3	3	4	
36	671	5	3.12	26	12	5		2	3	3	2	5	1	3	2	
37	672	5	7.93	58	34	2		5	1	3	4	3	2	5	5	
38	673	5	12.78	76	46	1		3	2	5	5					
39	674	5	11.82	76	58	1		8	1	2	5	5	1	3	4	3
40	675	5	4.82	26	11	5		8	2	2	5	2	3	3	5	
41	676	5	12.07	71	49	2		3	2	5	5					

Figure 2.5 Example of tree data template in a spreadsheet.

Diameter at breast height

The diameter of each tagged tree is measured at breast height (4.5 ft) (see fig. 2.6). Tree records are measured to the nearest 0.01 in. A band of red paint is applied around the bole with a paint stick at the place where the diameter measurement is taken. Figure 2.6 illustrates various deviations from a diameter measurement:

•If a tree is growing on a slope, the measurement is taken on the high (uphill) side of the tree at 4.5 ft above the ground **(**fig. 2.6b).

•If a tree is leaning, the measurement is taken on the up side of the tree (fig. 2.6c).

•If the stem of a tree is forked below breast height, each stem is treated as a separate tree (fig. 2.6d). Therefore, two numbered tags are placed at the base of the stem. They are both measured and recorded separately.

•If a tree has deformity on the bole at breast height which prevents an accurate or representative diameter measurement, the measurement is taken above or below the deformity where the bole resumes a “normal” taper **(**fig. 2.6e).

•Finally, if two stems have grown too close together to fit a tape measure between the stems, each stem is treated as a separate tree. Diameter is measured with a caliper, or a mark is placed halfway around the stem and a radial measurement is taken and multiplied by two for a diameter determination **(**fig. 2.6f).

The diameter is recorded to the nearest 0.01 in column C. If the tree is a young conifer, it may not be possible to take an accurate diameter measurement because of guard hairs (needles) surrounding the stem.

The crown class of each tree is entered in column F. Trees within a PSP are coded as either dominant, codominant, intermediate, suppressed, understory, or overstory.

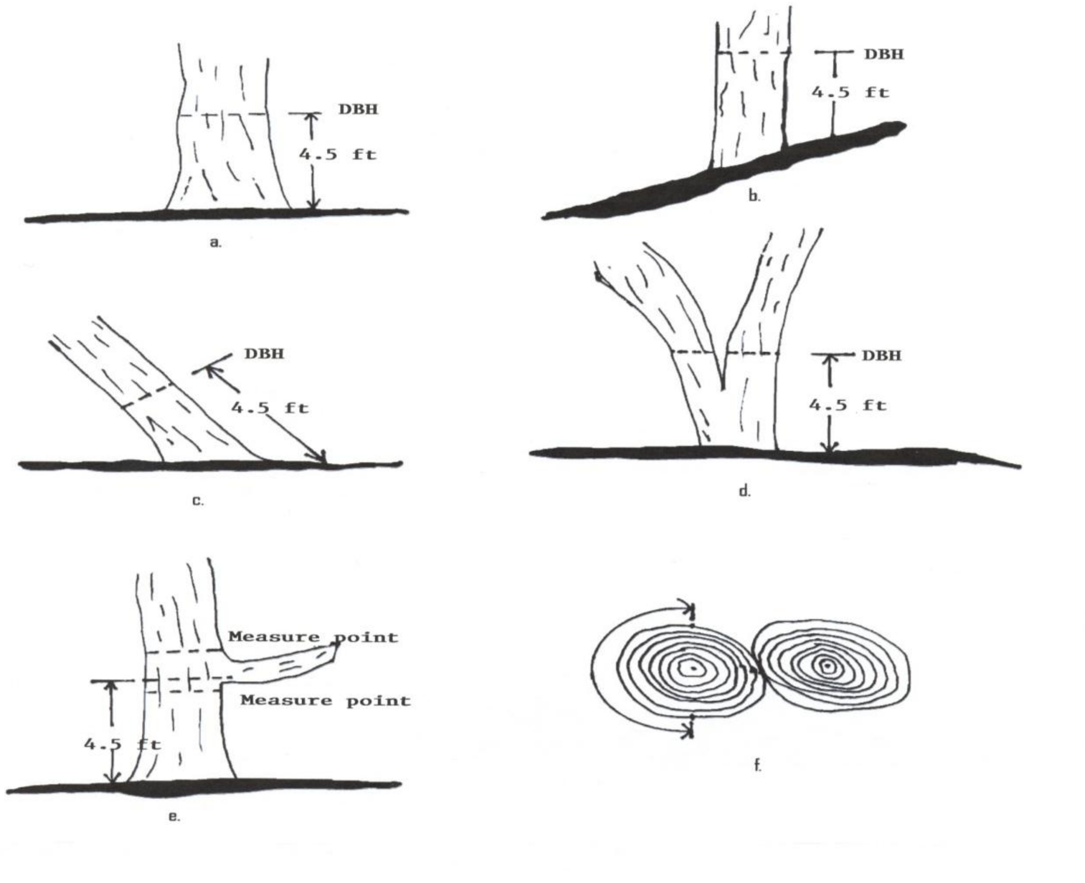


Figure 2.6 Methods for measuring diameter at breast height when (a) the tree is on level ground, (b) the tree is on a slope, (c) the tree is leaning, (d) the tree is forked below breast height, (e) the tree has an irregular bole at breast height, and (f) tree boles touch at breast height.

Tree status and visual defects

Tree status category lists a wide variety of tree conditions from live to dead to having a missing numbered tag from previous inventories. It also allows notation that a current inventory measurement is correct and a previous measurement was incorrect. The remaining 16 columns, H through W, in the tree data template (fig.2.5) identify visual defects on the tree for up to four damages. The damage is identified by its location on the tree (top, limbs, foliage, bole, base or roots), the severity, and the general and specific type of visual damage. This code classification is broken down into two parts: the general classification includes crown disease, bole disease, insects, and weather; the specific damage code includes spruce needle cast, fluting, ants, and winter burn. For example, the damage/defect code of a tree that is forked at the base would be 6332 (bole defect, severe damage, bole disease or abnormality, multiple stems or forks).

Tree height

Total tree height and live crown length are measured with a hypsometer (fig.2.7) and recorded into the tree data template in column D and E. There are numerous types of hypsometers such as a Biltmore stick, an Abney level, clinometer, relascope, and a laser hypsometer. Currently, the most accurate, fastest, and easiest instrument with which to measure heights is a laser hypsometer such as an Impulse laser hypsometer.

In an area such as an open stand where there is no obstruction between the laser instrument and the target tree, the distance measurement can be shot directly from the bole of the tree to the laser instrument. In most forested stands, however, there are too many obstructions for a laser beam to strike the target tree bole directly. The laser could hit a branch or leaf and give a false distance reading. In this case, the filter mode must be selected in the Impulse laser. To acquire an accurate distance measurement in the filter mode, a laser reflector must be placed at the bole of the tree. The first measurement of distance is shot at the laser reflector (fig.2.7, measurement 1). The person that is measuring diameter can hold up a laser reflector for the person measuring height. The measurements taken at the base and top are angle measurements and do not need to strike a laser reflector. In forested stands, where the laser operator must stand a long distance from the target tree, it is often necessary for someone to shake the tree so the correct tree top can be identified and measured.

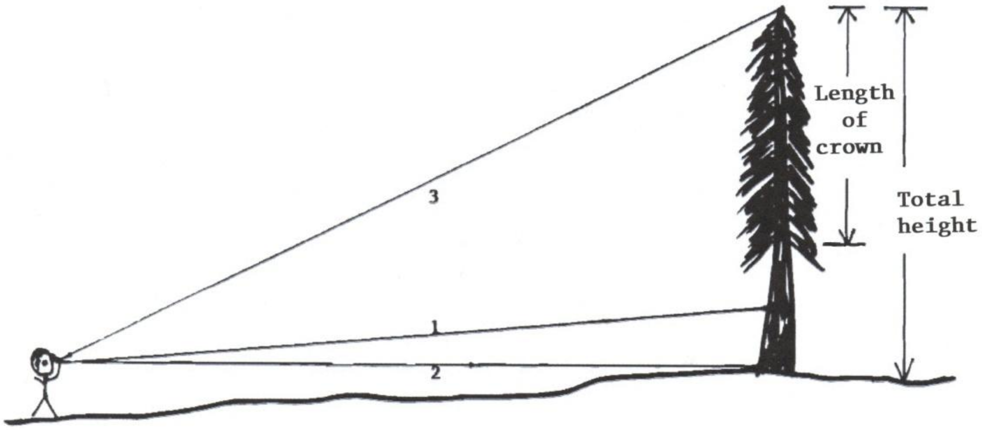


Figure 2.7 Tree height measurements where measurement 1 is the distance between the operator and the target tree, measurement 2 is the distance between the operator and the ground at the base of the target tree, and measurement 3 is the distance between the operator and the top of the target tree.

Crown class and length

Crown class is the relative position of the tree crown with respect to the competing vegetation around it. Crown class for each tree is judged visually in the context of its immediate environment, which includes trees or shrubs competing for sunlight with the subject tree. In CAFI, crown class categories include dominant, codominant intermediate, suppressed, overstory, and understory.

The live crown starts at a point where the first continuous live crown branches protrude from the bole, without regard for branch droop. epicormic branching, low on a bole, is not considered part of the continuous live crown. To acquire the length of live crown, the Impulse 200 is pointed at the bottom of the live crown to obtain the distance from the base of the tree to the bottom of the live crown. This distance is then subtracted from the total tree height to determine the length of live crown.

Regeneration Data Collection

There are five plots to estimate the amount of tree regeneration on each PSP (fig. 2.8). These regeneration plots are 1/250 of an acre in size. The radius of the plot is 7.45 ft. Use a piece of ½ in electrical conduit 7.45-ft long to determine plot radius.

The center of the first regeneration plot is at the PSP plot center. The other four regeneration plots are located 23 ft from plot center toward the PSP plot corners. From the plot center measure out 23 ft toward the northwest PSP corner and put in a flagged pin (same pins used to pin tree numbers to the ground). This is the center of the NW regeneration plot. Follow the same procedures to establish the regeneration plots toward the NE, SE, and SW corners.

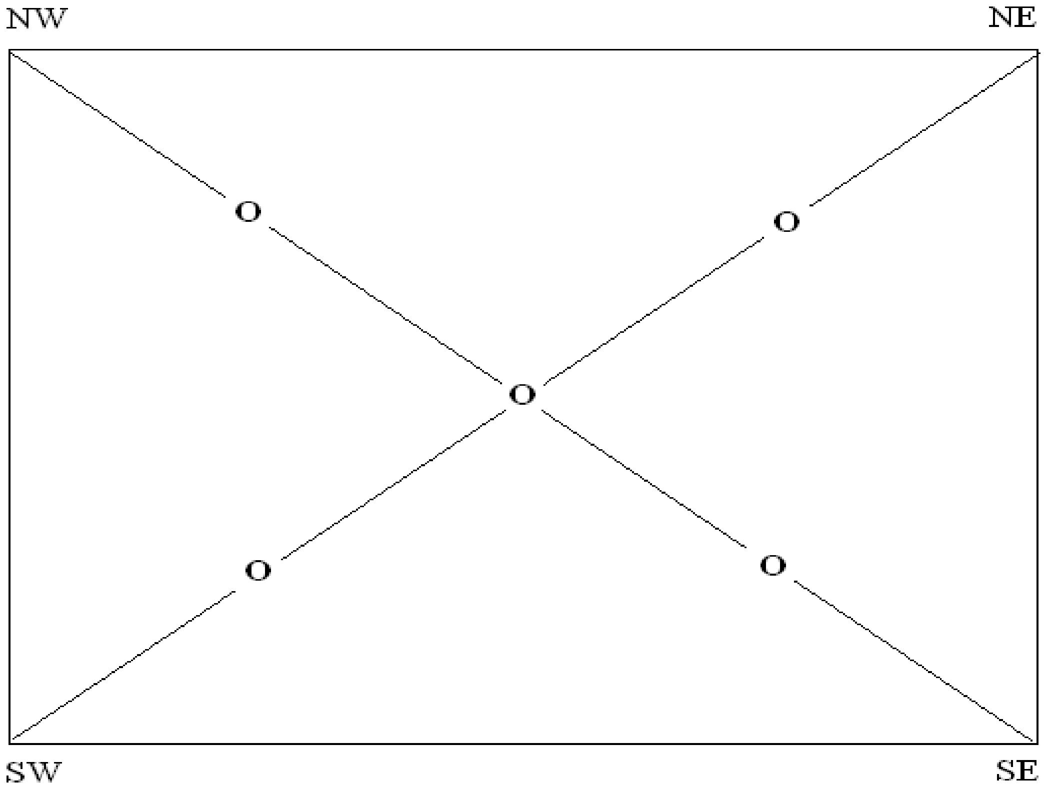


Figure 2.8 Regeneration plot layout.

Tree regeneration data is counted by species, size class, and tree vigor. The size class categories are: less than 0.5 ft, between 0.5 ft and 4.5 ft, and greater than 4.5 ft but not larger enough at dbh (0.51 in) to be considered a tree. The vigor categories are: poor

= seedling or sapling looks unhealthy and probably will not be alive at the next inventory; fair = almost no growth, could be crooked, injured; good = seedling or sapling shows normal growth and is free of major defect; excellent = tree has above average growth and is free of defect.

Holding one end of the regeneration pole at plot center, swing the pole around 360° and record a count of each seedling or sapling encountered in the regeneration plot.

Crown cover is measured at each regeneration plot center; record the percent crown cover using a convex spherical crown densitometer. Four readings are taken of crown cover over the plot center; one estimate in each of the cardinal directions and average the four readings. Record this data in the regeneration template.

Database Structure and Description

The CAFI database is composed of key tables and description tables stored in a single Microsoft® Office Access 2003 database. The current version of the database (CAFI 1.0) has four key tables: SITE, TREE_INVENTORY_1, TREE_INVENTORY_2, and TREE_INVENTORY_3. The definition of each coded variable was provided by the description tables in the same database.

The table provides detailed site-level records, including the location, geographic features, site characteristics, and crew records. TREE_INVENTORY_n provides tree-level records of the nth inventory (e.g., TREE_INVENTORY_1 contains tree records from the first inventory). All the key tables are related by the PSP identification numbers (PSP and TREE-ID, respectively) (fig.2.8) so that users can relate tree records to the characteristics of the site that these trees grow on.

The following sections give detailed description of site and tree records and summary statistics of all the measurements. For each coded attribute, there is a table explaining the description of all the classes.

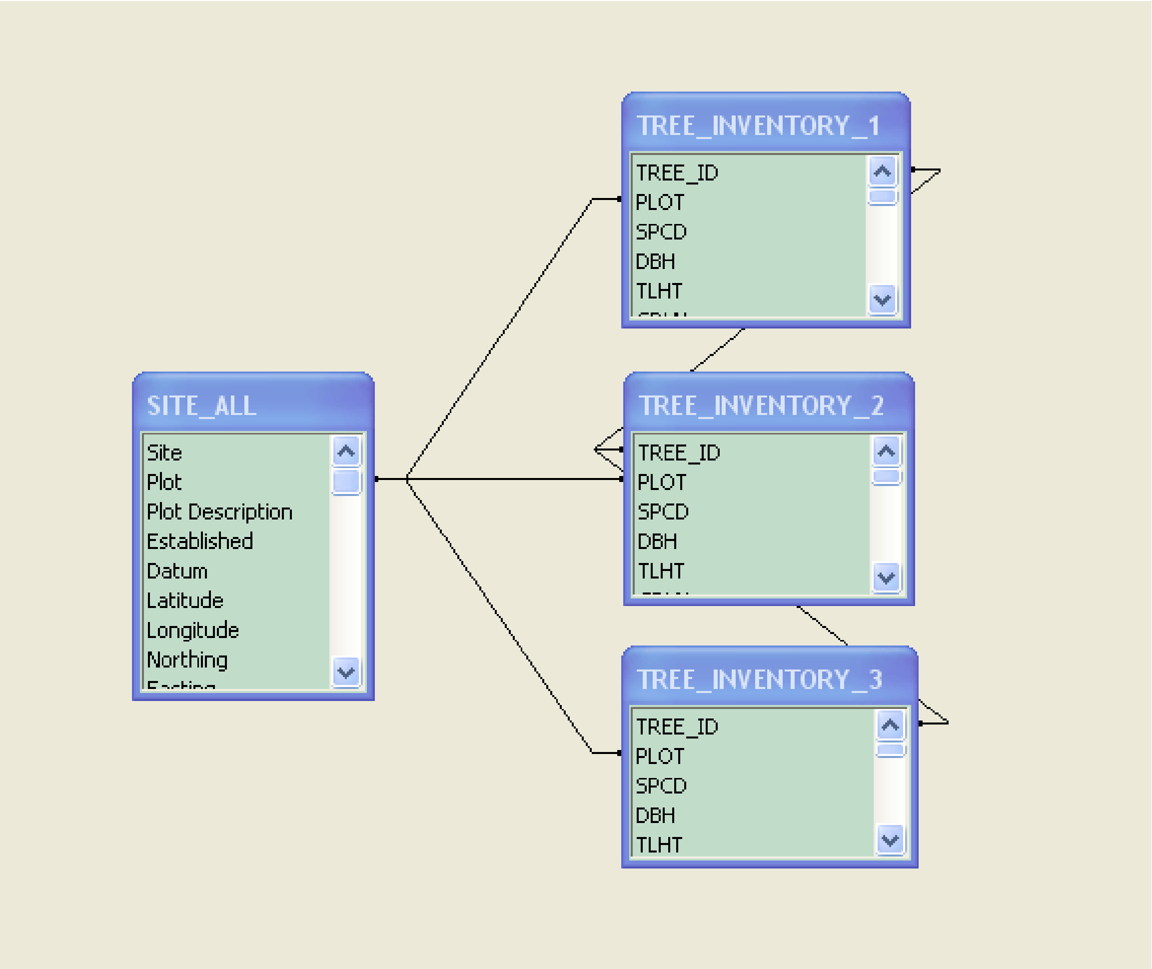


Figure 2.9 Relationships among the key tables.

