SELECTION MANAGEMENT OF INTERIOR DOUGLAS-FIR FOR MULE DEER WINTER RANGE

by

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ABSTRACT

A working plan for the Knife Creek block of the Alex Fraser Research Forest is presented. The plan recommends single-tree selection management of interior Douglas-fir (*Pseudotsuga menzesii* var. *glauca*) to maintain and enhance winter range habitat for mule deer (*Odocoileus hemionus hemionus*) near Williams Lake in central British Columbia. An extensive review of the literature describes the silvics of Douglas-fir, the ecology and history of the area, and the ecology of mule deer. Mule deer at Knife Creek are dependent upon Douglas-fir forests, because large Douglas-firs provide shelter from winter snow and wind-blown litterfall as forage. It is suggested that current stand structures are different from the condition that existed a century ago, and place winter range values at risk due to fire and insect attack. Single-tree-selection management will reduce those risks over time. Stand level regulation by the "Basal Area - Maximum Diameter - q Factor" method is pursued, and two target stand structures are recommended:

–Low to moderate cover is provided by B = 18 m^2/ha D = 60 cm dbh, and q = 1.25

–Moderate to high cover is provided by B = 25 m^2/ha D = 70 cm dbh, and q = 1.2

Cover for deer will vary within a stand depending upon time since harvest. A cutting cycle of 20 years is recommended, and forest level regulation is provided by area control. The Allowable Annual Cut is thereby established as 170.9 ha/year. A stand table projection model is offered without validation. Once completed, the model will be used to develop a volume check for the allowable cut, thereby developing a harvest queue that will provide relatively even flow of timber volume. Methodologies for sampling and describing stands, developing prescriptions, and implementing cutting plans are provided. A list of research and training required to implement this plan across similar winter ranges in the Cariboo Forest Region is provided. Implementation of this working plan will provide a blueprint for managing mule deer winter range by single-tree-selection management of Douglas-fir.

Key Words: Cariboo Region, Interior Douglas-fir zone, logging guidelines, mule deer, *Odocoileus hemionus hemionus*, *Pseudotsuga menzesii* var. *glauca*, single-tree selection management, Alex Fraser Research Forest, uneven-aged management

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INTRODUCTION

Aldo Leopold (1966) compares science to the study of musical instruments, and research to disassembling instruments in the interest of describing their function. The construction of musical instruments is the domain of scientists, but the detection of harmonies is the domain of poets (Leopold 1966). Perhaps silviculture can be described as the meeting of those two pursuits -- the arrangement of musical instruments (science) to play a composition with harmony. The music is not written by silviculturists, but by the landowner. The task of arranging the musical instruments to perform the composition requires artful silviculture.

O'Hara *et al.* (1994) discuss the role of silviculturists in the face of changing paradigms of forestry. They believe that silviculture must play a pivotal role in integrating all forest resource values into forest management. In the past, silviculture has been simple because it has responded to simple management objectives (O'Hara *et al.* 1994). Changing expectations for forestry imply that management objectives will become much more complex, and silviculturists must take up the challenge. Eastman *et al.* (1991) place the responsibility for managing wildlife habitats squarely on the habitat biologists and the silviculturists, and stress that "a willingness to try" is a critical ingredient of success. Weetman (1996) suggests that:

> "The future of forestry in British Columbia...will depend on the ability of foresters to develop sound silviculture prescriptions...to meet the stand management objectives set by higher-level forest planning."

This thesis, then, represents the aims of one forester to achieve the integrated resource management objectives set for a piece of land, by providing reasoned guidance for silviculture prescriptions. It describes a willingness to try to carry out complex silviculture in an effort to achieve complex management objectives.

The Alex Fraser Research forest is10,000 ha of public land, managed by the University of BC Faculty of Forestry. The forest land is managed under tenure from the provincial government; therefore the landowner is deemed to be the public, as represented by government.

Forest management is the pursuit of a landowner's goals through manipulation of the forest. In this author's opinion, industrial forest management in British Columbia generally interprets the landowner's goal as the commercial production of timber while protecting various "other" resources. This thesis, however, approaches a particular problem of forest management from a fundamentally different perspective. In the case of the Knife Creek block of the Alex Fraser Research Forest, the landowner's goal is the maintenance of mule deer winter habitat. The approach is to use silviculture to maintain and enhance mule deer winter range, which entails periodic timber harvest. This thesis follows the integrated resource management model proposed by Armleder *et al.* (1986, 1989).

Returning to Leopold's (1966) analogy, this thesis might be considered an arrangement of a complex composition. Society has written a piece that includes maintaining winter range for mule deer, providing timber for local industry and forage for cattle, and operating a teaching and research facility. The composition will be played in a dry Douglas-fir forest in central British Columbia. The principal instruments in the arrangement are: silvics and ecology; growth and yield; single-tree-selection management; and timber harvesting.

A core concept of this thesis is that cutting trees is the only available means to maintain mule deer winter range values at Knife Creek. The art in this arrangement is contained in a set of critical decisions; which trees to keep, how many to keep, how and when to cut the others. If these decisions are not artfully taken, the arrangement will be played by the correct instruments, but without harmony.

An often-quoted passage from Leopold (1966) is a fitting description of the art in those critical decisions:

> “I have read many definitions of what is a conservationist, ... but I suspect that the best one is written not with a pen, but with an axe. It is a matter of what a man thinks about while chopping, or while deciding what to chop. A conservationist is one who is humbly aware that with each stroke he is writing his signature on the face of his land. Signatures of course differ, whether written with axe or pen, and this is as it should be.”

> “I find it disconcerting to analyse ... the reasons behind my own axe-in-hand decisions. I find, first of all, that not all trees are created free and equal. Where a white pine and a red birch are crowding each other, I have an *a priori* bias...”

> “... there is skill in the exercise of bias. ... Such are the pros and cons the wielder of an axe must foresee, compare, and decide upon with the calm assurance that his bias will, on the average, prove to be something more than good intentions.”

This thesis describes a working plan for mule deer winter range in the Knife Creek block of the Alex Fraser Research Forest. It describes: the setting for the plan (the stage); the scientific understanding that enables the plan (the instruments); the goals of management (the composition); and the decisions that will effect the plan (the arrangement). Whether the plan is an artful and harmonious arrangement will only be determined in the future, when it has been practised.

DESCRIPTION OF THE KNIFE CREEK BLOCK

A. PHYSICAL DESCRIPTION

The Knife Creek block[1] is located in the Cariboo Forest Region of British Columbia, near Williams Lake (Figure 1). This block of the Alex Fraser Research Forest is located predominantly in the Fraser plateau variant of the dry cool interior Douglas-fir biogeoclimatic subzone (IDFdk3) (Meidinger and Pojar 1991), in what is commonly referred to as the "drybelt." Table 1 describes the biogeoclimatic subzones that comprise the Knife Creek block.

Table 1: Biogeoclimatic variants occurring on the Knife Creek block, showing typical vegetation and selected climatological data (Anon 1987; from Day 1997a).

SUBZONE (Meidinger and Pojar 1991)	CLIMAX TREE SPECIES[2]	ASSOC. TREE SPECIES	DOMINANT UNDERGROWTH	MEAN PRECIP (mm)		MEAN TEMP (°C)	
				Annual	Growing Season	Annual	Growing Season
Xeric-Mild Interior Douglas-fir (IDFxm)	Fdi	At,Ac,Sx,(Pli),Jt	snowberry-pinegrass bluebunch wheatgrass-forbs	389	204	4.1	13.3
Dry-Cool Interior Douglas-fir (IDFdk3)	Fdi	Pli,At,Ac,Sx,(Ep)	pinegrass-forbs	444	214	3.0	11.9
Moist-Cool Sub-boreal Pine Spruce (SBPSmk)	Sx	Pli, At, Ac, (Bl), (Fdi)	blueberry - pinegrass - forb	534	227	2.7	10.9

[1] Longitude 121°48' W, Latitude 52°03' N.

[2] Tree Species Symbols with common and Scientific names:

Ac -- cottonwood *Populus trichocarpa* Torr & Gray

At -- trembling aspen *Populus tremuloides* Michx.

Bl -- subalpine fir *Abies lasiocarpa* (Hook) Nutt.

Ep -- white birch *Betula papyrifera* Marsh.

Fdi -- Douglas-fir (interior form) *Pseudotsuga menziesii* (Beissin.) Franco *var. glauca*

Jt -- Rocky Mountain juniper *Juniperus scopulorum* Sarg.

Pli -- lodgepole pine (interior form) *Pinus contorta* Dougl. ex. Loud. *var. latifolia*

Sx -- interior (hybrid white x Engelmann) spruce *Picea glauca* (Moench) Voss. x *engelmannii* Parry

Figure 1: A location map showing the Knife Creek block of the Alex Fraser Research Forest, located in central British Columbia (From Day 1997a).

The forest cover of the Knife Creek block is dominated by uneven-aged stands of Douglas-fir, with some stands of even-aged lodgepole pine. Most stands have minor components of interior spruce, white birch, and trembling aspen. Although the forest is generally uneven-aged (at least 2 age classes), the forest inventory includes age as a means of describing each stand. The age of the stand is interpreted to be the age of the component of the stand that comprises the majority of the stand volume. The forest cover of the Knife Creek block is described by leading species and age class (Table 2). A map is included in Appendix 1, which shows the distribution of forest cover types by leading species and age class. A second map in Appendix 2 shows Douglas-fir stands which are age class 7 and greater, with medium and high crown closure. This latter map is intended to show the stands that are currently high-quality mule deer winter range, as described on page 31.

Table 2: Summary of forested area by species and age class for the Knife Creek block (from Day 1997a).

	Area by Species (ha)				
Age Class[3]	At	Fdi	Pli	Sx	Grand Total
1	20.6	33.4	68.2	0	122.2
2	1.42	227.5	53.9	0	282.8
3	0	720.8	0	13.2	734.0
4	0	481.3	17	0	498.3
5	1.96	139.3	26.3	0	167.6
6	11.96	339.4	215.3	0	566.7
7	0	91.2	0.1	0	91.3
8	0	955.3	0	0	955.3
9	0	0	0	0	0
Total	35.9	2,988.2	380.8	13.2	3,418.1

The forest cover of the Research Forest is dominated by the harvesting history (Table 3) which has determined the present forest structure. A map in Appendix 3 shows areas that have been logged, by the type of harvest. The type of logging employed indicates the structure of the residual stands, and has a significant impact on silviculture prescriptions. The areas harvested by diameter-limit cutting have had a significant change from the natural stand structure, with very dense saplings and poles resulting. Nearly 40% of these areas have been pre-commercially thinned (juvenile spaced) since 1984, under various arrangements funded by the Ministry of Forests. The areas that have been pre-commercially thinned are depicted in a map in Appendix 4.

Table 3: Areas harvested and pre-commercially thinned (PCT) on the Knife Creek block, with descriptions of resulting stands.

Period	Harvest Type	Resulting Stand Structure	Harvest Area (ha)	PCT Area (ha)
1942-1952	Bush Mill	Good Residual Structure	495	0
1955-1969	Low Diameter Limit	Poor diameter distribution, very little vertical structure, voids and over-dense thickets	1,308	488
1970-1980	High Diameter Limit	Poor diameter distribution, little vertical structure, voids and over-dense thickets.	286	125
1980-1983	Faller's Selection	Fair diameter distribution, fair vertical structure, dense thickets, few voids.	29	26
1980-1983	Clearcut with reserves	Poor diameter distribution, poor vertical structure, largely regenerated to Pl and At, little Fd regeneration.	152	0
1983-1984	Handbook logging	Good diameter distribution, good vertical structure, dense thickets, regenerated gaps.	139	12
	Total		2,409	651

B. HISTORY

The Knife Creek block is located between Knife Creek and Jones Creek, which flow westward to the San Jose River. The San Jose River valley was occupied by native villages before European settlement, and contains the Cariboo Wagon Road (later the Cariboo Highway) and the

[3] Age Classes are each 20 years, except age class 8 (141 to 250 years) and age class 9 (251+ years).

Prince George Eastern Railway (BC Rail). Due to the location of this block of the forest, the history of the Cariboo is written upon it. The old Wagon Road passes the west boundary of the forest. The oral history of the Williams Lake Indian Band indicates that the forest contains sacred ceremonial grounds, and the Jones Creek Valley was used as a travel route to summer camping areas. Its proximity to village sites assures one that the Knife Creek mule deer winter range has been an important winter hunting area.

Three periods of history have had a significant impact upon the Knife Creek block, and are discussed below. Much of the following information is not referenced, since the purpose is only to present some background on the current forest conditions. It represents the author's interpretation of information from a wide variety of sources, from the popular press to oral history, and includes ample deduction and speculation.

The early period (before 1860) was important to the area, because the aboriginals apparently used fire to manage their environment. The most probable reasons for burning include fire hazard reduction, and management of forests for particular hunted animals or food plants (refer to the discussion starting on page 16).

Settlement of ranches (1860's to 1940's) started along the wagon road during the Cariboo Gold Rush, to supply miners with meat and other supplies. The ranchers depended upon the forests for timber and for summer range for their cattle. Hay was cut from natural grasslands, meadows, and later from developed hayfields. Development of ranches adjacent to the Knife Creek block greatly altered the landscape, since natural grasslands and meadows in the valleys were expanded for production of feed crops under irrigation. Irrigation ditches are still in use on the south and west boundaries of the Forest.