Site Records

There are 37 site attributes. Their name, data type, and unit are listed in table 1. The detailed description is given below:

Site: A unique sequential number used to identify each site.

PSP: A unique sequential number used to identify each 0.1ac PSP.

Site description: A short paragraph describing location and other unique features of the site.

Established: Month, day, and year of the site establishment.

Ownership: Landowner and/or manager of the site area (coded list in table 2).

Datum: Set of reference points on the Earth's surface against which position measurements are made.

Latitude: Geodetic latitude of the PSP in decimal degrees.

Longitude: Geodetic longitude of the PSP in decimal degrees.

Elevation: Elevation of the PSP in feet obtained from GPS unit or USGS map.

MERI: USGS code for mapping Alaska.

TWSP: Township (USGS code).

RANG: Range (USGS code).

SECT: Section (USGS code).

QTSC: Quarter section (USGS code).

CREW: Initials of each crew member.

DATE: Month, day, and year of the current inventory.

ASPC: Aspect as measured with a hand held-compass to the nearest degree (1° to 360°). A zero is recorded if the PSP is flat.

SLOP: Percentage of as measured to the nearest percent (0 to 90 percent).

PERM: presence of permafrost (table 2.3).

SLPO: Slope position is the position of the PSP in relation to the surrounding topography as determined by observation. Detailed description in table 2.4 and illustration in fig. 2.9.

CONT: Contour shape is the general form of the land surface within the PSP as determined by observation. See a detailed description in table 2.5.

BDRK: Presence or absence of bedrock on or beneath the PSP. Observe parent material on or below the surface either in or near the site (table 2.6).

LNFM: Landform (table 2.7).

SOTX1 and SOTXII: Soil texture for mineral soil layers 1 and 2, respectively (table 2.8).

SOOR: Thickness of all surface organic horizons in inches.

SOOi: Thickness of the Oi horizon in inches.

SOOe: Thickness of the Oe horizon, if present.

SOOa: Thickness of the Oa horizon, if present.

SOMD: Depth of mineral soil to nearest 0.1 in

SOCI and SOCII: Color of the first and second mineral soil horizons.

SOMO: General soil drainage conditions (table 2.9).

DDWD: Percentage of dead wood cover (table 2.10).

CHAR: Percentage of the PSP covered with charcoal (table 2.10).

MNSO: Percentage of PSP with mineral soil exposed (table 2.10).

LTER: Percentage of PSP covered with litter (table 2.10).

SNAG: Number of snags on the PSP.

Table 2.1. **Permanent sample plots site and plot attributes**

Attribute	Full name	Data type	Value or unit
Site	Site number	Integer	Number
PSP	PSP number	Integer	Number
Site description	Site description	Character	Description
Established	Date of establishment	Date	MM/DD/YYYY
Ownership	Landowner/manager	Character	Code
Datum	Datum	WGS84	Code
Latitude	Latitude of the PSP	Real number	Decimal degrees
Longitude	Longitude of the PSP	Real number	Decimal degrees
Elevation	PSP elevation	Real number	Feet
MERI	Meridian	Character	Coded
TWSP	Township	Character	Coded
RANG	Range	Character	Coded
SECT	Section	Integer	Number
QTSC	Quarter section	Character	Two letters
CREW	Crew names, current inventory	Character	Name
DATE	Current inventory date	Date	MM/DD/YYYY
ASPC	Aspect	Real number	Degrees
SLOP	Slope	Real number	Percent
PERM	Permafrost	Integer	Coded
SLPO	Slope position	Integer	Coded
CONT	Contour	Integer	Coded
BDRK	Bedrock	Integer	Coded
LNFM	Landform	Integer	Coded
SOTXI	Soil texture 1	Integer	Coded
SOTXII	Soil texture 2	Integer	Coded
SOOR	Organic horizon thickness	Real number	Inches
SOOi	Thickness Oi (L)	Real number	Inches
SOOe	Thickness Oe (F)	Real number	Inches
SOOa	Thickness Oa (H)	Real number	Inches
SOMD	Thickness of mineral soil	Real number	Inches
SOCI	Soil color 1	Character	Coded
SOCII	Soil color 2	Character	Coded
SOMO	Soil moisture regime	Integer	Coded
DDWD	Deadwood current inventory	Integer	Coded
CHAR	Charcoal current inventory	Integer	Coded
MNSO	Mineral soil current inventory	Integer	Coded
LTER	Litter current inventory	Integer	Coded
SNAG	Number of snags current inventory	Integer	Number

Table 2.2. Land ownership description

Class	Description
STATE	State of Alaska Department of Natural Resources Division of Lands
STATEP	State of Alaska Department of Natural Resources Division of Parks
STATEM	State of Alaska Mental Health Trust Lands
STATEF	State of Alaska Department of Fish and Game
FNSB	Fairbanks North Star Borough
KPB	Kenai Peninsula Borough
MSB	Matanuska Susitna Borough
AHTNA	Ahtna Regional Native Corporation
CIRI	Cook Inlet Regional Native Corporation
DLVC	Dot Lake Village Corporation
NVC	Northway Village Corporation
UA	University of Alaska Statewide Land Management
UAAFES	University of Alaska Agricultural and Forestry Experiment Station
DODA	U.S. Department of Defense, Army
DODAF	U.S. Department of Defense, Air Force
BLM	U.S. Department of the Interior, Bureau of Land Management
KNWR	U.S. Department of the Interior, Fish and Wildlife Service, Kenai National Wildlife Refuge
WSENP	U.S. Department of Interior, National Park Service, Wrangell St. Elias National Park

Table 2.3. Permafrost classification

Code	Class	Description
1	Near surface	Permafrost obviously present. It is near the surface, within 2 ft, and is usually ice rich. In these situations the permafrost forms an impermeable layer blocking drainage. The soil is usually saturated near the surface and has a thick organic horizon. Tree growth is commonly stunted.
2	Probably	The active layer is thick (>3 ft) or there is not much ice present, permafrost may not be conclusively evident but some evidence suggests it is present. This may occur in better drained north-facing stony soils or in transition zones. Items to look for are thermokarst activity such as pits and tilting trees, or depressed growth rates of trees. Sites that are northeast - or northwest - facing are suspect. Upland slopes that have near saturated soils are suspect.
3	Probably Not	No real strong evidence indicates permafrost presence on this plot. The sites may be flat or near the lower portions of south-facing slopes or along the floodplain where the trees show vigorous growth. This situation may arise when a site obviously had permafrost at one time but the vegetation has been cleared so that the permafrost has melted to some depth.
4	None	Warm, well to moderately well-drained sites on south-facing slopes and along active river channels.
5	Unknown	

Table 2.4. Slope position

Code	**Class**	**Description**
1	Crest	The generally convex uppermost portion of a hill. It is usually convex in all directions. No distinct aspect. A moisture-shedding site
2	Upper slope	The generally upper portion of the slope of a hill. It has a convex surface profile with a specific aspect. It is a moisture-receiving and -shedding site
3	Mid slope	The area of the slope between the upper slope and the lower slope. The general profile is neither concave nor convex; it has a straight or undulating surface profile with a specific aspect. A moisture-receiving and -shedding site.
4	Lower slope	The area near the base of the slope of the hill; where the percentage of slope lessens. It generally has a concave surface profile with a specific aspect. It is a moisture-receiving site.
5	Toe	The lower part of the slope with greatly reduced percentage of slope. It may be demarcated by an abrupt leveling of slope and change in vegetation. Moisture-receiving site, often characterized by seepage.
6	Depression	Area concave in all directions. Typically flat or gently sloping topography. Normally, a poorly drained site, receiving moisture and possibly wet.
7	Stream bottom	Area near an active waterway characterized by level surface or slight slope toward stream. Surface and soil moisture controlled by fluvial activity.
8	Bench/flat	Area more-or-less level area and not directly influenced by adjacent topography. Little or no aspect. Moisture is from precipitation.

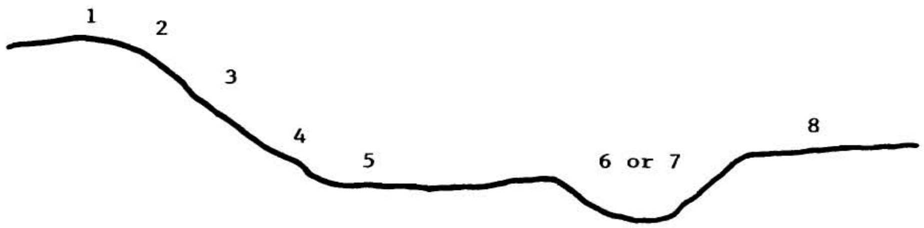


Figure 2.10 Slope position code in relation to the surrounding topography (see detailed description in Table 2.4).

Table 2.5. **Contour types**

Code	Class	Description
1	Convex	Surface curved upward like the top half of a sphere.
2	Straight	Surface generally free of curves, bends, and irregularities.
3	Concave	Surface that is curved inward like the inside of a bowl.
4	Undulating	Surface wavy; landscape fluctuates with rises and falls.

Table 2.6. **Bedrock types**

Code	Class	Description
1	Igneous	Igneous rock is formed by solidification from a molten or partially molten state. This designation involves both the deep-seated plutonic igneous rocks as well as the shallow intrusive and volcanic or extrusive igneous rocks.
2	Metamorphic	Metamorphic rocks are those formed by the alteration in composition, texture, or internal structure of preexisting consolidated rocks subjected to heat, pressure, and the introduction of new chemical substances.
3	Sedimentary	Sedimentary rocks are formed by the accumulation of sediment in water or from air. The sediments may consist of detrital fragments of various-size (conglomerate, sandstone, siltstone, shale) remains of products of plants or animals (coal, limestone), chemical action (precipitation), or evaporation (salt, gypsum, some carbonate rocks) or combinations of these minerals/processes.
4	None	Indeterminable.

Table 2.7. Landform

Code	Class	Description
1	Colluvial	Material moved down slope chiefly by gravity. Composition of deposits vary widely. Avalanche, rock glaciers, landside, mudflow, solifluction, and talus.
2	Aeolian	Deposits consist of silt and fine sand eroded, transported, and then deposited by wind action. Loess deposits in interior Alaska, sand dunes.
3	Floodplain (active)	Deposits consist of sediments transported and deposited by flowing rivers and streams. Generally fine-grained cover deposits laid down above the riverbed deposits during bank overflow. Usually an active floodplain is permafrost free and has active groundwater moving through. It is adjacent to the active channel and is occasionally flooded. Soil profile has alternating bands of deposition and frequently have buried organic horizons.
4	Floodplain (abandoned)	Older, generally frozen portion of a floodplain with a surface layer of ice-rich lowland loess and fine-grained material up to 10 ft thick over granular deposits. Commonly it has tussocks, bogs, and stunted black spruce. Removal of vegetation causes permafrost to recede.
5	Floodplain (other)	Other floodplain/fluvial deposits such as alluvial fan, terrace deposits, mud volcanoes, deltaic, and glacial outwash.
6	Lowland muck	“Re-transported deposits” of fine-grained, organic rich materials moved down slope by slope wash, solifluction, and in some cases by underground erosion. This landform is commonly frozen and contains massive ice. The lowland muck landform can be distinguished from abandoned floodplain in that it must have some slope to this landform.
7	Glacial	Formed in direct contact with glacial ice. Deposits range from unsorted, unstratified, silt, sand, gravel, and boulders, to poorly sorted sand and gravel with some boulders and some local stratification. Examples are moraines, till sheets, drumlins, and compacted till.
8	Lacustrine	Typically fine-grained sediments (silt and clay) that were deposited in both glacial and non-glacial lakes. Lake sediments are generally well stratified into very thin laminations.
9	Marine	Any materials deposited within saltwater bodies under an ocean and along the margins. Composed of very fine-grained to coarse-grained material. Examples: beach spit, bar, and coarse-grained shallow and inter-tidal deposits.

Table 2.7. continued

10	Organic	Decaying plant and animal matter; humus, muck, peat, with or without small amounts of fine-grained sediments (silt and clay). Examples are swamps, bogs, wet sedge fens, and muskegs.
11	Residual	Materials weathered in-place from underlying bedrock.
12	Manmade	Deposits or surface materials resulting from human activity, particularly construction and mining.

Table 2.8. Soil texture

Code	Class	Description
1	Gravel	Rock material. Gravel can range from pea size to boulders. It includes river gravel, which is smooth, to weathered bedrock, which can be chunky or platy
2	Sand	Particle size 2.0 to 0.05 mm. Individual particles feel gritty when the soil is rubbed between the fingers. Not plastic or sticky when moist
3	Loam	A mixture of sand, silt, and clay. It is fairly soft with evident graininess
4	Silt	Particle size 0.05 to 0.002 mm. Feels smooth and powdery when rubbed between the fingers. Not plastic or sticky when moist.
5	Clay	Particle size less than 0.002 mm. Feels smooth, sticky, and plastic when moist. Forms a ribbon when rolled in hand. Forms hard clods when dry.
6	Organic	Decomposing vegetative material. May contain small amounts of mineral soil and small amounts of partially decomposed roots.
7	Ash	Particle size less than 2.0 mm. Volcanic ash is fine rock and mineral particles that are ejected from a volcanic vent. Feels hard and abrasive to the touch.

Classes follow the Natural Resources Conservation Service definitions.

Table 2.9.Soil moisture

Code	Class	Description
1	Peraquic	Soil is saturated for most of the year when the soil is not frozen. During the driest part of the growing season, water is found above, at, or just below the surface of the mineral soil. Peraquic soil is commonly found in surface organic layers. The soil is extremely poorly drained.
2	Aquic	Soil is saturated during a large part of the year. During the driest part of the year, the water level in the soil may drop below the mineral soil surface but is always within 1 foot of the mineral surface. Thin organic horizons may dry out completely; organic horizons greater than 1-ft may be wet at low levels. The soil is poorly drained. Soil saturation may be due to high groundwater level because of nearby water courses or water perched by underlying permafrost.
3	Subaquic	Soil is saturated during a significant portion of the year. During the growing season the water level in the soil commonly drops below the surface of the mineral soil. The water table may fluctuate owing to runoff or changes in river level. Organic horizons may dry out; free water is not readily available to plants. The soil is somewhat poorly drained. Typically water is slow moving but may rise rapidly.
4	Perhumid	Soil is well- to moderately well-drained and has an abundant supply of moving well-oxygenated water. Generally the soil has adequate moisture in a portion of the rooting zone during the growing season. Often a distinct root mat occurs immediately above the surface in the zone of free-flowing water. With some exceptions, perhumid soil moisture is found between mid slope and valley floor or on benches and along streams or rivers.
5	Humid	Soil is classified as well-drained with an adequate water supply for growth during a majority of the growing season. Free water is only present during the spring thaw or following extended periods of rain.
6	Subhumid	Soil is dry for a considerable period of the growing season. Typically, subhumid sites occur only on southern exposures, on coarse soil material such as gravels or sands, or on convex slopes such as ridges and upper slopes.
7	Subxeric	Soils are extremely dry for growing conditions. These sites are confined to southern aspects and occasionally thin soils overlying bedrock. Water is a limiting factor for plant growth.
8	Xeric	Soil is dry in all parts of the rooting zone. Xeric soils are only found on south-facing aspects and steep slopes from upper through mid slopes. For most of the growing season, soil moisture is limiting for vegetative growth.