In 1913 and 1914 E.G. McDougall conducted reconnaissance surveys of the Lillooet and Cariboo Land Districts. The following passage from his report (McDougall 1913) describes the area around the Knife Creek block (brackets [ ] represent words that are not legible on the old carbon copy of his report):

> "The San Jose River flows north-westerly from Lac la Hache to Williams Lake, descending from 2700 feet to 1950 feet elevation. The valley is about two miles wide, and is bounded by escarpments rising to [ ] elevation. That on the south-west is precipitous, and the plateau behind it is stony for some distance: while that on the N.E. is gentle, and the plateau is well supplied with meadows. There are three tributary valleys coming in from the east, those of Knife Creek, Jones Creek, and 150 Mile Creek. All contain considerable areas of good bottom land. The plain above the main valley slopes gradually up to the base of some rocky hills, 4200 feet in elevation, which [ ] east of the Horsefly Road, and supply the headwaters of Knife Creek. Although fairly level, the plain is very stony in parts. Some of the meadows at the higher elevations, partake of a muskeg character. Nearly [all] the best land throughout this block has been taken up years ago, the cultivated portions produce excellent crops. Cultivation [ ] is frequently neglected in favour of the road-house business, on plan [sic] of scarcity of labour.
>
> The timber is distributed in belts along the sides of the main valley, and behind those belts lies the burned country, which [is] covered with a patchy Black Pine stand, from ten to fifty years [old]. The persistence of the old stands in positions so exposed to fire [must] be due to the former periodical removal of undergrowth and litter [by] light burning, and to some extent by the pasturing of horses and [ ]. Away from those influences, the forest would come into an extremely flammable condition, and when, at longer intervals, fire did reach [them,] the result would be total destruction.
>
> Portions of the stony plateau country might serve for [ ] pasture, but in general the land unfit for agriculture would be [ ] in forest. This part of the country seems to be well adapted to [dry] farming. It is traversed by the Cariboo Road and the P.G.E. now under construction."

McDougall (1913) reported that only 16% of the area surveyed was timbered, and 69% had been burned. Presumably "patchy stands of Black Pine" were not considered timber, since there was pressure from ranchers to allow burning of pine stands to increase grass. This had been a common practise until a fire control law was introduced.

In his more complete report, McDougall (1914) describes the forest types of the area as follows:

> "The Douglas Fir type formerly covered a large part of the interior; mostly above 3000 feet elevation; but it is now limited to certain strips and patches along the edge of the valley of the Fraser, San Jose, Bridge and Bonaparte Rivers, and to a few isolated patches elsewhere. It ascends to an elevation of 4000 to 5000 feet. The stand varies in density from 2000 to 6000 feet B.M. per acre.[4] Reproduction is usually good, taking place chiefly in openings, which are numerous. This forest is of some importance for local lumber supplies, but the poverty of the stand and the poor quality of the product would make it unavailable for outside markets.
>
> The Lodgepole Pine type is the most extensively distributed in the Interior, but is probably of a transitory character. It comes in on burned areas formerly occupied by other types, especially the Douglas Fir type; it may also occupy areas that were formerly prairie. As a rule it is wind-thrown before reaching maturity, but sometimes attains saw size, and in favourable locations might yield 2000 feet B.M. per acre. The stand is very dense, and the trees well-formed, though small; they often show frost cracks and other defects. This forest is used locally for fencing, building logs, etc., and might be utilized for pulp."

The earliest records of industrial timber harvesting on the Knife Creek block date from 1942. It is likely, however, that small hand-logging sales for hand-hewn railway ties began at about the time the railroad came to Williams Lake around 1920. Thwaites (1964) states that:

> "Lumbering in the Cariboo is almost entirely a post-World-War-II industry. It had its beginnings with local ranchers and others cutting timber on their lands and selling the logs or sawing them into cants or rough lumber."

From the 1940's to the early 1960's (the Bush Mill era) the drybelt fir stands in the Williams Lake area were exploited for railroad ties and saw timber. Most of this logging was done with horses skidding to tractor roads, and tractors were used to forward the logs to the portable sawmills. Except along the tractor roads, most of the trees selected were of a diameter to allow one tie to be cut. The horses were able to skid the smaller logs fairly easily, and therefore greater distances. This type of cutting resulted in good stocking remaining in most size classes after logging, except close to the mills and adjacent to the tractor roads. Horses gave way to crawler-tractors and arch trucks[5] by the early

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[4] 1000 board feet per acre is approximately 10 m^3/ha. Such low volume estimates reflect the utilization standards in place at the time McDougall wrote his report. Lodgepole pine was not used, and only large logs of high quality would have been considered merchantable.

[5] Arch truck -- a truck with an A-frame on the deck, over which a mainline travelled to reach out to timber from the road. These trucks were apparently able to skid a large load.

1960's. According to Thwaites (1964) the bush mills were primarily established by loggers moving up from the coast, and since they were principally loggers, the milling operations were simple. Utilization was poor by today's standards, with up to 40% of each log lost to sawdust and shavings, and trim-ends were burned. Scattered bush mills meant that no utilization of the waste was possible (Thwaites 1964).

Administration of the forest resource by the BC Forest Service was divided between the Kamloops Forest District and the Prince George Forest District. Mills in the Cariboo drew two-thirds of the volume from Kamloops Forest District (Thwaites 1964). Under the structure of the 1960's, the Forest District was analogous to the current title of Forest Regions. Between 1952 and 1962 the volume cut in the Kamloops Forest District increased by 126%, and in 1962 66% of the harvest volume was Douglas-fir (Thwaites 1964).

In the 1960's forest policy changed; sawmills were required to manufacture chips from sawmill waste, to feed a developing pulp industry in the interior. Very rapidly the bush mills began to shut down, and rights to public timber were bought up by the owners of planer mills in town. The planer-mill owners then used their new quota to build stationary sawmills. The centralized sawmill operators preferred to avoid logging, due to the expense of supervising the logging operations and the cost of owning and operating logging equipment, so contract loggers were used (Thwaites 1964).

With the advent of stationary sawmills in town, the technique shifted to diameter-limit cutting. All the trees within the cutblock over a certain diameter were harvested. Diameter-limits varied through time, from as low as ten inches (25 cm) in the mid-1960's to as high as 18 inches (45.7 cm) in the late 1970's. In the mid- to late-1960's lodgepole pine became merchantable. Areas logged in Knife Creek before 1967 had lodgepole pine left standing, but after that time the pine was cut. Although the diameter-limit system was usually successful in maintaining advanced regeneration, it often failed to maintain a good representation of thrifty mature trees, particularly with low diameter limits. Also, this system tended to produce a stand that was poorly distributed, with voids and patches of excessive density.