Table 2.10. **Deadwood, charcoal, mineral soil, litter, and tree cover class**

Class	Cover on the Permanent sample plot
0.5	Trace percent
1	1 to <5
2	5 to <25
3	25 to <50
4	50 to <75
5	75 to <95
6	>95

Tree Records

There are 28 tree attributes. Their names, data types, and units are listed in table 2.11. Detailed descriptions are given below:

TREE_ID: Unique 5 digit number assigned, in the database, for each tree.
(linked to plot and TAG_NUMBER).

PSP: PSP number.

TAG_NUMBER: Tag number assigned in the field to each tree.

SPCD: Tree species by a number code. See table 2.12 for details.

DBH: Present diameter measured at 4.5 ft aboveground on the high side of tree (to the nearest 0.01 in).

TLHT: Present total tree height measured from ground to top of live crown (to the nearest foot).

CRLN: Present crown length measured from bottom of live crown to top of live crown (to the nearest foot).

PREVDBH: Diameter at breast height measured at the previous inventory (to the nearest 0.01 in).

PREVTLHT: Total tree height measured at the previous inventory (to the nearest foot).

PREVCRLN: Crown length at the previous inventory measured from bottom of live crown to top of live crown (to the nearest foot).

CRCL: Coded crown class. See table 2.13 for details.

STAT: Status of each numbered tree. See table 2.14 for details.

DLO1 to DL04: Location of the four most prominent visual damages on tree. See table 2.15a for code details. DLO1 represents the most outstanding damage, and DLO4 the least. Location codes:

0 = No damage
1 = Damage not specified
2 = Tip of tree
3 = Foliage
4 = Limb
5 = Bole, 2 ft and above
6 = Base, below 2 ft
7 = Roots
8 = Leaning or bent tree
9 = Down tree

DSV1 to DSV4: Severity of the four most prominent visual damages on tree. DSV1 represents the most outstanding damage, and DSV4 the least. See table 2.15b for code details. Severity codes:

0 = Unspecified.
1 = Minor; ≤ 10 percent defect/damage.
2 = Moderate; 11 to 40 percent defect/damage.
3 = Severe; > 40 percent defect/damage.

DTY1 to DTY4: General type of the four most prominent visual damages on tree. DTY1 represents the most outstanding damage, and DTY4 the least. See table 2.15c for code details.

DSP1 to DSP4: Specific cause and nature of the four most prominent visual damages on tree. DSP1 represents the most outstanding damage, and DSP4 the least. See specific damage codes in table 2.15c.

Table 2.11. Tree inventory variables

Column	Name	Data type	Value or unit of measure
TREE_ID	Tree ID	Integer	Index
PSP	PSP number	Integer	Index
TAG_NUMBER	Tag number	Integer	Index
SPCD	Species code	Integer	Coded
DBH	Diameter at breast height	Real number	Inches
TLHT	Total height	Real number	Feet
CRLN	Crown length	Real number	Feet
PREVDBH	Diameter at breast height for the previous inventory	Real number	Inches
PREVTLHT	Total height for the previous inventory	Real number	Feet
PREVCRLN	Crown length for the previous inventory	Real number	Feet
CRCL	Crown class	Integer	Coded
STAT	Status	Integer	Coded
DLO1	Damage location 1	Integer	Coded
DSV1	Damage severity 1	Integer	Coded
DTY1	Damage type 1 (general)	Integer	Coded
DSP1	Damage specific 1	Integer	Coded
DLO2	Damage location 2	Integer	Coded
DSV2	Damage severity 2	Integer	Coded
DTY2	Damage type 2 (general)	Integer	Coded
DSP2	Damage specific 2	Integer	Coded
DLO3	Damage location 3	Integer	Coded
DSV3	Damage severity 3	Integer	Coded
DTY3	Damage type 3 (general)	Integer	Coded
DSP3	Damage specific 3	Integer	Coded
DLO4	Damage location 4	Integer	Coded
DSV4	Damage severity 4	Integer	Coded
DTY4	Damage type 4 (general)	Integer	Coded
DSP4	Damage specific 4	Integer	Coded

Table 2.12. Tree species code

Code	Common name	Scientific name
1	Alaskan birch	*Betula neoalaskana* Sarg.
3	Black cottonwood, balsam poplar	*Populus trichocarpa* Torr. &Gray, *P. balsamifera* L.
4	Quaking aspen	*Populus tremuloides* Michx.
5	White spruce	*Picea glauca* (Moench) Voss
6	Black spruce	*Picea mariana* (Mill.) B.S.P.
7	Tamarack	*Larix laricina* (DuRoi) K.Koch
8	Kenai birch	*Betula kenaica* W.H. Evans
9	Lodgepole pine	*Pinus contorta* Dougl. Ex Loud.
10	Mountain hemlock	*Tsuga mertensiana* (Bong.) Carr.
12	Lutz spruce	*Picea Lutzii* Little
13	Sitka spruce	*Picea sitchensis* (Bong.) Carr.
14	Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.

Nomenclature per Flora of North America north of Mexico,1993.

Table 2.13. Crown class description

Code	Class	Description
0	No estimate	Code 0 is entered if no other entry is present.
1	Dominant	Crown extends above the general canopy layer for the stand. The crown intercepts direct light across the top and along sides of the upper branches. Crown is well developed and large, although usually somewhat crowed along the lower branches. Tree diameter is usually among the largest in the stand.
2	Codominant	Crown within and helping to form the main crown canopy for the stand. Crown intercepts direct sunlight across the top but only at the tips of the upper side branches. The crown is well developed but of only medium size and crowded at the sides. Tree diameter among the upper range of those present, but not the largest in the stand.
3	Intermediate	Crown extends somewhat into the lower part of the main canopy. The crown intercepts direct sunlight only at a limited area on the top and none at the sides. Crown is narrow and short with limited leaf surface area and a low live-crown ratio. Tree diameter within the lower range of those present but not necessarily the smallest.
4	Suppressed	Crown is entirely below the main canopy and covered by branches of taller trees. No direct sunlight strikes any portion of the crown. The crown is small, often lopsided, flat-topped, and sparse. Tree diameter is among the smallest in the stand. Suppressed trees will probably not respond to release.
5	Understory	Crown is entirely below the main canopy including below intermediate tree crowns. Understory trees are shade tolerant species and will probably respond to release.
6	Overstory	Tree in an even-aged stand that is substantially older than the average age of the main canopy.
7	Off-site tree	A site tree or buffer strip tree located off the site property. This tree may be measured for site estimates or included in stem maps but excluded from site summaries.

Table 2.14. Tree status description

Code	Class	Description
0	Live	Tree is alive.
1	Live, cut	Tree is alive but has been cut such as a tree cut above snow level where the remaining portion of the tree lives.
2	Dead	A tree that is numbered within the site but has died of natural causes. It is counted as a snag.
3	Ingrowth	Tree has grown from regeneration size (≤0.50 in) to tree size (≥0.50 in) since the last measurement period. Prior to 2002, the threshold of regeneration size was 1.50 in.
4	New tree previously missed	Tree that is too large to be considered ingrowth. It obviously was not tagged/measured as a tree in the previous inventory.
5	Dead, cut	Tree is dead. It was cut by humans.
6	Site tree	An off-plot tree selected to be measured for site estimates.
7	Crop tree	An off-plot tree selected to become a component of a future commercial harvest.
8	New tree, smaller diameter class	In 2002 the forest growth and yield program changed the definition of a tree. Previously a tree had a dbh of >1.50 in and a tree species ≤1.50 in dbh was considered regeneration. Since 2002 a tree has included tree species with a DBH > 0.50 in.
9	Correct measurement	Tree was measured incorrectly during the last measurement period. This year’s measurement is correct.
10	Missing number tag	Tree was previously numbered, but numbered tag cannot be found at the base of the tree.
11	Correct tree species	Tree species was incorrectly identified in the previous inventory.
12	Incorrect diameter	Tree dbh measurement is extreme/incorrect in this inventory.
13	Incorrect height	Tree height measurement is extreme/incorrect in this inventory.

Table 2.15a. Tree damage location

Class	Description
0	No damage or no information
1	Damage present but unspecified
2	Tip
3	Foliage
4	Limbs
5	Bole, other than class 2 or 6
6	Basal, less than 2-ft
7	Roots
8	Leaning or bent tree
9	Down tree, but still alive

Table 2.15b. Severity of damage

Class	Description
0	Unspecified
1	Minor, <10% damage
2	Moderate, 11% - 40% damage
3	Severe, > 40% damage

Table 2.15c. Tree damage code description

Code	Class	Specific Cause and Nature
0	Unknown or Unspecified Damage	0 Unknown or Unspecified Damage
1	Human Activity	0 Unknown or unspecified
		1 Logging
		2 Foliage sprays
		3 Bole treatment
		4 Root or soil treatment
		5 Pruning
		6 Peeled bark
		7 – 9 User defined
2	Crown Disease and abnormalities	0 Unknown or unspecified
		1 Unhealthy appearance
		2 Foliage diseases
		3 Broom rust/Mistletoe
		4 Dieback (birch)
		5 Leaner
		6 Multiple tops
		7 Spruce needle cast
		8 Spruce needle rust
		9 User defined
3	Bole Diseases and abnormalities	0 Unknown or unspecified
		1 Bole rot
		2 Multiple stems and forks
		3 Stem cankers / burls / galls
		4 Sweep or crook
		5 Dead or broken top
		6 Epicormic branching
		7 Fluting
		8 Scare
		9 Layering
4	Root Diseases	0 Unknown or unspecified
		1 Root Throw
		2 – 9 User defined
5	Insects	0 Unknown or unspecified
		1 Defoliators
		2 Bark beetles
		3 Sucking insects
		4 Aphids
		5 Spruce bud worm
		6 Leaf roller
		7 Ants
		8 Leaf miner
		9 Ips beetle

Table 2.15c continued

6	Mammals and birds	0	Unknown or unspecified
		1	Moose, deer, elk, caribou
		2	Bear
		3	Livestock
		4	Porcupine
		5	Beaver
		6	Hare
		7	Bird
		8 – 9	User defined
7	Fire	0	Unknown or unspecified
		1	Wild fire
		2	Controlled burn
		3 – 9	User defined
8	Weather	0	Unknown or unspecified
		1	Wind
		2	Snow / ice
		3	Freeze
		4	Drought
		5	Winter burn
		6 – 9	User defined
9	Miscellaneous	0	User defined
		1 – 9	User defined

Summary Statistics

Table 2.16 summarizes the mean, standard deviation, maximum, minimum, and count of all the site data. Summary statistics of all the tree data from the three inventories are shown in tables 2.17 through 2.19. Because only a proportion of PSPs have been remeasured, tables 2.18 and 2.19 represent fewer PSPs than does table 2.17.

Table 2.16. Summary statistics of site attributes

Variable	Unit	Mean[a]	Std[b]	Maximum	Minimum	Count
Elevation	Foot	355	246.96	1071	0	556
Latitude	Degree	62	4.79	65	0	556
Longitude	Degree	146	11.17	152	0	556
ASPC	Degree	151	109.32	368	0	566
SLOP	Percent	11	12.62	77	0	567
PERM	Coded	4	0.88	5	0	566
SLPO	Coded	4	2.56	13	1	563
CONT	Coded	2	1.03	4	1	566
BDRK	Coded	3	0.52	4	0	566
LNFM	Coded	7	2.50	11	1	567
SOTXI	Coded	4	0.84	6	1	534
SOTXII	Coded	3	1.92	7	1	253
SOOR	Inch	457	2068.43	9915	0.50	548
SOOi	Inch	1	1.33	12	0	406
SOOe	Inch	2	6.75	135	0	406
SOOa	Inch	127	1104.72	9911	0	398
SOMD	Inch	939	2880.79	9930	0	525
SOMO	Coded	5	1.32	8	0	540
DDWD1	Coded	1	0.78	4	0	566
DDWD2	Coded	1	0.68	4	0	406
DDWD3	Coded	2	0.66	4	1	93
CHAR1	Coded	0	0.41	3	0	566
CHAR2	Coded	0	0.32	2	0	406
CHAR3	Coded	0	0.43	3	0	93
MNSO1	Coded	0	0.38	3	0	566
MNSO2	Coded	0	0.38	4	0	406
MNSO3	Coded	0	0.28	2	0	93
LTER1	Coded	2	1.69	6	0	566
LTER2	Coded	3	1.65	6	0	406
LTER3	Coded	4	1.20	6	1	93
SNAG1		14	17.94	119	0	558
SNAG2		15	22.68	209	0	386
SNAG3		23	20.18	117	0	89

[a]: Median if records are discrete or coded.

[b]: Standard deviation.

Table 2.17. Summary statistics of tree records in the first inventory

Variable	Unit	Mean[a]	Std[b]	Maximum	Minimum	Count
DBH	Inch	4	2.77	33.62	0.51	46027
TLHT	Foot	29	17.12	123	1	42519
CRLN	Foot	15	10.59	99	1	42414
CRCL	Coded	3	1.24	9	1	46378
STAT	Coded					0
DLO1	Coded	5	1.95	9	1	32070
DSV1	Coded	2	0.79	5	1	32071
DTY1	Coded	3	0.95	8	1	32062
DSP1	Coded	4	1.67	9	1	32056
DLO2	Coded	5	1.71	9	1	13902
DSV2	Coded	2	0.74	8	1	13897
DTY2	Coded	3	1.14	9	1	13892
DSP2	Coded	4	1.94	9	1	13882
DLO3	Coded	3	1.68	8	1	4369
DSV3	Coded	2	0.72	8	1	4370
DTY3	Coded	3	1.18	9	2	4369
DSP3	Coded	4	2.01	9	1	4367
DLO4	Coded	4	1.72	8	1	981
DSV4	Coded	2	0.75	8	1	981
DTY4	Coded	3	1.20	9	2	981
DSP4	Coded	4	2.05	9	1	981

[a]**: Median if records are discrete or coded.**

[b]**: Standard deviation**.

Table 2.18. Summary statistics of tree records in the second inventory

Variable	Unit	Mean[a]	Std[b]	Maximum	Minimum	Count
DBH	Inch	4	3.05	142	0.27	31028
TLHT	Foot	31	19.00	118	1	28914
CRLN	Foot	16	11.63	100	1	28904
CRCL	Coded	3	1.28	44	1	31453
STAT	Coded	3	2.89	11	1	10010
DLO1	Coded	5	2.05	9	1	24066
DSV1	Coded	2	0.84	8	1	24061
DTY1	Coded	3	1.03	9	1	24069
DSP1	Coded	4	1.60	9	1	24055
DLO2	Coded	5	1.78	9	1	12727
DSV2	Coded	2	0.76	6	1	12724
DTY2	Coded	3	1.09	9	1	12722
DSP2	Coded	4	1.76	9	1	12713
DLO3	Coded	3	1.63	8	1	4744
DSV3	Coded	2	0.72	5	1	4743
DTY3	Coded	4	1.25	9	1	4740
DSP3	Coded	4	2.09	9	1	4735
DLO4	Coded	4	1.56	8	1	1179
DSV4	Coded	2	0.78	8	1	1179
DTY4	Coded	4	1.25	6	2	1176
DSP4	Coded	4	2.36	9	1	1175

[a] **: Median if records are discrete or coded.**

[b] **: Standard deviation**.

Table 2.19. Summary statistics of tree records in the third inventory

Variable	Unit	Mean[a]	Std[b]	Maximum	Minimum	Count
DBH	inch	4	3.85	215	0.40	8247
TLHT	foot	35	19.89	111	1	7540
CRLN	foot	18	12.68	93	1	7531
CRCL	coded	3	1.26	9	1	8337
STAT	coded	3	3.05	10	2	3335
DLO1	coded	5	2.14	9	1	6548
DSV1	coded	2	0.86	12	1	6554
DTY1	coded	3	1.19	33	1	6551
DSP1	coded	5	1.84	9	1	6526
DLO2	coded	3	1.74	8	1	3825
DSV2	coded	1	0.76	7	1	3826
DTY2	coded	3	1.16	13	1	3822
DSP2	coded	5	2.04	9	1	3810
DLO3	coded	3	1.59	9	1	1294
DSV3	coded	2	0.76	8	1	1298
DTY3	coded	4	1.21	8	1	1296
DSP3	coded	5	2.20	8	1	1292
DLO4	coded	4	1.45	8	1	196
DSV4	coded	2	0.86	5	1	196
DTY4	coded	4	1.22	8	2	195
DSP4	coded	5	2.39	8	1	193

[a]: Median if records are discrete or coded.
[b]: Standard deviation.