In the late 1970's it was recognized that the diameter-limit approach was not as successful as it should have been, and that signalled the onset of the faller-selection methods. The faller-selection method is based upon the principles of single-tree-selection management. It seeks to remove about 50% of the volume from all of the merchantable diameter classes, and leave the healthiest trees to regenerate openings and add increment. Little logging was done on the Knife Creek block during the period of faller-selection, probably due to increasing conflict over harvesting on mule deer winter range.

In the early 1980’s an intensive study of mule deer ecology was initiated on the Knife Creek block by the Ministry of Forests. The study was born out of conflict; the forest industry wanted continued access to the Douglas-fir, and Ministry of Environment saw continued harvesting on winter range as a threat to mule deer habitat. The objective of that study[6] was to seek methods of integrating timber harvesting with mule deer ecology. The methods developed were based upon the faller-selection method, but restricted harvesting to low volumes and long re-entry periods.

In 1987 the Alex Fraser Research Forest was created and the first Resident Forester (the author of this plan) was hired. Little harvesting was carried out for the following decade, except the salvage of trees killed by bark beetles. With funding from the Ministry of Forests, Research Forest staff have been able to focus on improving the condition of disturbed stands, through pre-commercial thinning and brushing.

[6] The study was led by Harold Armleder, RPF, Regional Habitat Ecologist. It is thoroughly documented starting on page 25.

NATURAL HISTORY

A. SILVICS OF INTERIOR DOUGLAS-FIR

1. Range

Interior Douglas-fir has the greatest latitudinal range of any commercial conifer of western North America (Hermann and Lavender 1990; Van Hooser *et al.* 1991), and the broadest ecological amplitude of any western tree (Arno 1991).

The principal limiting factors on the range of Douglas-fir are low temperatures and moisture stress. Low precipitation and high evaporation restrict the distribution of interior Douglas-fir in the Rocky Mountains (Hermann and Lavender 1990; Arno 1991). In the northern part of its range, Douglas-fir is restricted by cold, particularly growing season frost. In dry ecosystems such as the Interior Douglas-fir zone (IDF) of British Columbia, Douglas-fir is the climax species (Arno 1991; Hope *et al.* 1991). Interior Douglas-fir grows in extensive pure stands, both uneven-aged and even-aged (Hermann and Lavender 1990).

2. Reproduction

Flowering occurs in May and June in Northern Idaho, and seedfall occurs in mid-September; the majority of seeds fall within 100 m of a seed tree or stand edge. Seed quality declines rapidly during winter (Hermann and Lavender 1990).

Burton (1996) studied germination and survival of interior Douglas-fir in the wet warm interior Douglas-fir and dry warm sub-boreal spruce biogeoclimatic subzones (Meidinger and Pojar 1991). He found that "... moss is a universally poor seedbed, while rotten wood is generally the most superior, supporting germination and survival levels better than mineral soil in many instances." Ryker (1975) found that natural regeneration of Douglas-fir was better on litter-covered seedbeds than on mineral soil. Some level of canopy retention promotes superior germination and survival in all climates tested (Ryker 1975; Burton 1996). According to Hermann and Lavender (1990), regeneration is generally poor in drier ecosystems. However, this author's experience indicates that regeneration under a partial canopy is generally abundant in the interior Douglas-fir zone.

3. Growth

Throughout its range in British Columbia, Douglas-fir varies from very shade tolerant to very shade intolerant (Province of BC 1995a). It most-often occupies dry to fresh soil-moisture regimes and medium to rich soil-nutrient regimes (Province of BC 1995a). Interior Douglas-fir in the IDFdk3 subzone near Williams Lake, B.C. is classed as moderately shade-tolerant (Chen *et al.* 1995). Douglas-fir is sensitive to growing-season frost, and a risk of frost damage exists on all subzones of the IDF in the Cariboo Forest Region, particularly on lower topographic positions (Province of BC 1995a).

Hermann and Lavender (1990) and Arno (1991) describe interior Douglas-fir as a climax species in dry habitat types, and suggest that in those habitat types it is suitable for true selection management.

Stand growth varies widely in response to biogeoclimatic conditions and genetic control (Monserud 1987; Arno 1991). Arno (1991) quotes mean annual volume growth capabilities of 0.7 to 7 m^3/ha/yr depending upon habitat type.

Douglas-fir responds well to thinning, but trees that have grown in a closed stand develop very slender form and short crowns, and are therefore susceptible to damage by snow-breakage and windthrow (Hermann and Lavender 1990).

4. Genetic Resources

Interior Douglas-fir displays a great deal of genetic variability, with patterns of variation in traits observed over latitudinal, longitudinal, and elevational transects (Hermann and Lavender 1990). Variation also occurs between populations within local regions (Hermann and Lavender 1990) in adaptation to environmental gradients (Rehfeldt 1991). Variability remains high within populations (Rehfeldt 1991).

B. NATURAL DISTURBANCE

Stand productivity is dependent on disturbance because disturbance controls leaf area index (LAI) and recycles biomass accumulated in the ecosystem (Waring and Schlesinger 1985). Disturbance reduces LAI by causing mortality of individual plants, and lower LAI increases growth efficiency of individual plants. High LAI's result in high gross production at the stand level, but when LAI's exceed a threshold level, net production decreases due to higher mortality (Waring and Schlesinger 1985). Therefore, as LAI continues to increase in the absence of disturbance, growth efficiency of individual trees falls, as does net production at the stand level.

Efforts at controlling disturbance may prevent one kind of mortality from occurring but increase the risk of another type of disturbance (Waring and Schlesinger 1985). Competition increases and growth efficiency decreases, in the absence of disturbance. Individuals become so limited by resource availability that few reserves are available for protective responses. Disturbance will inevitably occur and thereby modify the stand structure. If the frequency of disturbance has been reduced, forests are more susceptible to normal catastrophic disturbances (Waring and Schlesinger 1985).

A conceptual diagram of natural disturbance and succession in the Knife Creek block is presented in Figure 2. Natural disturbances are discussed more fully in the following text.

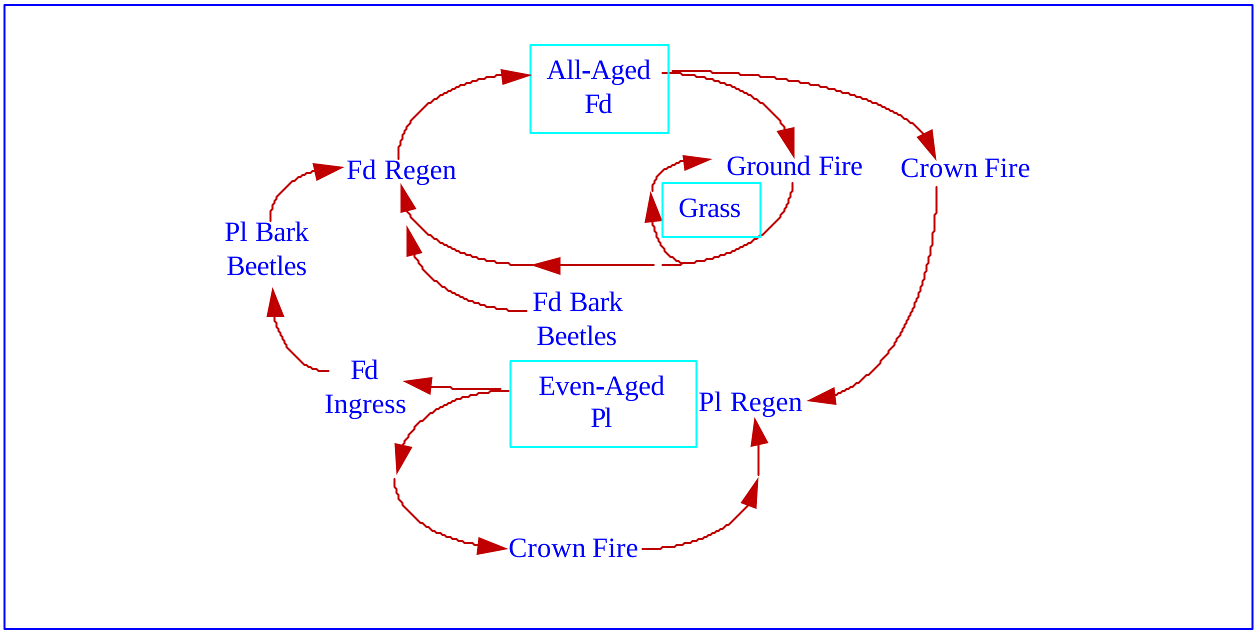


Figure 2: Gap dynamics (disturbance and succession) shift stands between grasslands, Douglas-fir (Fd) forests, and lodgepole pine (Pl) forests in the IDFdk3 at Knife Creek.

1. Fire Regimes In The IDF

Douglas-Fir grows in a wide variety of ecosystems and associates with a wide range of species in various seral roles (Hermann and Lavender 1990). These ecosystems have a wide range of natural fire regimes (Arno 1980). Various reports describe average fire return periods (number of years between events) which range between 5 and 140 years (Parminter 1978; Arno 1980; Steele *et al.* 1986; Daniels *et al.* 1995). Fire return interval and fire severity combine to form the fire regime, which is a product of climate, topography, vegetation, fuel structure, and ignition sources (Kilgore 1981).

Frequent burning at low intensity causes development of uneven-aged stands comprised of even-aged groups of trees in various age classes (Weaver 1967, referenced by Kilgore 1981). Decreases in fire frequency result in diameter distributions skewed towards smaller trees, higher total densities, stagnation and more saplings under mature trees (Kilgore 1981).

As fire frequency declines, fire return intervals increase, and burning is postponed (Heinselman 1981). The resulting changes in stand structure described above change the structure of fuel in the stand, and prepare the stand for stand-replacing fires. Large fuel accumulations (living and dead) and laddered fuels (a vertical arrangement of fuel, from ground level to the tops of mature trees) allow fires access into tree crowns. Large trees that are otherwise fire-resistant are killed (Arno 1980; Kilgore 1981; Steele *et al.* 1986).

Fire regime selects for species and successional pathways adapted to the regime (Heinselman 1981). It follows, therefore, that a change in fire regime will cause a change in species composition, stand structure, and successional pathways.

The structure and composition of Interior Douglas-fir forests implies a complex historical interaction with fire. Pre-settlement fire regimes range from frequent surface fires to infrequent stand replacing fires depending on ecosystem (Arno 1991). Arno (1991) states that changes in fire frequency have enabled Douglas-fir to expand its range, and to dominate grasslands and dry ponderosa pine (*Pinus ponderosa* Laws) types.

Many authors show fire return periods prevailing in uneven-aged Douglas-fir stands which range between 8 and 50 years in frequency (Parminter 1978; Arno 1980; Kilgore 1981; Daniels *et al.* 1995). These fires ranged in severity between fire events, and within stands (Steele *et al.* 1986). Drought and high winds would act to cause intense burning conditions, whereas low fuel conditions would act to reduce fire intensity (Steele *et al.* 1986). The resulting variable burning conditions yield a patchwork of stand conditions on the landscape, in which some areas are burned intensely while other areas are completely missed (Arno 1980; Province of BC 1995b).

The Interior Douglas-fir biogeoclimatic zone was naturally maintained as a fire climax, so that forests were open uneven-aged stands interspersed with gaps of grass and shrub lands (Province of BC 1995b). Surface fire frequency ranged between 4 and 50 years, and crown fires occurred at 150 to 250 year intervals (Province of BC 1995b).

Researchers are in unanimous agreement that fire interval has increased since approximately 1900. Writing in 1955, Benteli comments that:

> "It seemed as if there had been a maximum of fire occurrences in the past 50 years, with a sudden decrease in the past 20 years."

This change coincides with settlement history in most studies, and Steele *et al.* (1986) blame it on:

1. cessation of aboriginal use of fire as First Nations communities were moved to reserves and reservations and use of fire was stopped by European settlers intent on protecting buildings, livestock and timber;
2. organized wildfire suppression began; and
3. unregulated grazing by livestock which reduced fuel loads.

Arno (1980) suggests that some fire frequencies may have been maintained at a short interval because of aboriginal use of fire. First Nations people used fire to enhance production of food and medicinal plants, and to enhance forage production for hunted game such as deer and elk (Shirley Mah, Masters candidate, UBC Faculty of Forestry, pers. comm., 1996).

In a study on the Knife Creek block, Daniels *et al.* (1995) found that two stands in the IDFdk3 demonstrate a pre-settlement fire interval of 16.6 to 18.0 years, which ceased in 1915. Parminter (1978) found, in his study nearby at Riske Creek (in the IDF biogeoclimatic zone[7]), a fire interval of 9.8 years, which ceased in 1926.

There is little doubt that cessation of natural fires has led to increased densities of saplings. Parminter (1978), Kilgore (1981), and Arno (1991) all conclude that cessation of fires in uneven-aged

[7] Parminter classified the area as the Cariboo Aspen Lodgepole Pine zone after Krajina. This area has now been included in the IDF (Hope *et al*. 1991).

forests has resulted in an increase in the proportion of smaller stems. Arno (1991) points out that occasional severe stand-replacing fires have occurred.