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Metric Equivalents

When you know:	**Multiply by:**	**To find:**
Inches (in)	2.54	Centimeters (cm)
Feet (ft)	.3048	Meters (m)
Miles (mi)	1.609	Kilometers (km)
Square feet (ft^2)	.0929	Square meters (m^2)
Square feet per acre (ft^2/ac	.2294	Square meters per hectare (m^2/ha)
Acres (ac)	.4050	Hectares (ha)
Degrees Fahrenheit (°F)	.56(F-32)	Degrees Celsius (°C)

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Glossary[2]

acre—A unit of land containing 43,560 ft^2 of area. 0.4 ha.

alluvial fan—A fan-shaped mass of sediment, especially silt, sand, gravel, and boulders, deposited by a river when its flow is suddenly slowed. Alluvial fans typically form where a river pours out from a steep valley through mountains onto a flat plain. Unlike deltas, they are not deposited into a body of standing water.

aphids—Members of the *Homoptera* family. See sap-sucking insects.

aspect—A position facing a particular direction usually expressed as a compass direction in degrees. The direction land faces.

bark—The outer layer of a tree stem outside the vascular cambium derived from cell division.

bark beetle—Member of the family Scolytidae and the genera: *Dendroctonus, Ips*, or *Scolytus*. Adults and larvae tunnel in the cambial region of trees and can cause severe damage. Some are carriers of disease.

bedrock—The solid rock that underlies the soil and other unconsolidated material that is exposed at the earth's surface.

bole—The trunk or main stem of a tree.

borderline tree—A tree that is difficult to judge as being in or out of a site because it is located close to the PSP border.

boustrophedonic numbering—A system of numbering alternate lines in opposite directions; numbering one line from right to left and the next line from left to right.

breast height—4.5 ft (137 cm) aboveground. A standard location for measurement of tree diameter.

broom rust—This fungus, *Chrysomyxa arctostaphyli,* infects spruce trees and causes dense perennial witches' brooms. It causes reduced growth, bole deformation, and an entry court for decay fungi.

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[2] Definitions from *The Dictionary of Forestry*. (Helms, 1998) and *Merriam Webster's Collegiate Dictionary 10th ed*. (1995).

browse/browsing—Any woody vegetation consumed or fit for consumption by livestock or wild animals; mainly ungulates. To forage or graze on the buds, stems, and leaves of woody growth.

budworm—A larva of the family Tortricidae that feed on and in buds and young shoots.

burl—Globe-shaped woody growth on boles or branches of both conifers and hardwoods. The cause of burls is not known, but infection by bacteria, viruses, or mycoplasms, and insects are suspected.

canker—A localized usually well-defined sunken or swollen necrotic lesion to stem, branch, or root; caused by disease or insects.

conifer—A cone-bearing tree; gymnosperm.

canopy—The cover of foliage formed by tree crowns.

cardinal direction—One of the four principal directions on a compass: 0° or 360°, north; 90°, east; 180°, south; and 270°, west.

charcoal—A form of carbon derived from the incomplete combustion of animal or vegetable matter.

chroma—A relative purity, strength, or saturation of a soil color; directly related to the dominance of the determining wavelength of the light and inversely related to grayness of soil. Chroma is one of three variables of color used to describe soils.

clinometer—An instrument for measuring angles of elevation or depression.

codominant tree—Tree whose crown receives full light from above and little from the sides. These crowns usually form the general level of the upper canopy.

compass—A calibrated instrument for determining directions by means of a magnetic needle turning freely on a pivot and pointing to magnetic north.

conk—The visible fruiting body of a wood-destroying fungus, which projects from the trunk, roots, or other tree parts. They commonly indicate the presence of rot in the underlying wood.

contour—The general form of the land surface, from straight to undulating.

controlled burn/prescribed burn—A deliberate burning of wildland fuels in either their natural or a modified state. Planned resource management objectives can be attained by controlling the timing, intensity, and size of burns.

crown—The part of a tree or woody plant bearing live branches and foliage.

crown base—The point of attachment of the lowest live whorl on the bole of a tree.

crown class—The relative position of the tree crown with respect to the competing vegetation around it. Crown class for each tree is judged in the context of its immediate environment – those trees or shrubs that are competing for sunlight with the subject tree. In this manual, crown class categories include codominant, dominant intermediate, overstory, suppressed, and understory.

crown cover—The ground area covered by the crowns of trees and other woody vegetation as delimited by the vertical projection of crown perimeters. It is expressed as a class of crown cover.

crown length-Live crown of a standing tree. The vertical distance from the tip of the leader to the base of the live crown, measured to the lowest live whorl without regard for branch droop.

crook—An abrupt bend or curvature in the bole of a tree. A crook is a sound-cull deduction from gross merchantable volume.

database—A collection of data stored in a systematic manner such that the data can be readily retrieved, modified, and manipulated to produce information.

dead tree—A tree having no viable meristematic tissue but self-supporting and with the upper bole standing (not in contact with the surface).

densiometer—An instrument for determining optical density. In forestry applications, a calibrated spherical crown densitometer determines percentage of crown cover.

diameter at breast height (dbh)—A measure of the tree bole, (4.5ft or 137 cm) above ground outside the bark and perpendicular to the tree bole.

diameter tape—A measure specifically graduated so that tree diameter can be read directly from the tape when placed around a tree stem.

disease—A harmful deviation from normal function of physiological processes; pathogenic or abiotic in origin.

dominant tree—Tree whose crown receives full light from above and partial light from the sides. Crown extends above the general level of the upper canopy.

drumlin—An elongated or oval hill formed by glacial sediments.

edge effect—The modified environmental conditions or habitat along the margins (edges) of forest stands.

epicormic branching—A shoot arising spontaneously from a dormant bud on the stem or branch of a woody plant, often following exposure to increased light.

fern—A nonwoody vascular plant.

flagging—Colored plastic or paper ribbon attached to trees, bushes, or stakes to mark boundaries or to make stakes and other objects more visible.

fluting—Swelling of a tree bole owing to disturbances or rapid growth.

floodplain—The level or nearly level land with alluvial soils on either or both sides of a stream or river.

abandoned floodplain—Land in a floodplain that is no longer subject to periodic flooding.

active floodplain—Land that commonly has newly deposited fluvial sediments and debris moved by floodwaters.

forest—An ecosystem characterized by a more-or-less dense and extensive tree cover, often consisting of stands varying in characteristics such as species composition, structure, age class, and associated processes, and commonly including meadows, streams, fish, and wildlife.

gall—A pronounced swelling or abnormal growth, usually localized, of greatly modified tissue structure arising on plants in response to irritation by a foreign organism (commonly an insect or pathogen).

geographic information system (GIS)—An organized collection of computer hardware, software, geographic and descriptive data, and procedures designed to efficiently capture, store, update, manipulate, analyze, report, and display forms of geographically referenced information and descriptive information.

global positioning system (GPS)—A hand-held, satellite-based navigational device that records x, y, z coordinates and other data allowing users to determine their location on or near the surface of the earth.

grass—A nonwoody vascular plant that is a member of the Poaceae family.

growth model—A set of relationships, usually expressed as equations and embodied in a computer program, which estimates future stand development given initial stand conditions and a specified management regime. Growth and yield models are used to generate managed-stand yield tables, predict future stand conditions for management planning, update inventories, and compare predicted results of alternative possible management regimes.

herbs—Nonwoody vascular plants such as grasses, grasslike plants, and forbs.

horizon, soil—A layer of soil approximately parallel to the land surface and differing from adjacent genetically related layers in physical, chemical, or biological properties or characteristics such as color, texture, or consistency. Soil taxonomy identifies horizons in a systematic manner.

hue—A measure of chromatic composition of light that reaches the eye. Hue is one of three variables of color used to describe soils.

humus (organic matter, soil)—Black or brown organic material of complex composition that is the end product of microbial breakdown of plant and animal residue under or on the soil surface.

hypsometer—Any instrument for measuring the height of an object (trees) from observations taken at some distance from the object.

increment borer—An auger-like instrument with a hollow bit and an extractor used to extract thin radial cylinders of wood (increment cores) from trees having annual growth rings, to determine diameter increment or age.

insect—A member of the class Insecta characterized by a body segmented into three distinct regions. Often considered a forest pest.

ingrowth tree—A tree that has grown past a diameter or height threshold on a site since previous inventory to become a measurement tree.

intermediate tree—Tree whose crown receives little direct light from above and none from the sides. Crowns are below or extend into the general level of the upper canopy.

lacustrine—Relating to a lake or a standing body of water.

landform—The physical process that formed the topographic features of an area.

latitude—A method to measure the Earth representing angles of a line extending from the center of the Earth to the Earth’s surface; with 0° representing the equator, angles measured in degrees north or south until 90° is obtained at the North and South Poles.

layering—A form of vegetative reproduction in which an intact branch develops roots as the result of contact with soil or other growing media.

leaf miner—Various species of leaf miner attack birch, quaking aspen, balsam poplar/black cottonwood, and numerous shrubs of the genus *Alnus* and *Salix*. Larvae enter the leaf and mine between the epidermal layers reducing photosynthetic area. Heavy repeated attacks could reduce tree growth and cause branch dieback.

leaf roller—Numerous species of the genus *Epinotia*, which attack birch, willow, alder, aspen, and balsam poplar. Larvae roll leaves that are skeletonized; these leaves turn brown and drop prematurely. Branch dieback and tree mortality rarely occurs.

leaning tree—The deflection of a tree stem from a vertical line passing through the center of the base and top of the main stem.

lichen—A nonvascular composite organism formed from the symbiotic association of a true fungus and an alga.

litter—The surface layer of a forest floor that is not in an advanced stage of decomposition; usually consisting of freshly fallen leaves, needles, stems, twigs, bark, and fruits.

live crown length—The straight-line distance measured parallel to the main bole of a tree from the top of the live crown to the base of the live crown.

live tree—A tree having viable meristematic tissue and roots in contact with mineral soil.

loam—A soil texture class containing roughly equal amounts of sand, silt, and clay.

loess—Material transported and deposited by wind and consisting of predominantly silt-sized particles.

longitude—A method to measure the Earth representing angles of a line extending from the center of the Earth to the Earth’s surface; with a line extending from the North to the South Pole and passing through Greenwich, England, as 0°. Angles are measured in degrees east or west until 180° is obtained at the opposite side of the earth from 0° longitude.

meridian—A line running vertically from the North Pole to the South Pole along which all locations have the same longitude. The prime meridian, 0°, runs through Greenwich, England; both east and west longitudes range from 0° to 180° relative to the prime meridian.

mesoscale—Of intermediate size on the landscape.

mineral soil—A soil consisting predominantly of, and having its properties determined predominantly by, mineral matter.

munsell color system—A system that specifies the relative degrees of the three variables of color: hue, value, and chroma.

modeling—A simplified framework designed to illustrate complex processes.

moraine—An accumulation of glacial drift (sediments and rocks) that forms topographic features built chiefly by direct glacial movement. Moraines often develop parallel to (lateral moraine) or perpendicular to (terminal moraines) glaciers as they move.

moss—Short soft nonvascular plants of the division Bryophyta.

native species —An indigenous species that is normally found as part of a particular ecosystem.

needle/leaf cast—Any untimely shedding of foliage, most often caused by a fungus.

nonvascular plant—Relating to plants not having phloem-and xylem-conducting elements such as bryophytes.

organic soil—Vegetative and animal matter almost completely decomposed. Organic soil may contain other material, but at least 75percent must be organic material.

overstory tree—A tree that has survived from the previous stand and is usually larger or older than trees that originated as part of the present stand.

parent material—The unconsolidated and more-or-less chemically weathered mineral or organic matter from which the soil horizons are developed.

pedogenic—The process whereby soil is formed from parent material, i.e., rocks. Any process related to soil formation.

permafrost—Soil that has had a temperature below freezing for 2 or more years; perennially frozen soil.

permanent sample plot (PSP)—Field plots used in forest research. A system of plots established and periodically remeasured to sample forest conditions and provide long-term data. In this system it is a 0.1ac square with 66-ft sides.

pruning—The removal of side branches or multiple leaders from a standing tree. Dead or live foliage is cut flush to the stem.

regeneration—A young stand of trees smaller than commercial timber or the understory tree component of a multistoried stand designated as seedlings and saplings. The established progeny from a parent plant.

rock —Relatively hard, naturally formed mineral or petrified matter greater than 0.75 inches in diameter appearing on or near the soil surface, as small to large fragments, or as relatively large bodies, cliffs, outcrops, or peaks.

rot—Decomposition of wood by fungi or bacteria; decay.

sample—A part of a population consisting of one or more sampling units selected and examined as representative of the whole.

sample plot—An area of land chosen as representative of a much larger area.

sap sucking insects—In Alaska, mostly aphids that attack both conifers and hardwoods. Trees are injured in two ways: sap sucking reduces the food supply and water to the tree, which reduces growth, and it creates an entry point for secondary insects and fungal disease. Identified by enlarged growth, galls, leaf curling, bleaching, or yellowing foliage.

sapling—A tree whose stem is greater than 4.5 ft in height and less than 0.51 in dbh.

seedling—A tree whose stem is less than 0.51 in dbh and less than 4.5 ft in height and has root contact with mineral soil.

seed—The ripened ovule of a plant containing an embryo, seed coat, and nutritive tissue.

shrub—A woody perennial plant differing from a perennial herb in its persistent and woody stem, and differing from a tree in its lower stature and general absence of a well-defined main stem.

site—An experimental unit to which a treatment is randomly assigned.

site index—A species-specific measure of actual or potential forest productivity expressed in terms of the average height of dominant and/or codominant trees at a specified base age.

site tree—A normally formed live tree in the dominant or codominant crown class. A site tree may have minor damage but can only have minor visible defect, and no evidence of suppression. Site trees are used to determine the site index.

slope—A measure of deviation of the surface elevation over distance, expressed in degrees or percentage.

slope position—The position of a site in relation to the surrounding topography.

snag—A standing dead tree in the current inventory. A snag must be large enough to be a tree (>0.50 in dbh and 4.5 ft in height) and not severed from its rootstock or uprooted.

solifluction—The slow creeping of saturated soil down slope. This usually occurs in regions of perennial cold climate.

soil—The unconsolidated mineral or organic material on the immediate surface of the earth that serves as the natural medium for the growth of land plants.

soil color—The color of soil horizons determined from the Munsell soil color chart. The notation for color consists of separate notations for hue, value, and chroma, which are combined in that order to form a color designation.

soil moisture—The amount of water in the soil, which is indicative of the general soil drainage.

soil texture—A characteristic consistency of soil determined by relative proportions of various soil fractions: sand, silt, clay, and rock fragments.

species—The main category of taxonomic classification into which genera are subdivided, comprising a group of similar interbreeding individuals sharing a common morphology, physiology, and reproductive process. A numeric code identifies each tree species in the CAFI database.

stand—A contiguous group of trees sufficiently uniform in age-class distribution, composition, and structure and growing on a site of sufficiently uniform quality to be a distinguishable unit.

stand age—The mean age of a forest stand that best characterizes the stand. Stands can be even-aged or uneven-aged.

stem —The principal axis of a plant from which buds and shoots develop; stems may be of any age or diameter.

stump—The basal portion of a tree remaining in contact with the soil.

suppressed tree—A tree having its crown in the lower layer of the canopy and whose leading shoot is not free to grow. The crown receives no direct sunlight.
sweep—A broad arc in a bole of a tree or log.

talus—A slope landform typically covered by coarse rock debris forming a more-or-less continuous layer that may or may not be covered by organic material.

tree—A woody perennial plant, typically large, with a single well-defined stem carrying a more-or-less definite crown. In the CAFI database, a tree has a dbh of at least 0.51 in and is greater than 4.5 ft in height.

understory—All forest vegetation growing under an overstory.

value—The degree of lightness or darkness of a soil color in relation to a neutral gray scale extending from black to white. Value is one of three variables of color used to describe soils.

vascular—Relating to plants having phloem- and xylem-conducting elements.

vegetation code—Coding system used to identify vegetative items in this survey.

vegetation cover—The cover of all vegetation occupying an area.

weathering—All physical and chemical changes produced in rocks at or near the earth's surface by atmospheric agents.

windthrow/root throw/blowdown—Tree or trees felled or broken off by wind.

winter burn—The desiccation of foliage and twigs by dry winds at times when water conduction is restricted by frozen plant tissue. Foliage turns brown and dieback of twigs can occur.

xeric—Pertaining to sites or habitats characterized by decidedly dry conditions.

Chapter 3 A bark thickness model for white spruce in Alaska northern forests[1]

Abstract

Here we developed a simple linear model to estimate white spruce bark thickness in the northern forests of Alaska. Data were collected from six areas throughout interior and south-central Alaska. Geographic variation of bark thickness was tested between the Alaska statewide model and for each geographic area. The results show that the Alaska statewide model is accurate, simple, and robust, and has no practical geographic variation over the six areas. The model provides accurate estimates of the bark thickness for white spruce trees in Alaska for a wide array of future studies, and it is in demand by landowners and forest managers to support their management decisions.

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[1] Malone, T. and J. Liang. 2009. A bark thickness model for white spruce in Alaska northern forests. International Journal of Forestry Research Vol. (2009): 876965. 5 p. Minor revisions were made from the publication.

Introduction

Estimating bark thickness is an important part of the research of forest growth and yield, economics, and fire control. Timber volume and value cannot be correctly estimated without knowing the thickness of bark (Meyer 1946). Although bark accounts for a small percentage of tree volume, managers know that the amount of bark purchased with standing trees matters to their bottom line (Marden et al. 1975). For many years, bark had been an unwanted byproduct of milling operations, since its disposal, typically through burying or combustion often increases the cost of operations (Haygreen and Bowyer 1996). Bark has been used for centuries, on a small scale, for medicinal purposes, food, baskets, boats, and tannins (Small 1884). As mill operators and researchers have determined the properties of bark, several new uses have been identified. The most basic use of bark is to produce energy or heat through combustion. Bark can also be used as a landscape material. Industrial operations continue to develop uses for large quantities of bark.

The outside-bark volume of standing trees can be estimated from measurements of their height and diameter at breast height outside bark. With bark thickness models, the volume of wood inside the bark can also be estimated for forest growth, productivity, and economic analysis (Farr 1967); therefore, models that provide accurate estimates of the amount of bark in standing trees are useful.

Bark thickness varies by tree species. For example, white spruce (*Picea glauca* (Moench) Voss) and black spruce (*Picea mariana* (Mill.)B.S.P.) are considered thin-bark species with average thickness of 0.6 to 1.3 cm (Viereck and Little 1972), while white fir (*Abies concolor* (Gord. and Glend.)Hildebr.) is a thick-bark species with an average bark thickness of 10.2 to 17.8 cm (Harlow et al. 1996).

As the most valuable commercial species in the northern forests of Alaska, white spruce accounts for 64-81 percent of the commercial volume of this biome (Hutchinson 1967). The northern forests of Alaska cover all the forest types of interior and south-central Alaska including the boreal forests but excluding the coastal forests. White spruce grows throughout the interior and south-central areas from the Canadian border in the east to the Bering Sea in the west and from the Kenai Peninsula in the south to the Brooks Range in the north (Harlow et al. 1996). White spruce grows on a wide variety of sites, from sand, silt, and clay, to organic matter. White spruce is a commercially valued species. It is widely used for dimension lumber, paneling, pulpwood, and firewood (Harlow et al. 1996).

Unfortunately, study of bark thickness is limited for species in Alaska. Yarie et al., (2007) developed equations to estimate bark biomass for species native to interior Alaska. The results, due to the limited sample size and geographic coverage, are susceptible to significant bias when applied statewide.

For management purposes, the State of Alaska Division of Forestry (DOF) has divided interior and south-central Alaska region into six geographic areas: Delta, Glennallen/Copper River Valley, Fairbanks, Kenai Peninsula, Mat-Su Valley, and Tok (fig. 3.1). Each area has adopted a variety of bark thickness and volume models. None of these models, however, was developed for statewide application.

The objective of this study was to develop a single model to estimate bark thickness of white spruce in Alaska. A universal model covering all six DOF areas in interior and south-central Alaska was developed for simplicity and maximum geographic coverage. A bark thickness equation was developed for each of the six DOF areas based on samples from that area. The statewide model was tested against the six area models for robustness of geographic variation.

Data and Methods

We selected 600 white spruce bark thickness samples from the six geographic areas of interior and south-central Alaska (fig. 3.1).

Within each of these areas, we randomly located 10 sites representative of the forest types of the area. For budget and safety reasons, the sites were selected from 30-km-wide corridors surrounding the existing highways. All the sites were classified as commercial forest land (Helms 1998). Within each site, 10 trees were sampled, for a total of 600 trees sampled. Sample trees at each site were randomly selected from each of these crown classes: dominant, codominant, intermediate, and suppressed trees. Bark thickness was measured using a hand-held Swedish bark gauge at 3 equidistant points around the stem at breast height, to the nearest 1.27 mm (0.05 inch). To reduce measurement errors, all bark thickness measurements used in this data set were collected by a single individual. Table 1 provides summary statistics of dbh and bark thickness data for the dataset.

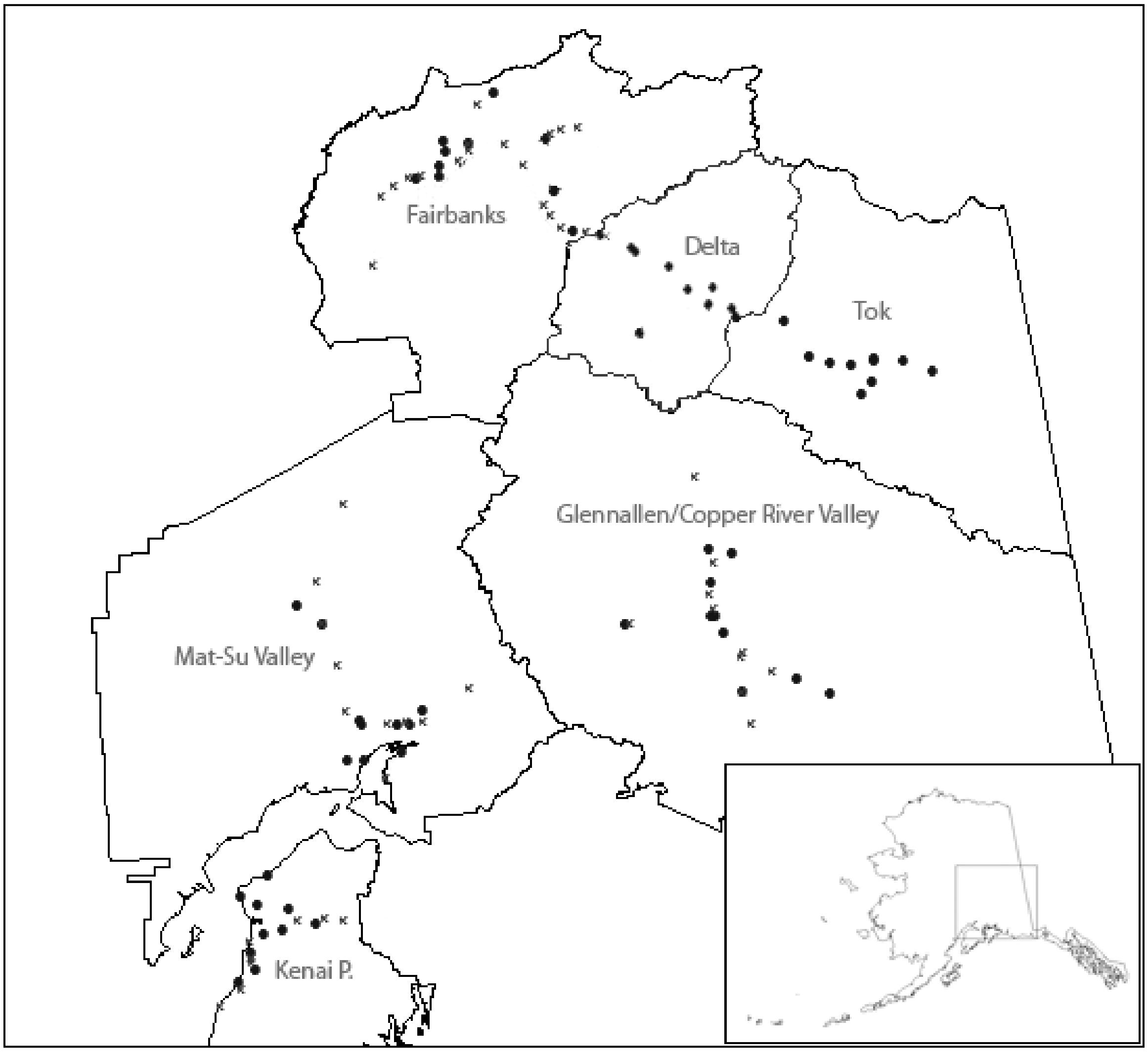

Figure 3.1. Geographic distribution of the 60 bark thickness sample sites (dots) and 15 post-sample validation sites (Xs) and their relative locations within the state of Alaska (inset).

Table 3.1. Summary statistics of sample and post-sample tree records.

	Sample		Post-sample	
statistic	**bark thickness (cm)**	**dbh (cm)**	**bark thickness (cm)**	**dbh (cm)**
Mean	1.12	23.83	1.02	23.47
SD	0.41	9.55	0.30	8.92
Max	2.54	64.77	1.85	48.51
Min	0.30	9.14	0.46	9.14
n	600	600	247	247

The bark thickness model has the following form:

$$y = \beta_0 + \beta_1 x + e \tag{3.1}$$

where y is bark thickness (cm) and x is dbh (cm). βs are parameters estimated from the Generalized Least Squares (Nelder and Wedderburn 1972*)* regression, and e is the error term assumed to follow a normal distribution independent of the geographic areas. Geographic difference was tested by comparing the predicted bark thickness values for each geographic area with those predicted by the statewide models (fig. 3.1).

The accuracy of this model was determined by the prediction errors, the difference between the actual bark thickness and the predicted value. The test was done on 247 post-sample trees (see the summary statistics in table 1). These post-sample measurements were obtained from across the northern forest region of Alaska (fig.3.1). For validation purposes, all post-sample measurements were collected from forest plots with different locations and characteristics from the sample plots. The predictions of the Alaska model were further compared against two existing bark thickness models calibrated for white spruce in British Columbia and the Lake States (Kozak and Yang 1981, Gevorkiantz and Olsen 1955). To test if the 247 post-sample trees could further improve the model, the post-sample data were added to the original sample to form a larger sample that was composed of 847 tree records. A reference model was estimated from the larger sample and was compared against the Alaska statewide model to see if there was any significant difference in the parameters.

Results

The parameters of the Alaska model were highly significant ($P<0.01$), and the coefficient of determination ($R^2=0.63$) represented a good fit (table 3.2). Figure 3.2 shows that the residuals for the Alaska model were normally distributed, with no discernable pattern. There were a few suspicious outlying residuals but their standard influence on predicted value (Belsley et al. 1980) suggests that none of them were influential outliers.

Table 3.2. Parameters of the six area models and the statewide model to estimate the bark thickness of white spruce in Alaska northern forests.

Model	Estimated right hand side of equations	R^2	N
Copper River Valley	0.412* + 0.037 × dbh*	0.77	100
Delta area	0.115* + 0.043 × dbh*	0.69	100
Fairbanks area	0.239* + 0.034 × dbh*	0.74	100
Kenai Peninsula	0.313* + 0.038 × dbh*	0.76	100
Mat-Su Valley	0.314* + 0.028 × dbh*	0.59	100
Tok area	0.247* + 0.034 × dbh*	0.54	100
Alaska	**0.303* + 0.035 × dbh***	**0.63**	**600**

Note: Response variable is the thickness of bark (cm), dbh stands for the diameter-at-breast height (cm). * represents that the coefficient is significant at 0.01 level. R^2, coefficient of determination; N, number of sampled trees.

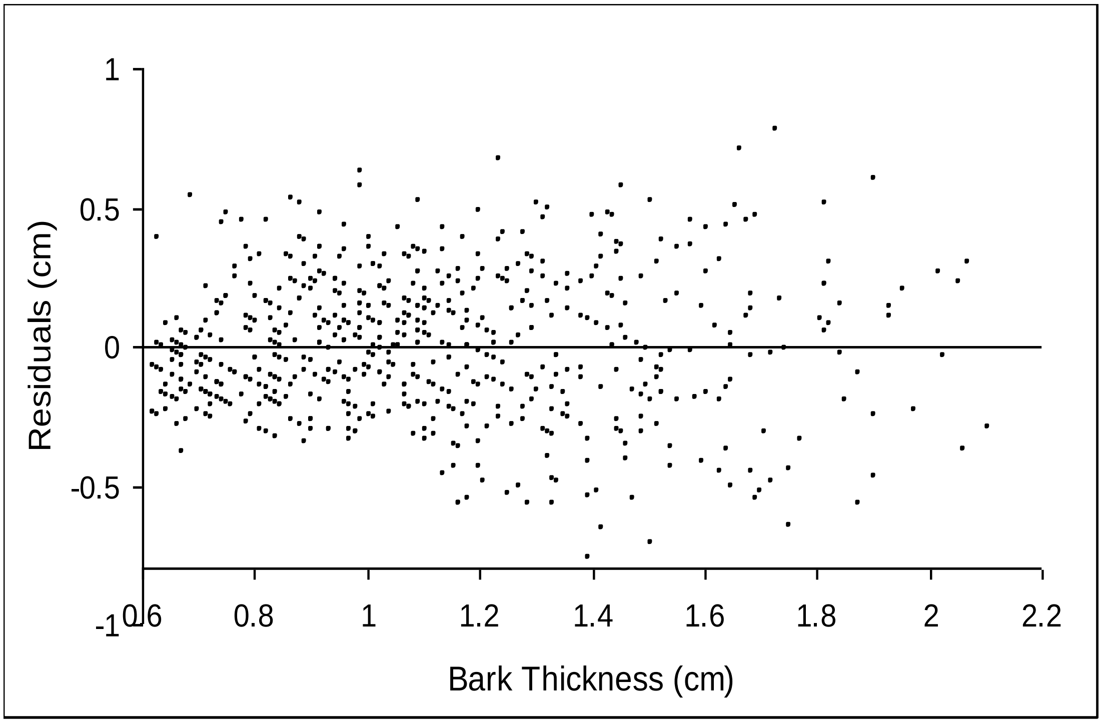

Figure 3.2. Residual plot of the Alaska bark thickness model.

Figure 3.3 shows that the predicted bark thickness for six individual areas all fell within the 90 percent confidence interval of the predicted values of the Alaska model. In other words, within the range of our sample, the predictions between the Alaska model and the models developed for the six areas were nearly the same, and therefore the Alaska model developed in this study was an accurate estimate of white spruce bark thickness across the northern region of Alaska.

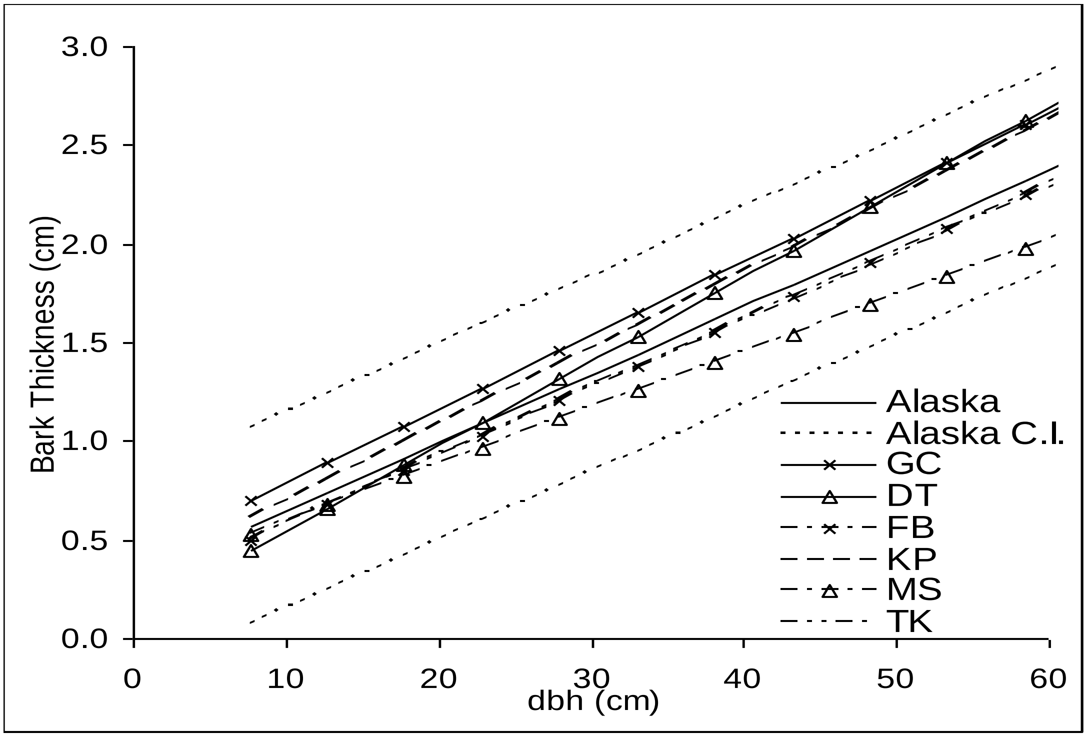

Figure 3.3. Predicted bark thickness (cm) from the Alaska model (Alaska) with 90% confidence interval (Alaska C.I.), and from the models fit for the six individual areas: Glennallen/Copper River Valley (GC), Delta (DT), Fairbanks (FB), Kenai Peninsula (KP), Mat-Su Valley (MS), and Tok (TK).