It has been said (Province of BC 1995b) that "Ecosystems developing under fire suppression are generally atypical and not adequate substitutes for ... fire maintained stands." The change in fire regime and stand structure has significant implications:

- a community of species adapted to the ecosystem is displaced;
- accumulation of fuel and changes in fuel structure create a much higher risk of crown fire;
- crown fire would have a catastrophic effect on the mule deer winter range, and could potentially cause significant property loss to adjacent private-land owners.

Forest management on the Knife Creek block will include three activities directed at fire-hazard and risk reduction:

1. maintenance of a low-fuel zone between the Big Meadow Road and the Rodeo Drive subdivision, to reduce the risk of a wildfire destroying private property or a backyard fire destroying stands on the Research Forest;
2. reduction of stand density and fuel ladders by harvesting and thinning;
3. gradual re-introduction of low-intensity surface fires to reduce surface-fuel accumulations, on an experimental basis.

2. Forest Health

A healthy forest is one that is sufficiently free of insect or pathogen damage to meet management objectives (Byler and Zimmer-Gorve 1991). Forest health is maintained by regulating composition and density (Furniss and Carolin 1980), and maintaining tree vigour (Boyce 1961; Anderson and Rice

1993). Practices that simulate natural stand conditions provide the best resistance to native diseases (Boyce 1961), and maintain ecological processes (Province of BC 1995b).

a) Douglas-fir Bark Beetles

Douglas-fir bark beetles (*Dendroctonus pseudotsugae* Hopk.) are a very serious problem in IDF stands in the Cariboo Forest Region, and present a significant challenge in the management of mule deer winter range (Mule Deer Winter Range Strategy Committee 1996). The Research Forest harvested 35% of its allowable cut from bark beetle infestations between 1988 and 1994, primarily from Douglas-fir bark beetle infestations. At the peak of that epidemic, approximately 3,500 m^3 were harvested in one year from the Knife Creek block. Douglas-fir bark beetles are always present in endemic populations, primarily infesting windthrown or broken trees. However, conditions that reduce tree vigour favour Douglas-fir bark beetles (Humphreys 1995). Epidemics can develop when susceptible trees are abundant (Humphreys 1995) as a result of prolonged drought, fire, or windthrow.

A clear relationship exists between tree vigour and attacks by mountain pine bark beetles (*Dendroctonus ponderosae* Hopk.) in ponderosa pine (Larsson *et al.* 1983). In discussing bark beetles, Furniss and Carolin (1980) cite Keen (1936) who found that bark beetles attack the oldest, slowest growing codominants and intermediates in a ponderosa pine stand -- the trees one would expect to be least vigorous.

Referencing methods developed by others,[8] Larsson *et al.* (1983) showed that density (both numbers and basal area) influenced tree vigour. Average tree vigour decreased with denser spacing and with higher leaf area indices. Attacks by bark beetles decreased as average tree vigour increased, and below a tree-vigour threshold significantly more attacks were recorded.

Larsson *et al*. (1983) also found that vigour varied from tree to tree within treatments. The variation was highest (60%) in unthinned controls, which suggests that some trees in dense conditions are able to maintain their vigour at the expense of other individuals. Variability in vigour within thinned plots was significantly lower (20%), and average vigour was increased after thinning.

Results of Larsson *et al.* (1983) compare favourably with other authors they cite[8], working in lodgepole pine and ponderosa pine. They recommend maintaining stocking below a critical threshold to avoid mortality caused by bark beetles in endemic population cycles.

It seems reasonable that, if stocking is not controlled by thinning or by fire, low-vigour individuals will continue to be suppressed by more vigorous neighbours. The wide range of vigours found by Larsson *et al.* (1983) in unthinned stands is probably the normal condition in all natural stands, regardless of species.

Several authors suggest that subordinate canopy layers play a significant role in the vigour of superior layers. Sterba *et al.* (1993) found that removal of a dense coppice from around oak standards improved the increment of the standards even though the standards were growing completely free of crown competition. Dolph *et al.* (1995) report results of a 50-year study in north-eastern California. They found that, in the absence of fire and thinning, understory densities progressively increased, while overstory trees died out of the stand. They suggest that extreme competition for moisture and nutrients with dense understories has reduced the vigour of overstory trees and rendered them susceptible to bark beetles.

While there is no direct evidence, it seems likely that the same variables of density, vigour, and bark beetle-induced mortality are at work in Douglas-fir at Knife Creek:

[8] Waring, R.H. and G.B. Pitman. 1980. A simple model of host resistance to bark beetles. Oregon State University For. Res. Lab and Res. Note 65, 2p.

- Douglas-fir bark beetles prefer freshly killed host -- they are the primary cause of mortality only during epidemics (Humphreys 1995);
- the last outbreak of Douglas-fir bark beetle began in 1989 (Erickson 1992), during drought conditions (when tree stress is highest) and ended in 1993 when the drought had ended and populations had collapsed.

It follows, then, that low-vigour Douglas-fir trees under additional stress (whether from drought or from other causes) are the likely host for bark beetles.

b) Defoliators

Western spruce budworm (*Christoneura occidentalis* Freeman) and Douglas-fir tussock moth (*Orgyia pseudotsugata* McDunnough) are two significant defoliators of Douglas-fir in the IDF. The tussock moth has not been reported north of Clinton in the Cariboo Region (Andrews 1987; Erickson 1992), and is therefore not considered to be a pest at Knife Creek. The spruce budworm, on the other hand, has been identified at Becher's Prairie (1975) and at Canim, Mahood, Horsefly and Quesnel Lakes (1986-88) (Erickson 1992). It should therefore be considered a potential pest at Knife Creek. The spruce budworm is a significant pest which has the ability, during outbreak phases, to cause widespread mortality and top kill in Douglas-fir.

A relationship between tree vigour, stand density and damage to Douglas-fir has been demonstrated for western spruce budworm. As the vigour of the tree declines, its ability to recover foliage biomass suffers; trees of low vigour also have smaller crowns and therefore suffer greater proportional defoliation (Wulf and Cates 1985). In addition, stress modifies foliage qualities to favour budworm development by enhancing survivorship and growth of budworms (Cates *et al.* 1991).

Budworm defoliation is also intensified by multi-layered stand structures such as develop in the absence of fire or thinning (Carlson *et al*. 1985; Wulf and Cates 1985; Byler and Zimmer-Gorve 1991).