Figure 3.3 shows the errors in predicting the bark thickness from dbh on 247 post-sample white spruce bark thickness records. The predictions of this model all fell within the 95 percent confidence interval of the observations. The reference model estimated from the larger sample (the Alaska model plus the 247 post-sample data) was almost the same as the present model, viz. P=1.00 for the test of the hypothesis that the difference between the coefficients from the two models was zero. Therefore, the present Alaska statewide model was representative of the study area and adding the post-sample records to the sample would not further improve the model.

In comparison, the model developed for commercial trees in British Columbia (Kozak and Yang 1981) underestimated bark thickness. As trees grow larger, the predictions errors became more significant. The Lake States model (Gevorkiantz and Olsen 1955), conversely, overestimated diameter inside bark of white spruce trees, and for trees larger than 24 cm. in diameter, the errors were significant at the 5 percent level. It suggests that even though both the British Columbia and Lake States models were fit for white spruce, they are not capable of providing accurate estimates of bark thickness of white spruce trees in the northern forests of Alaska, for which climate conditions and growing season differ considerably (Van Cleve et al. 1983).

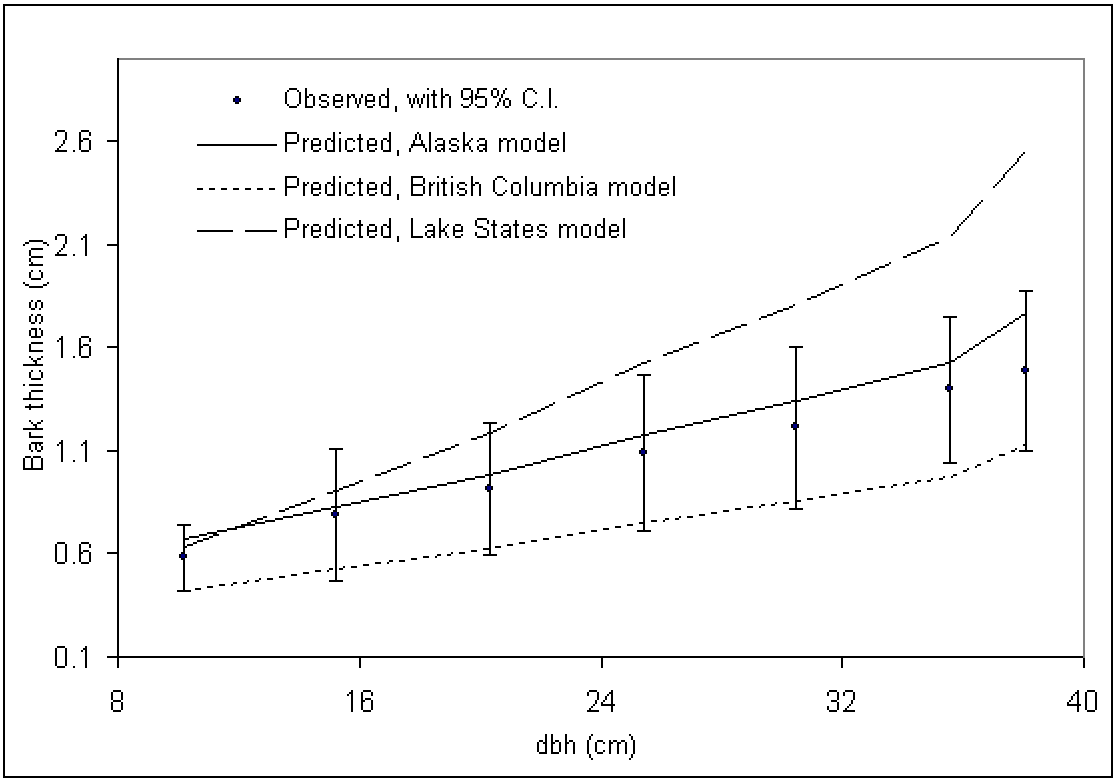

Figure 3.4. Average predicted and observed (with 95% confidence interval) bark thickness (cm), on 247 post-sample white spruce trees in Alaska. Predictions were obtained with British Columbia model, Lake States model, and the Alaska model presented here.

Discussion and Conclusion

We developed a model to estimate bark thickness of white spruce in the northern forests of Alaska. The model was tested and found to be more accurate for Alaska over existing models calibrated for other regions (fig. 3.4). This model covers all the six areas of Alaska northern forests: Delta area, Glennallen/Copper River Valley, Fairbanks area, Kenai Peninsula, Matanuska-Susitna Valley, and Tok area. Although the statewide model may be less accurate than an area model for that specific area, the errors of the statewide model were almost negligible for each area (table 3.3). The prediction errors were close to the measurement errors, and a single statewide model was much simpler than several area models especially for statewide studies. The systematic overestimation by the statewide model for the post-sample trees (fig. 3.4) was presumably caused by the fact that the post-sample data were collected in the winter time, while all the sample data were collected in summer time. Thickness of bark is usually larger in summer time than in winter when the trees are frozen (e.g. Zweifel and Häsler 2000).

Table 3.3. Differences between predicted and observed bark thickness with the Alaska model on post-sample white spruce trees.

Area	mean (cm)	std (cm)	n
Copper River Valley	0.16	0.02	50
Delta area	0.13	0.20	15
Fairbanks area	0.31	0.16	82
Kenai Peninsula	0.09	0.06	50
Mat-Su Valley	0.09	0.02	50
Tok area	—	—	—
Overall	**0.11**	**0.11**	**247**

Note: std, standard deviation; n, number of sampled trees. There is no post-sample data from the Tok area.

This model is able to estimate white spruce bark thickness with a wide range of diameters from 8 to 66 cm. Since white spruce is a thin-bark species and its stem tapers quickly from a small root collar at the base, the model can be used to estimate bark thickness at various tree heights and to address wood volume along the stem inside-bark. Meyer (1946) used dbh and bark thickness measurements to estimate volume along the stem inside-bark of various tree species, and the results show that the predicted volumes inside-bark are close to the observed values.

Researchers have attempted to improve bark thickness models by using various forms of dbh (quadratic, exponential), or adding other attributes such as tree age, height, and site characteristics (e.g. Hale 1955, Dimitrov 1976). This study considered dbh as the only necessary explanation variable due to the following four reasons. First, research on bark thickness of coniferous trees (e.g. Kozak and Yang 1981) shows that bark thickness is very linear to the diameter at breast height and the ratio of diameter inside-bark to outside bark is close to constant along the stem. Second, tree age and height are highly correlated with dbh, and putting them in the model could cause multicollinearity-related problems. Third, a complex model is less useful because it costs more to measure other tree and site attributes. Finally, the simple linear model proposed here was capable of producing accurate predictions of bark thickness of post-sample trees (fig. 3.4).

Estimates for volume of white spruce in Alaska have been developed (Gregory and Haack 1964, Larson and Winterberger 1988). Neither of these publications, however, offers models that are widely accepted to estimate the volume of white spruce in Alaska, because of their limited geographic sample coverage, and lack of control for bark thickness. With the bark thickness model developed in this study, previous white spruce volume models could be updated and improved. As a follow up of this study, an Alaska statewide volume model for white spruce is currently under development by the authors.

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Chapter 4 Total and Merchantable Volume of White Spruce in Alaska[1]

Abstract

An accurate model to determine the volume of white spruce (*Picea glauca* (Moench) Voss) trees in Alaska is in great demand. White spruce is a valuable commercial species generally located in interior and southcentral Alaska. Multiple volume models were developed for white spruce to estimate total and merchantable cubic-foot volume to a 2-in, 4-in, and 6-in top. These multiple-entry (diameter and height) models were developed for both inside and outside bark volume from a 6-in. stump. The Alaska white spruce volume models were of superior accuracy to other white spruce models when tested on post-sample validation samples collected at various geographic locations in Alaska.

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[1] Prepared for the Western Journal of Applied Forestry.

Introduction

Individual tree volume models are an essential tool for forest management activities (Avery and Burkhart 2002). They are used to estimate individual tree and total stand volume, and to study biomass, carbon sequestration, and forest growth and yield (Brackley et al. 2010, Liang 2010, Woodall 2010). Resource managers have been estimating the volume of wood in trees for as long as there has been a forest products industry. The most common units of measuring tree volume are board feet, cubic feet, and cubic meters. Volume estimates were originally presented in volume tables. With the advent of computers, empirical volume equations became more widely used than volume tables. Equations are more convenient and flexible as they can be loaded into spreadsheets and data loggers. Currently the nomenclature for volume estimation tools is volume model although the terms volume table and equations are still in use. Oettelt (1765) estimated tree volume by comparing it to a cylinder of equal diameter, and Smalian(1837) improved the model by comparing tree sections to the frustums of conoids (Bruce and Max 1989). Today, volume models are developed for individual tree species or for multiple species in composite models (Avery and Burkhart 2002). Volume models are developed from a variety of explanatory variables such as diameter, height, tree form, and age; with the first two being the most common explanatory variables (Schreuder et al. 1993, Huang et al. 2000, Avery and Burkhart 2002).

White spruce (*Picea glauca* (Moench)Voss) is a transcontinental species and the most widely distributed conifer in North America. It has high commercial (Harlow et al. 1996) and ecological importance (Nienstaedt and Zasada 1990). White spruce is used commercially as structural lumber, house logs, plywood, musical string instruments, and pulpwood (Nienstaedt and Zasada 1990). It’s also a valuable source of firewood and biomass. In Alaska, white spruce accounts for 64 to 81 percent of the commercial forest volume of the boreal forest (Hutchison 1967). White spruce is widely distributed in the region from the Canadian border in the east to the Bering Sea in the west, and from the Brooks Range in the north to the Kenai Peninsula and the Bristol Bay area in the south. White spruce grows on a variety of soil origins including: glacial, lacustrine, marine, alluvial (Nienstaedt and Zasada 1990), aeolian, residual, and colluvial (Soil Staff Survey 1999). In Alaska the largest white spruce are approximately 130 ft tall and 34 in at dbh. White spruce is a thin bark species (Viereck and Little 2007) with a root collar which tapers quickly from the stump to the main stem.

Existing white spruce volume models in Alaska are of limited applicability due to small sample size or limited sample geographic coverage. With the rising global and local demand of timber and wood-based energy (State of Alaska 2007), a statewide model to estimate both merchantable and total stem volume of white spruce is of great need and importance. Of existing models, the volume model of Gregory and Haack (1964) was developed with 434 sample trees mostly from interior Alaska. Larson and Winterberger (1988) developed volume models from 244 white spruce and 43 black spruce trees harvested from the Matanuska and Susitna Valley. In addition there are numerous unpublished volume models based on datasets from small and scattered geographic areas.

The objective of this study was to develop a single model to estimate cubic-foot volume of white spruce in Alaska in each of eight categories (total stem and merchantable volume to a 2-in, 4-in, and 6-in top; both outside and inside bark).

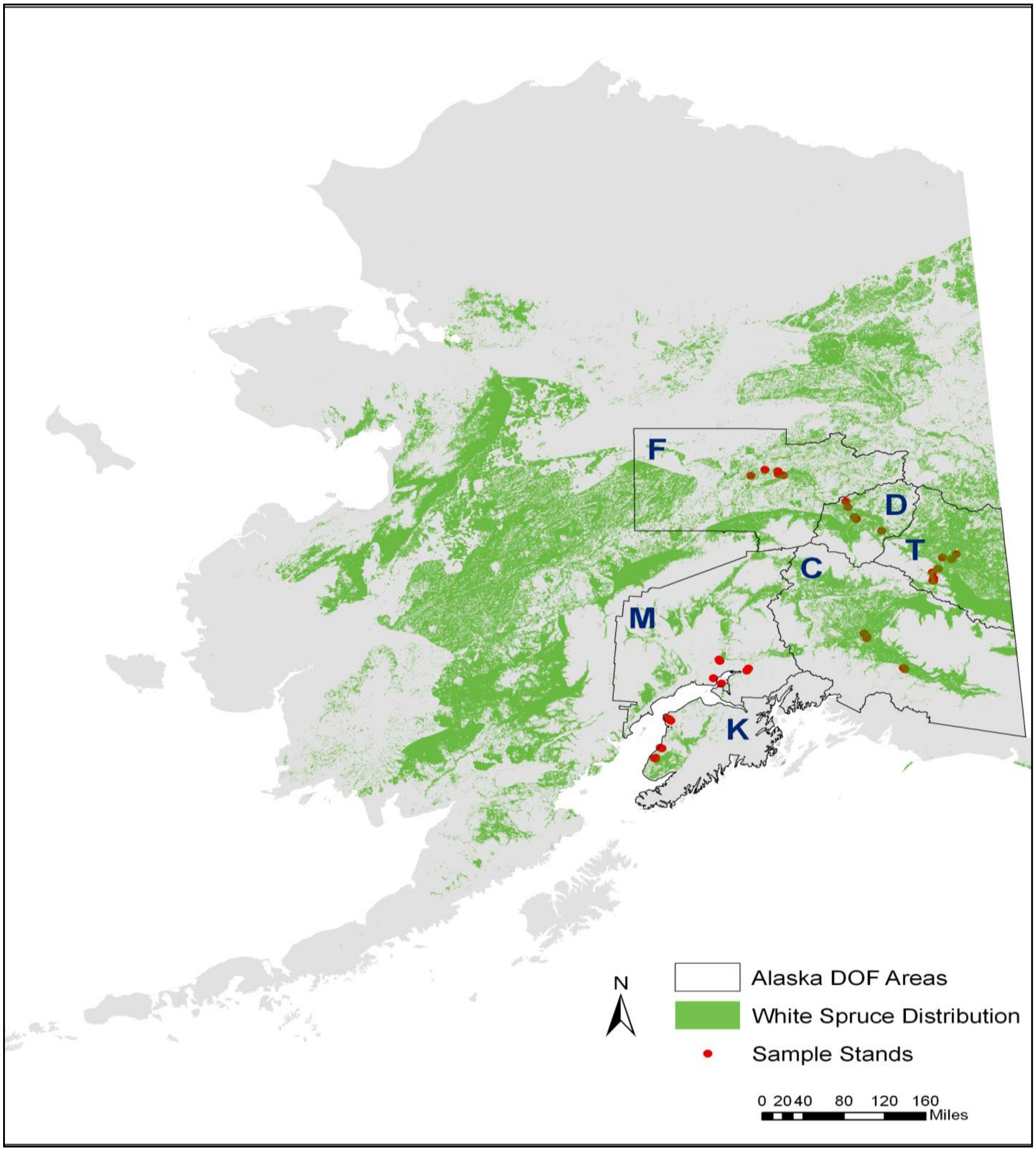

Figure 4.1. Geographic distribution of the 43 sample sites. C, Copper River Valley; D, Delta area; F, Fairbanks area; K, Kenai Peninsula; M, Matanuska-Susitna Valley; T, Tok area (Ruefenacht et al. 2008).

Data and Methods

Data Collection

A total of 2,016 white spruce trees were sampled from 43 commercial forest stands located throughout six Alaska Department of Forestry (DOF) designated areas (Maisch 2009) of interior and south-central Alaska: Copper River Valley, Delta, Fairbanks, Kenai Peninsula, Matanuska-Susitna Valley, and Tok (fig. 4.1). Within each DOF area, stands were randomly selected from where trees were being commercially harvested or where trees were available to cut. Sample trees were randomly selected in each stand with four criteria: first, sample trees must be felled and situated in a safe location for measurement; second, sample trees were free of major defects from the base to the tip; third, sample trees must have a dbh no less than 2 in; and fourth, no more than 150 trees would be sampled per stand. Sample trees were representative of dominant, codominant, intermediate, and understory crown classes (table 4.1).