Wulf and Cates (1985) report that spruce budworm damage is sensitive to stand structure since the dispersing larvae must land on host material to continue maturation feeding. Well-developed vertical structure provides more host in subordinate positions for dispersing larvae. Carlson *et al*. (1985) indicate that uneven-aged management of Douglas-fir stands is inadvisable in consideration of budworm, because the multi-layered stands are most susceptible to damage, particularly if stocking is not controlled to maintain high vigour.

Unger (1995) recommends that practices to reduce the risk and severity of infestations include:

- managing for single layered stands;
- maintaining low stand density;
- establishing multi-species stands;
- maintaining stand vigour; and
- harvesting prior to culmination.

This plan advocates single-tree-selection management of Douglas-fir, which is contra-indicated by the preceding discussion. However, due to the silvics of Douglas-fir at Knife Creek, stand structure will be horizontally diverse, since gaps of up to one tree-length in diameter will be created for regeneration. Small trees will not be arranged directly below larger trees. Repeated entries will thin all layers in the stand, and thus maintain tree vigour. Managing the stands in that fashion should help reduce damage by budworm in the event of an outbreak.

c) Root Disease

Root disease, particularly Armillaria *(Armillaria ostoyae* (Romagn.) Herink), is a significant disease problem in mule deer winter ranges. Only one Armillaria centre has been identified in the Knife Creek block, but other centres of Armillaria or Phellinus (*Phellinus weirii* (Murrill) R.L. Gilbertson) may be present and as yet undetected. The Mule Deer Winter Range Strategy Committee (1996) recommends not harvesting in areas with trees symptomatic of Armillaria until biological control methods are available.

The one Armillaria infection site identified to date in the Knife Creek block appears to have maintained its pathogenicity through ongoing regeneration and infection of Douglas-fir. The pathogenicity has remained high well past the time when post-harvest stumps are expected to support the fungus saprophytically (B.J. van der Kamp, UBC Faculty of Forestry, pers. comm., 1997). This suggests that Armillaria is much more difficult to manage in an uneven-aged stand.

Tree vigour also has implications in disease/tree interactions. McDonald (1991) suggests that stress or vigour profiles are important host attributes for Armillaria expression. Entry *et al.* (1991) found that thinning may produce Douglas-fir trees that are more resistant to infection by Armillaria, but caution that the benefit of individual tree resistance is easily overcome if significant inoculum remains on site in the form of roots and stumps. McDonald (1991) shows that site quality (described by site index) is an important factor in Armillaria expression. High- and low-quality sites only rarely have significant Armillaria problems, whereas moderate-quality sites have common problems. Morrison and Mallett (1996), on the other hand, state that damage by Armillaria is greater in more productive ecosystems.

Morrison and Mallett (1996) conclude that partial cutting increases the incidence of infection and mortality in residual trees as compared to uncut stands. They cite a study where incidence of disease increased from 10% to 47% 30 years after partial cutting. The result of this increased disease severity is serious understocking, since ingrowth into the stand fails to reach merchantable sizes before being killed by the Armillaria (Morrison and Mallett 1996).

Armillaria centres on the Knife Creek block should not be harvested unless viable control options such as the following are available:

- stump removal operations that will not significantly degrade soils;
- biological control through application of saprophytic fungi antagonistic to Armillaria.

This strategy requires identification of root disease centres during pre-harvest stand examinations.

C. MULE DEER

The Rocky Mountain mule deer (*Odocoileus hemionus hemionus*) ranges from the Yukon in northern Canada nearly to the US-Mexico border and east into the prairies of the US and Canada (Geist 1990). In the Cariboo Forest Region of central British Columbia, mule deer are at their northern limit of continuous high-density distribution (Cowan and Guiguet 1978).

Winter range is important to mule deer, because it allows deer to maintain their energy balance on an annual basis (Armleder *et al.* 1986). Good winter range minimizes energy losses by providing shallow snow, adequate food, security cover, and favourable thermal conditions (Armleder *et al.* 1994). In the absence of good winter range, energy losses in the winter exceed energy gains from the summer, leading to poor recruitment and increased mortality (Armleder *et al.* 1986).

Mule deer have been studied in the Cariboo for more than 20 years, and many of those studies have included the Knife Creek block of the Research Forest. The numerous published and unpublished reports prepared by staff of the BC Forest Service and Ministry of Environment extensively document mule deer ecology in this region. This discussion attempts to summarize that work.

1. Forage

Mule deer are relatively selective feeders that require ample high-quality forage to balance their seasonal energy budgets (Mule Deer Winter Range Strategy Committee 1996). High quality spring and summer forage are easily available. However, both quality and availability decline in the fall and winter when herbs and forbs die and when woody plants transfer their nutrients to stems and roots. Moreover, the energy needs of deer increase in the winter as temperatures drop, movement becomes more difficult, and high-quality feed is covered by snow. Energy must therefore be balanced for the year as a whole, so that stored fat reserves may compensate for inadequate forage in winter months (Armleder *et al.* 1986; Armleder and Dawson 1992).

Mule deer prefer to eat shrubs rather than Douglas-fir, and more shrubs provide a higher-quality diet (Armleder *et al.* 1986; Waterhouse *et al.* 1994). Waterhouse *et al.* (1994) compared food habits among deer on various winter ranges in the Cariboo Region, and state that mule deer on dry winter ranges such as the Knife Creek range (IDFdk3) have significantly less shrub and more conifer in their diet. Deer on dry winter ranges are unable to substitute shrubs for Douglas-fir in low-snow conditions, because the dry ecosystems simply do not support sufficient biomass of shrubs. Nevertheless, deer seek out a wide variety of plant species. Waterhouse *et al.* (1994) listed 54 species of vegetation (trees, shrubs, forbs, grasses, ferns, lichens, and mosses) detected in fecal pellets from Knife Creek over three winters (Table 4).

Douglas-fir foliage averages 73% of the winter diet, and accounts for up to 89% in some months at Knife Creek (Waterhouse *et al.* 1994). A 95 kg female mule deer would need approximately 1.9 kg (oven dried) of Douglas-fir foliage each day to maintain her condition (Waterhouse *et al.* 1991a).

Table 4: A partial list of forage species and their proportion by fecal pellet analysis for Knife Creek from December 1982 to March 1985. From Waterhouse *et al.* (1994).

Species	**Mean Proportion (%)**
Total Conifers	**76**
Douglas-fir	73
Lodgepole pine	detected
Total Shrubs and Decid. Trees	**14**
Blueberry spp.	detected
Oregon grape	6
Red-osier dogwood	detected
Sage spp.	detected
Saskatoon	3
Soopalallie	detected
Willow spp.	detected
Total Forbs	**3**
Total Grasses	**4**
Total Lichens	**3**
Total	100

Foliage is available to mule deer as litterfall, wind-thrown trees, or broken branches. In addition to the Douglas-fir foliage, litterfall often includes arboreal lichens that are favoured by mule deer. Waterhouse *et al.* (1991a) found that foliage litterfall is highest under mature trees in an uneven-aged stand. The majority of foliage litterfall occurred in association with episodes of intense cold and wind events. Waterhouse *et al.* (1991a) estimated that litterfall from an overmature even-aged forest near Quesnel could support 0.33 deer/ha/month.