All the sample trees were felled and delimbed along the top and on one side of the stem to facilitate accurate height and diameter measurements. The following data were collected for each sample tree: crown class, total height, length of live crown, and diameter outside bark every 4-ft along the main stem from a 6-in high stump to the tip. Diameter was measured every 4-ft along the stem regardless of bole abnormalities. Length was measured to the nearest 0.1 ft and diameter was measured outside bark to the nearest 0.1 in.

Table 4.1. Distribution and number of sample trees by total height and diameter at breast height for both the Alaska model dataset and the validation (post-sample) dataset.

	Total height (ft)									
DBH (in)	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100+**	**Total**
					Calibration dataset					
2	1	2								3
4	14	47	20	2						83
6	1	30	98	60	12	1				202
8		1	39	135	127	47	5			354
10			5	53	202	148	47	10		465
12				11	87	127	70	30	3	328
14				1	21	69	53	39	19	202
16					4	16	18	24	16	78
18					1	8	17	5	17	48
20						1	3	10	22	36
22+								1	15	16
Total										1815
					Validation dataset					
2										
4	3	5		1						9
6		3	12	10	3					28
8				14	13	6	2			35
10				5	28	13	6			52
12				2	4	13	8	3		30
14					3	5	6	2	3	19
16						1	5	4	3	13
18						1		2	3	6
20						1	2		1	4
22+									5	5
Total										201

Approximately 10 percent of the samples from each DOF area (table 4.2) were randomly selected and reserved to validate model accuracy. A total of 201 validation trees were selected and the remaining 1,815 trees were used to develop the models.

Table 4.2. Sample distribution by DOF area.

DOF Area	Calibration Dataset	Validation Dataset	Total
Copper River Valley	328	36	364
Delta area	323	36	359
Fairbanks area	307	34	341
Kenai Peninsula	353	39	392
Mat-Su Valley	205	23	228
Tok area	299	33	332
Total	1815	201	2016

Stem volume outside bark of each sample tree was calculated as the sum of the volume of each 4-ft section, which was estimated with the Smalian formula (Husch et al. 1993). Stem volume inside-bark was estimated from diameter inside-bark by subtracting bark thickness from diameter outside bark. Bark thickness was estimated with the white spruce bark thickness model of Malone and Liang (2009) developed from the same geographic areas as this volume data. In estimating the merchantable volume, the top section of each sample tree was set as the first section containing a merchantable top diameter, Viz. 2-in., 4-in., or 6-in.

Model Estimation and Validation

The models to estimate total stem volume outside (V_1) and inside (V_2) bark were selected from a series of candidate models based on the goodness-of-fit, level of significance, and residual patterns. The candidate models consisted of various forms of dbh (D) and height (H) including D, D^2, $ln(D)$, (DH), (D^2H^2), H, H^2, $D^{-2}H^{-1}$, and $ln(H)$. Two different forms of dependent variables, V and $ln(V)$ were also tested. While all models tested were of high goodness-of-fit (R^2>90%) and high levels of significance ($P<0.05$), most models were rejected due to abnormal patterns of residuals.

The selected total stem volume model is:

$$lnV_1 = \alpha_0+\alpha_1 \cdot lnD+\alpha_2 \cdot lnH$$

$$lnV_2 = \beta_0+ \beta_1 \cdot lnD + \beta_2 \cdot lnH \tag{4.1}$$

where α and β's were parameters estimated with the generalized least squares (GLS) method (Nelder and Wedderburn 1972).

Merchantable volume ($M_{i,j}$) was determined by total stem volume (V_1 or V_2), dbh (D), and height (H) with a linear model:

$$M_{i,j} = \gamma_0+ \gamma_1 \cdot V_i +\gamma_2 \cdot D +\gamma_3 H \tag{4.2}$$

where $M_{i,j}$ represented merchantable volume outside (i=1) and inside (i=2) bark, to a j-in top, and γ's were parameters to be estimated with GLS. The original data was used as V_1 and V_2 in developing the merchantable volume models and not by inserting the total stem volume model (4.1).

Total and merchantable volume models were examined with the coefficient of determination (R^2) and residual patterns and were further tested for accuracy and geographic variation. The accuracy of chosen models was determined by the post-sample prediction errors, the difference between the predicted and actual observed total and merchantable volume of the 201 validation sample trees. Predictions of the merchantable volume model to a 4-in top were compared against observed values and predictions of three other white spruce volume models that have been used in Alaska (Haack 1963, Beagle 1979, Larson and Winterberger 1988). To test the hypothesis that a statewide volume model could be accurate for applications at various sub-regions, the 201 post-sample trees were further compared with those predicted by the models calibrated for each of the six DOF areas. The total stem volume outside bark model is presented as an example of the accuracy of the Alaska statewide models.

Results

The model of total stem volume outside bark developed for white spruce in Alaska was:

$$lnV_1 = -5.7308+(1.7837\ lnD)+(1.0613\ lnH) \tag{4.3}$$

For users who are not familiar with logarithmic transformations, the above model is also presented in exponential form:

$$V_1 = 0.00324\ D^{1.7837}\ H^{1.0613} \tag{4.4}$$

The model of total stem volume inside bark was also developed with the same form (table 4.3). The model to estimate merchantable volume outside bark to a 2-in top was:

$$M_{1,2} = -0.0734 + 0.9999*V_1 - 0.00003D + 0.000094H \tag{4.5}$$

The models of merchantable volume inside and outside bark to a 4 and 6 in top were also developed in the same form (table 4.3).

Table 4.3. Alaska models to estimate total and merchantable volume of white spruce in Alaska.

Model	Estimated parameters	R^2	P	N
Total stem volume				
Outside bark	$lnV_1 = -5.7308 + (1.7837 lnD) + (1.0613 lnH)$	0.994	<0.0005	1815
Inside bark	$lnV_2 = -6.1352 + (1.8517 lnD) + (1.0691 lnH)$	0.994	<0.0005	1815
Merchantable volume				
Outside bark to a 2-in top	$M_{1,2} = -0.0734 + 0.9999V_1 + 0.00003D + 0.0001H$	0.999	<0.0005	1815
Inside bark to a 2-in top	$M_{2,2} = -0.0720 + 0.9999V_2 + 0.0001D + 0.0001H$	0.999	<0.0005	1814
Outside bark to a 4-in top	$M_{1,4} = -0.7100 + 0.9982V_1 + 0.0354D - 0.0028H$	0.999	<0.0005	1806
Inside bark to a 4-in top	$M_{2,4} = -0.8940 + 0.9963V_2 + 0.0488D - 0.0032H$	0.999	<0.0005	1783
Outside bark to a 6-in top	$M_{1,6} = -3.1100 + 0.9891V_1 + 0.2036D - 0.0146H$	0.999	<0.0005	1692
Inside bark to a 6-in top	$M_{2,6} = -3.5510 + 0.9840V_2 + 0.2541D - 0.0198H$	0.999	<0.0005	1620

Note: R^2 = coefficient of determination; P = level of significance: N = number of samples; V_1 = total volume outside bark; V_2 = total volume inside bark; *ln* = log transformation; *D* = dbh; *H* = height; M = merchantable volume; $_1$ = .volume outside bark; $_2$ = volume inside bark; $_{2, 4, 6}$ = merchantable volume to a 2-in, 4-in, 6-in top.

All the selected total and merchantable models (table 4.3) show high coefficients of determination (R^2 >99%) and high levels of significance ($P < 0.0005$). Residuals of the total stem volume inside and outside bark were normally distributed without any discernable pattern of bias (fig. 4.2.A, B). Residual patterns of the merchantable volume models appear to be more complex (fig. 4.2.C-H), but as the merchantable top diameter increases from 2 to 6 in the residuals became centered around zero with a less discernible pattern. There were a few suspicious outlying residuals (fig. 4.2.A, B), but the Student T-test ($P \geq 0.05$) indicated that none of them was an influential outlier.

Table 4.4. Parameters of the candidate models and the final model of total stem volume.

Model	Estimated parameters	R^2	P	Residual pattern
1	$V = a_1+a_2 D+a_3H$	0.947	<0.0005	funnel
2	$V = a_1+a_2 D^2+a_3H$	0.987	<0.0005	funnel
3	$V = a_1+a_2 D^2+a_3H^2$	0.953	<0.0005	curved band
4	$V = a_1+a_2 D+a_3H+(D2H)$	0.989	<0.0005	funnel
5	$lnV = a_1+a_2 lnD^2+a_3lnH$	0.999	<0.0005	curved band
6	$lnV = a_1+a_2 lnD^2+a_3lnH^2$	0.990	<0.0005	curved band
7	$lnV = a_1+a_2 lnD+a_3lnH$	0.994	<0.0005	satisfactory

Note: R^2 = coefficient of determination; P = level of significance; *V* = volume; *D* = dbh; *H* = height; *ln* = log transformation.

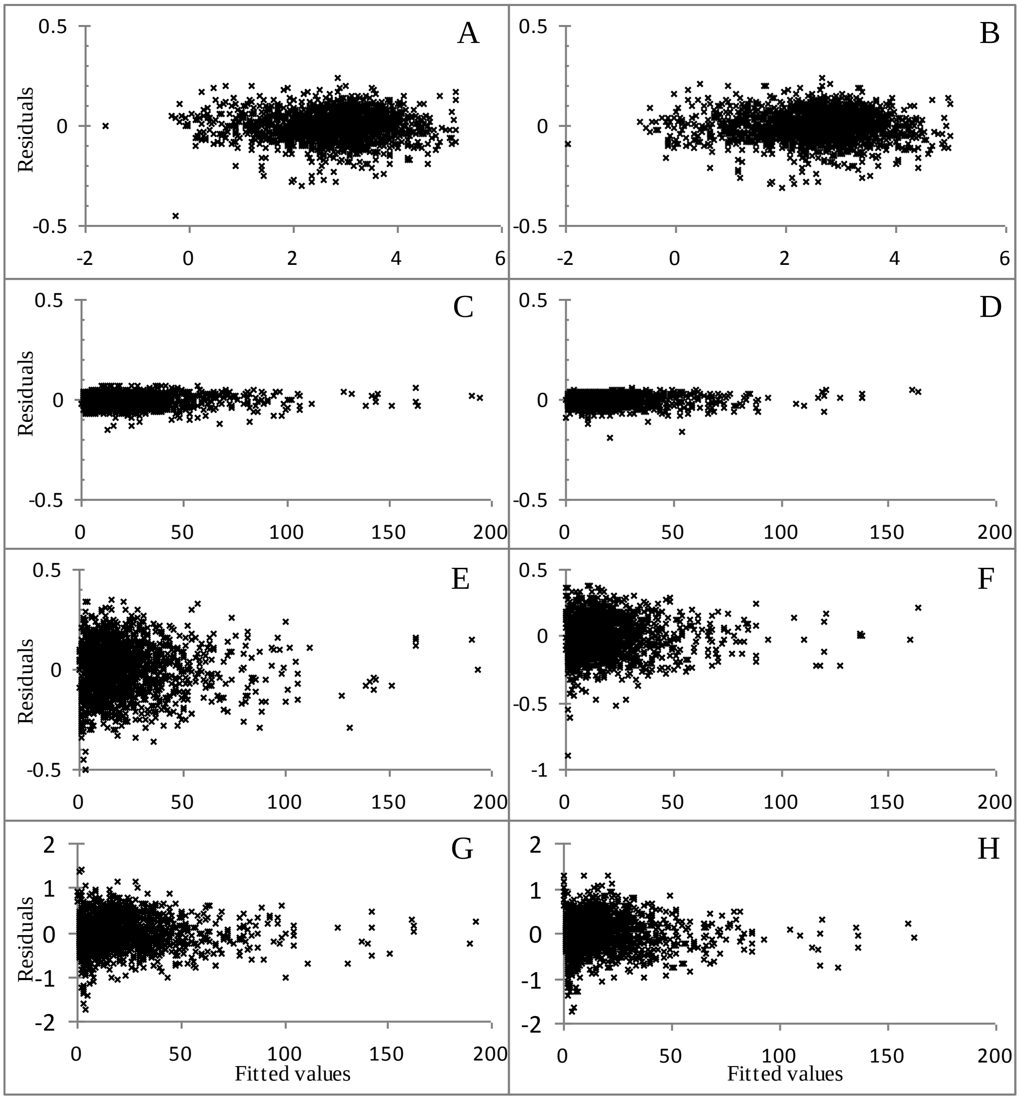

Figure 4.2. Residual vs. fitted values of the total and merchantable volume models of white spruce in Alaska. A, total stem volume outside bark; B, total stem volume inside bark; C, merchantable volume to a 2" top outside bark; D, merchantable volume to a 2" top inside bark; E, merchantable volume to a 4" top outside bark; F, merchantable volume to a 4" top inside bark; G, merchantable volume to a 6" top outside bark; H, merchantable volume to a 6" top inside bark.

The accuracy of the merchantable volume model to a 4-in top inside bark was analyzed by comparing the predicted stem volumes against the observed values of the 201 validation samples. Figure 4.3 was developed to test the accuracy of four white spruce volume models with an independent set of post-sample data. Three of the models are published white spruce volume models and the fourth model is the Alaska statewide model. The Alaska statewide merchantable volume model was obviously more accurate than the three other volume models (Haack 1963, Beagle 1979, Larson and Winterberger 1988), which overestimated the merchantable volume of trees of all sizes. For all the validation samples, the average predicted Alaska merchantable volume were all within the 95 percent confidence interval of the observed mean (fig. 4.3). The average difference between the mean predicted and the observed stem volumes is -0.06 ft^3, which accounts for less than 0.1 percent of the observed mean.

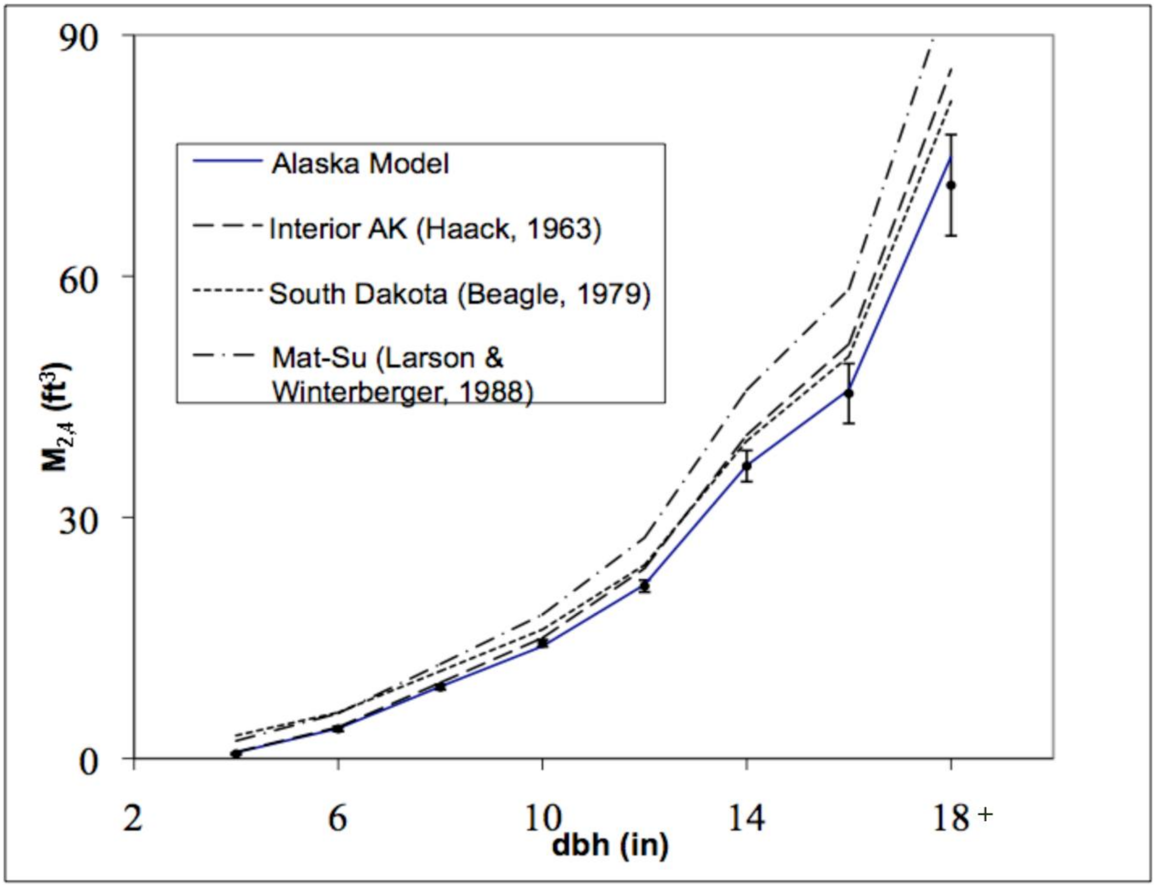

Figure 4.3. Mean predicted and observed (with 95% C.I.) merchantable volume to a 4-in top inside bark of the 201 validation sample trees. Predictions were obtained with the Alaska model and three other white spruce volume models. $M_{2,4}$, merchantable volume to a 4” top inside bark.

Compared with the six DOF individual-area models, the Alaska statewide total volume model exhibited no practical or statistical difference in predictions of the 201 validation samples. Total volumes by dbh estimated with the statewide model and the six individual-area models were all similar and fell within the 95 percent confidence interval of the observed means (fig. 4.4). Therefore, we found no significant geographic difference in total volume estimation within the State of Alaska, all the statewide volume models were tested to be accurate when applied to any of the six DOF areas.

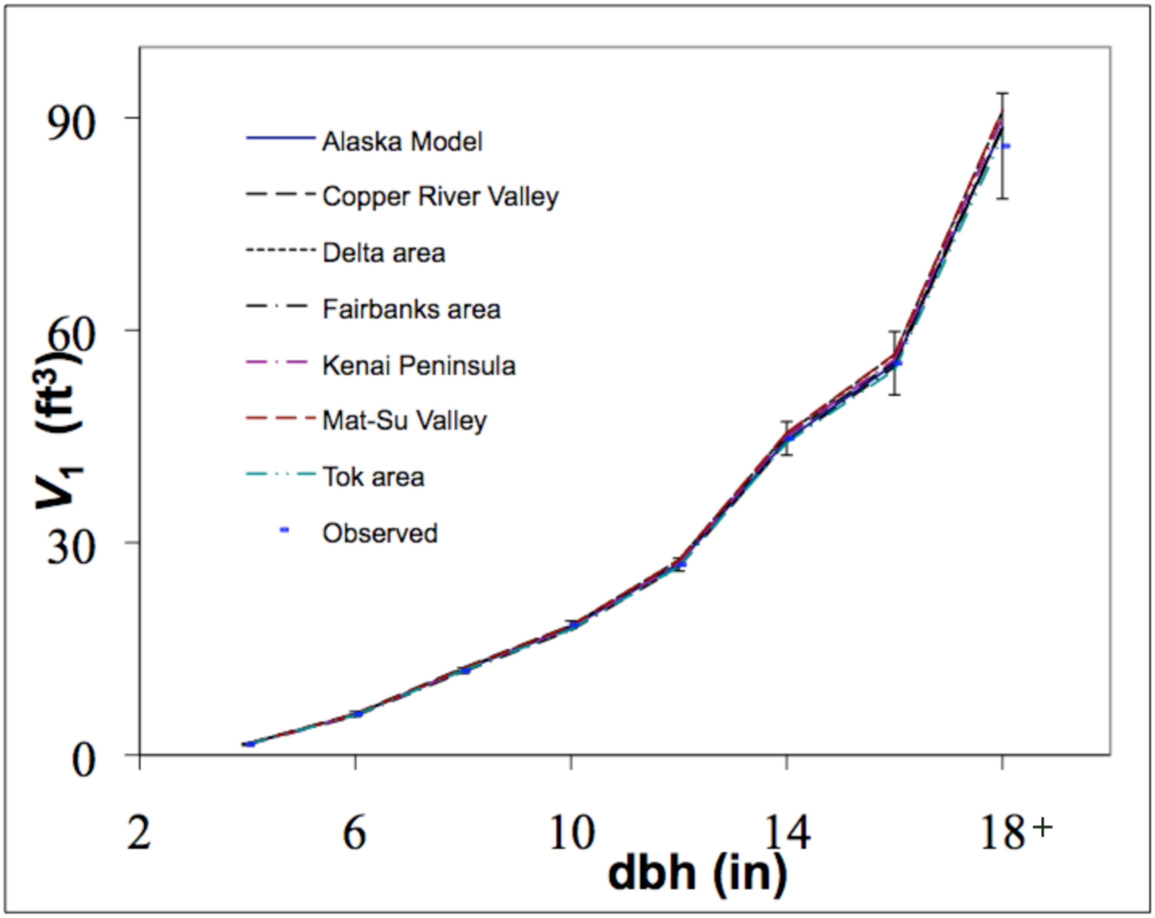

Figure 4.4. Mean predicted and observed total volume outside bark (ft^3) of the 201 validation sample trees, with 95% confidence interval (vertical bars) of the observations.

Discussion and Conclusion

Each of the eight Alaska statewide volume models was tested to be accurate at estimating the cubic-foot volume of white spruce in Alaska. The total stem and merchantable volume models developed in this study display excellent goodness-of-fit ($R^2 \geq 0.994$) and high levels of significance ($P<0.000$). When tested on the validation sample set, both the total stem and merchantable volume models were accurate and the prediction errors were not significantly different from zero (fig. 4.3). The high coefficient of determination (R^2) is a function of the growth pattern of white spruce trees and the sampling method. White spruce is a medium size tree which tapers quickly from a small root collar so the entire stem is close to the geometric shape of a paraboloid, cylinder, and cone. Also, the sample trees were measured in 4-ft lengths so each section was close to a geometric shape which lessened the natural variation. This produced a total stem model close to a function of D^2H which describes the geometric shape of a cone, thus producing a high R^2.

Compared to three existing volume models of white spruce, the Alaska merchantable model was of superior accuracy. The South Dakota (Beagle 1979) and the Mat-Su (Larson and Winterberger 1988) models overestimate merchantable volume of all tree sizes. The interior Alaska model developed by Haack (1963) was accurate for small diameter trees but the errors increased with increasing dbh (fig. 4.3).

Most existing tree volume models estimate volume from a 1-ft high stump. Modern logging equipment, such as feller-bunchers, cut stumps at 6 in above the ground, which captures more volume at harvest. This difference in harvestable volume can be significant because about half of the volume of a white spruce tree is in the first log; in a random subsample of 50 trees used in this study, 54 percent of the volume was found in the first log. To reflect that increase in harvestable volume due to modern logging equipment, we estimated total and merchantable volume from a 6-in stump.

A Kuskokwim River Valley white spruce model (Dippold and Farr 1971) estimates merchantable volume to a 4-in. top outside bark. Compared to the merchantable volume model developed in this study, the Kuskokwim-River-valley model underestimates merchantable volume of the validation sample. The difference between the two models may be largely due to different sampling procedures instead of geographic difference. The Kuskokwim dataset contains only trees above 5-in dbh and volume was calculated from a 1-ft stump instead of a 6-in stump for the present model. The trees from the Kuskokwim dataset were measured in 8.15-ft sections and the Smalian formula was used to calculate volume. The Smalian formula estimates volume accurately for short logs such as the 4-ft sections of this study. However, the Smalian formula is less accurate at estimating volume of logs longer than 4-ft (Husch et al. 1993; Avery and Burkhart 2002).

This study presents cubic-foot volume estimates of standing white spruce trees for Alaska; many existing models present board-foot volume. Cubic-foot volume is more common for the contemporary forest products industry which is capable of utilizing the entire tree instead of only solid sawn lumber (Nilsson and Wernius 1976). A board-foot scale does not account for bark, sawdust, slabs, and small-diameter wood. In addition, for trees sold on an international market, cubic-foot volume can be easily and accurately converted to metric scale by multiplying a factor ($1\ \mathrm{ft}^3 \times 0.02832 = 1\ \mathrm{m}^3$). Board-foot volume must be converted to metric scale on an individual stem basis which is time-consuming. For these reasons, cubic-foot or cubic-meter volume estimates are a more appropriate unit of measure for trees in North America.

The Alaska models were developed with data collected from 2,016 trees of various sizes and from 43 forest stands throughout interior and southcentral Alaska. These models provide a simple and accurate tool for researchers and resource managers to estimate white spruce total and merchantable cubic-foot volume, both inside or outside bark from a 6-in stump.

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Chapter 5 General Conclusion

This thesis provides three tools to promote improved management of the northern forests of Alaska. Researchers can also use this information to expand or update their research. The white spruce bark thickness model and the volume models were developed, in part, to compliment the CAFI inventory project.

Cooperative Alaska Forest Inventory

The CAFI database and user's manual provides valuable information for the management of the northern forests of Alaska. The data are being extensively used by numerous researchers and agencies. With the expansion of the CAFI project through the establishment of new PSPs and remeasurement of existing PSPs, this database will become more valuable. The plots which are remeasured periodically provide a long-term view of the dynamics and health of forests within the study area.

White spruce bark thickness model

The bark thickness model developed here estimates inside-bark thickness for white spruce volume models (Chapter 4). It can also be included in other white spruce volume models to improve or update them. An existing cubic-foot outside bark volume model can be expanded to include inside-bark volume estimates by including this model.

Data was collected from six State Division of Forestry areas to develop this bark thickness model (fig. 3.1). A model was developed for each area and additional samples were collected for a validation dataset to test the statewide model accuracy. Analysis shows that there is no practical or statistical difference between the statewide model and the area models. The Alaska statewide model was also compared with two existing white spruce bark thickness models and this analysis shows that the Alaska model was more accurate for application in Alaska.

White spruce volume models

The Alaska statewide white spruce volume models were tested and proven to accurately estimate volume of individual trees, volume per unit area, and to develop biomass equations.

The statewide volume models estimate total stem volume both outside and inside bark and merchantable volume both outside and inside bark to a 2-in, 4-in, or 6-in top; from a 6 in high stump. Volume data was collected from 43 forest stands in six DOF areas throughout interior and south-central Alaska. A total of 2,016 trees were sampled and approximately 10 percent of these trees were removed for model validation (table 4.2). Similar to the bark thickness model, volume models were developed for each DOF area from data collected in that area and compared to the Alaska statewide model using the validation dataset. There was no practical or statistical difference between the Alaska model and the models developed for each DOF area (fig. 4.4). Three published white spruce volume models were also compared to the Alaska statewide model (fig. 4.3), and the later was proven to be more accurate in estimating tree volume.

The Alaska statewide models estimate cubic-foot volume because it is the appropriate unit of measure for the current forest products industry and can be easily converted to a metric scale for international markets.

Land managers and researchers can use the Alaska statewide white spruce cubic-foot volume models to estimate individual tree volume as well as white spruce volume per unit area in northern Alaska.

Forest managers asked for the tools which are presented in this thesis to answer specific questions concerning basic forest growth and tree volume. The data collected and analyzed through these projects can provide much more information.

As previously stated, climate change models predict numerous changes to the ecosystem of northern Alaska and the CAFI project will allow researchers to ground-truth their predictions. The data collected in the field will track changes that occur in ecosystem processes such as: forest succession, expanding forests, species diversity, changes in insect infestations, and carbon sequestration. There are studies underway which monitor forests after disturbance (Bernhardt et al. 2011) and studies like this can be expanded throughout the large geographic distribution of this permanent sample plot system.

While this thesis does not deal directly with resource economics there are numerous economic issues (environmental and social) that face managers and policy makers concerning the northern forests of Alaska. Should we increase resource development/extraction, how will climate change issues affect values, the economics of carbon sequestration and disturbances. However we decide to treat our lands and forest resources, monitoring forests conditions and knowing the economic value in our forests will help to develop better long-term strategies.

Bark thickness can be used to indirectly estimate bark volume. In combination with volume models they can be used to assess the potential of white spruce bioenergy resources in Alaska. While climate change will affect tree growth (positively or negatively) these white spruce bark thickness and volume models will remain accurate and useful for generations. Tree growth varies from year to year based in-part on the weather and climate but tree allometry will not change rapidly. That is an evolutionary change which will take generations to realize and will only occur if there are large-scale changes in the climate.

The path toward improved management of the northern forests of Alaska is multi-faceted and the management tools presented in this thesis will help direct the way.

Future Research

The CAFI permanent sample plot system should be expanded to coincide with the distribution of tree species in the northern forests of Alaska and extended especially into western Alaska. Additional plots should also be established in targeted forest stands in interior and south-central Alaska. These new plots could cover a wider range of forest stand characteristics such as species composition, stand ages, and various site characteristics (e.g. slope, aspect, landform, and soils).

Bark thickness and improved cubic-foot volume models need to be developed for the other trees species of northern Alaska including: black spruce, Alaska birch, Kenai birch, aspen, and balsam poplar.

Literature Cited

Bernhardt, E. L., T.N. Hollingsworth, and F.S. Chapin, III. 2011. Fire severity mediates climate-driven shifts in understory community composition of black spruce stands of interior Alaska. *J. of Veg. Sci.* 22(2011):32-44.

Appendix 1.A: List of Cooperators

Organization	Support provided
Alaska Department of Natural Resources	
Division of Forestry	- permit to cut/measure trees in State timber sales. -personnel assist in measurements - permit to establish PSPs - permit to collect bark data
Division of Parks and Recreation	- permit to measure trees in Parks where trees are being cut. - permit to establish PSPs
University of Alaska	
Statewide Office of Land Management	- permit to cut/measure trees in existing timber sales. - permit to establish PSPs
Ag & Forestry Experiment Station	- employees assist in measurements. -fuel and vehicle maintenance. - permit to establish PSPs
United State Department of Defense	
U.S. Air Force	- permit to cut/measure trees in existing timber sale and firewood cutting area. - permit to establish PSPs
U.S. Army	- permit to cut/measure trees in area where trees are being removed. - personnel assist in measurements. - permit to collect bark data - permit to establish PSPs

United State Department of Agriculture	
U.S. Forest Service	- permit to cut/measure trees in existing timber sales. - permit to collect bark data.
United State Department of Interior	
Bureau of Land Management	- permit to cut/measure trees in area where trees were being removed. - permit to establish PSPs.
USFS Kenai Wildlife Refuge	- permit to establish PSPs.
NPS Wrangell-St. Elias Nat'l Park	- permit to establish PSPs
Matanuska-Susitna Borough	- permit to cut/measure trees in existing timber sales. - personnel assist in measurements. -permit to establish PSPs
Fairbanks North Star Borough	- permit to establish PSPs.
Kenai Peninsula Borough	- permit to establish PSPs.
Chitina Village Corporation	- permit to cut/measure trees in existing timber sale.
Dot Lake Native Corporation	- permit to establish PSPs.
Ninilchik Native Corporation	- permit to cut/measure trees in existing timber sale.
Northway Native, Inc.	- permit to establish PSPs.
Salimantof Native Corporation	- permit to cut/measure trees in existing timber sale.
Tetlin Native Corporation	- permit to cut/measure trees in existing timber sale.
Toghottele Corporation	- permit to cut/measure trees in existing timber sale.

Ahtna Regional Corporation	- permit to cut/measure trees in existing timber sale. - permit to establish PSPs
Cook Inlet Regional Corporation	- permit to cut/measure trees in existing timber sale. - permit to establish PSPs
Copper River Native Association	- secured permit to cut/measure trees in existing timber sale. - personnel assist in measurements.
Tanana Chiefs Conference	- secured permit to cut/measure trees in existing timber sale. - personnel assist in measurements.
Circle Dee Pacific Logging	- permit to cut/measure trees in existing timber sale.
Copper River Forest Products	- permit to cut/measure trees in existing timber sale. - room and board for field crew.
Emcon Inc.	- assisted in securing permits.
Northland Wood Forest Products	- permit to cut/measure trees in existing timber sale.
Su Valley Landclearing	- permit to cut/measure trees in existing timber sale.

Appendix 2.A: List of equipment used to establish a PSP

GPS unit
Hand-held field computers with shoulder straps
Camera with extra batteries
Laser hypsometer with extra batteries
Laser reflector target
Compass
Clinometer
Convex spherical crown densiometer
Clipboard
100 ft tape (2)
Diameter tapes
Increment borer
Shovel
Regeneration pole
DHB stick (4.5 ft)
Tree data classification sheet
Munsell soil color chart book
Permit from Landowner
CAFI user's manual

Appendix 2.B: List of expendable supplies used to establish a PSP

Previous inventory data sheets for remeasurement plots
Blank write-in-the-rain data sheets for site, tree, and regeneration files
Permanent marker pens
Tree core holder tray (2)
Stakes/Corner posts (15 per site)
Numbered tags
Pins for numbered tags
Flagging
Lumber crayon
Paint sticks
Rubber gloves
Zip-lock bags for vegetation samples
Permit from landowner to enter land
Emergency contact phone numbers
Site coordinates