Dawson *et al.* (1990) found that forage preference was correlated with tree diameter, showing a marked preference for foliage from trees greater than 40 cm dbh. Foliage from trees less than 25 cm dbh was virtually unused, while browsing consumed nearly all of the foliage from trees over 40 cm dbh.

Fruticose arboreal lichens (*Bryoria* spp., *Alectoria* spp., and *Usnea* spp.) contribute up to 12% of the mule deer winter diet by fecal fragment analysis, and up to 26% by rumen analysis (Waterhouse *et al.* 1994). Waterhouse *et al.* (1994) cite references that suggest that lichens may be underestimated by fecal fragment analysis because of their very high digestibility. It seems probable that lichens play a significant role in mule deer winter diet due to their high digestibility, and perhaps through synergistic effects on digestion. Litterfall is the primary source of lichens (Waterhouse *et al.* 1991a). Dawson *et al.* (1990) found that mule deer consumed arboreal lichens in preference to Douglas-fir foliage.

Older stands and trees produced significantly more lichen litterfall than younger stands and trees in two sites studied. A diameter-limit cut stand produced significantly less lichen than an adjacent uncut stand (Waterhouse *et al.* 1991a). Stand age and the structural characteristics of age affect lichen litterfall production, presumably because old stands provide better conditions for lichen growth (micro-climate, attachments, source of fragments, standing dead trees) (Waterhouse *et al.* 1991a). Older trees may also have more brittle branches.

Waterhouse *et al.* (1991b) sought to find the determinants of preference by mule deer for Douglas-fir foliage. The only significant positive correlation they found was phosphorus content; concentrations of the chemicals studied varied from tree to tree, from site to site, and from year to year. Although there were problems with the design of the study (as recognized by the authors), clearly the evidence for browse-preference is neither simple nor easily explained.

Mule deer rely heavily on litterfall in their winter diet, particularly in moderate or severe winters when snow buries ground forage (Armleder and Dawson 1992). According to Waterhouse *et al.* (1991a) litterfall is best provided by:

- large-diameter Douglas-fir trees;

- adjacent crowns that are close enough to contact one-another in the wind, increasing breakage of small twigs;
- arboreal lichens, which are slow growing and therefore reach their greatest biomass on older trees close to a source of lichen fragments (other lichen-bearing trees).

2. Cover

Throughout much of their range, mule deer move to winter ranges where snowfall is low. However, in winter ranges over the northern third of their distribution, mule deer can experience deep snow even on the best topographic locations (Armleder *et al.* 1994). Forest structural attributes on northern winter ranges provide three benefits to mule deer; snow interception cover, thermal cover, and security cover (Armleder *et al.* 1994). As snow depth increases the energy required for locomotion increases exponentially, such that deer moving through 50 cm of snow require nearly 500% more energy than for no snow (Parker *et al.* 1984[9], cited in Armleder *et al.* 1994). If forest canopies are available to intercept and hold the snow, the reduced snow depth reduces energy demands of the deer and makes ground forage more accessible (Armleder *et al.* 1986). Forests also reduce wind velocity and consequently the radiation heat loss and energy requirements (Armleder *et al.* 1986; Armleder and Dawson 1992). The screening effect of small trees provides security cover thereby reducing the energy demands from flight and stress (Armleder *et al.* 1986; Armleder and Dawson 1992).

Typically authors describe the availability of cover in terms of stand crown closure (Mule Deer Winter Range Strategy Committee 1996). Crown closure is a useful surrogate for cover, but it does not describe cover entirely. High-crown-closure stands do not provide good cover unless they have appropriate age and structural characteristics.

[9] Parker, K.L., C.T. Robbins, and T.A. Hanley. 1984. Energy expenditures for locomotion by mule deer and elk. J. Wildl. Manage. 48:474-488.

Armleder *et al.* (1994) studied 23 radio-collared mule deer at Knife Creek to examine habitat selection within a winter range. The forest cover within the winter range was classified according to existing Ministry of Forests cover maps. Forest cover labels described stand age (most abundant age present), species composition, and crown closure. These forest cover labels provide only an approximation of stand structure, which is useful in the absence of a more quantitative description. Despite the fact that the forest cover maps do not adequately describe the structure of uneven-aged stands, Armleder *et al.* (1994) were able to show significant relationships between forest cover, snow pack, and use by deer:

1. at all snow depths, deer used old stands more frequently than availability would indicate, and used mature stands less than availability would indicate;
2. as snow depths increased, use of old stands increased;
3. mule deer prefer stands dominated by Douglas-fir in moderate and deep snow, and use of Douglas-fir stands equalled availability in low-snow conditions;
4. deer use low crown-closure stands less than availability would indicate, and use moderate and high crown-closure stands more than availability would indicate;
5. selection for warm aspects and steep slopes within the winter range was not detected at the scale of mapping available, but winter ranges tend to have a high proportion of warm aspects.

In this study Armleder *et al.* (1994) conclude that timber harvesting that significantly changes the structure of winter range stands is detrimental to mule deer. This conclusion supports the adoption of the integrated management option described by Armleder *et al.* (1986).

3. Microhabitat

Certain parts of stands and landscapes are more important to deer than other parts (Armleder *et al.* 1986; 1994). Deer select micro-habitat based upon a number of variables, the sum of which provide an optimum condition for a given snow depth (Armleder *et al.* 1994). Each of these microhabitats is described in Figure 3.

4. Winter Range Requirements

Mule deer in the Cariboo Forest Region range through widely dispersed and varying habitats in the late spring, summer and fall. In late fall, however, mule deer migrate to winter ranges (Mule Deer Winter Range Strategy Committee 1996), travelling as far as 100 km (Harold Armleder, Cariboo Forest Region, pers. comm.). Mule deer have fidelity to particular winter ranges, and may cross other suitable winter ranges to arrive at their "own" range (Mule Deer Winter Range Strategy Committee 1996).

With reference to Armleder *et al.* (1986), the Knife Creek block of the Research Forest has all of the biophysical attributes of mule deer winter range in the moderate snowpack zone:

- gentle to moderately steep slopes;
- warm aspects (south or west facing);
- below 1500 m elevation;
- covered predominately by uneven-aged Douglas-fir forests;
- adjacent to open range or grassland for spring range.

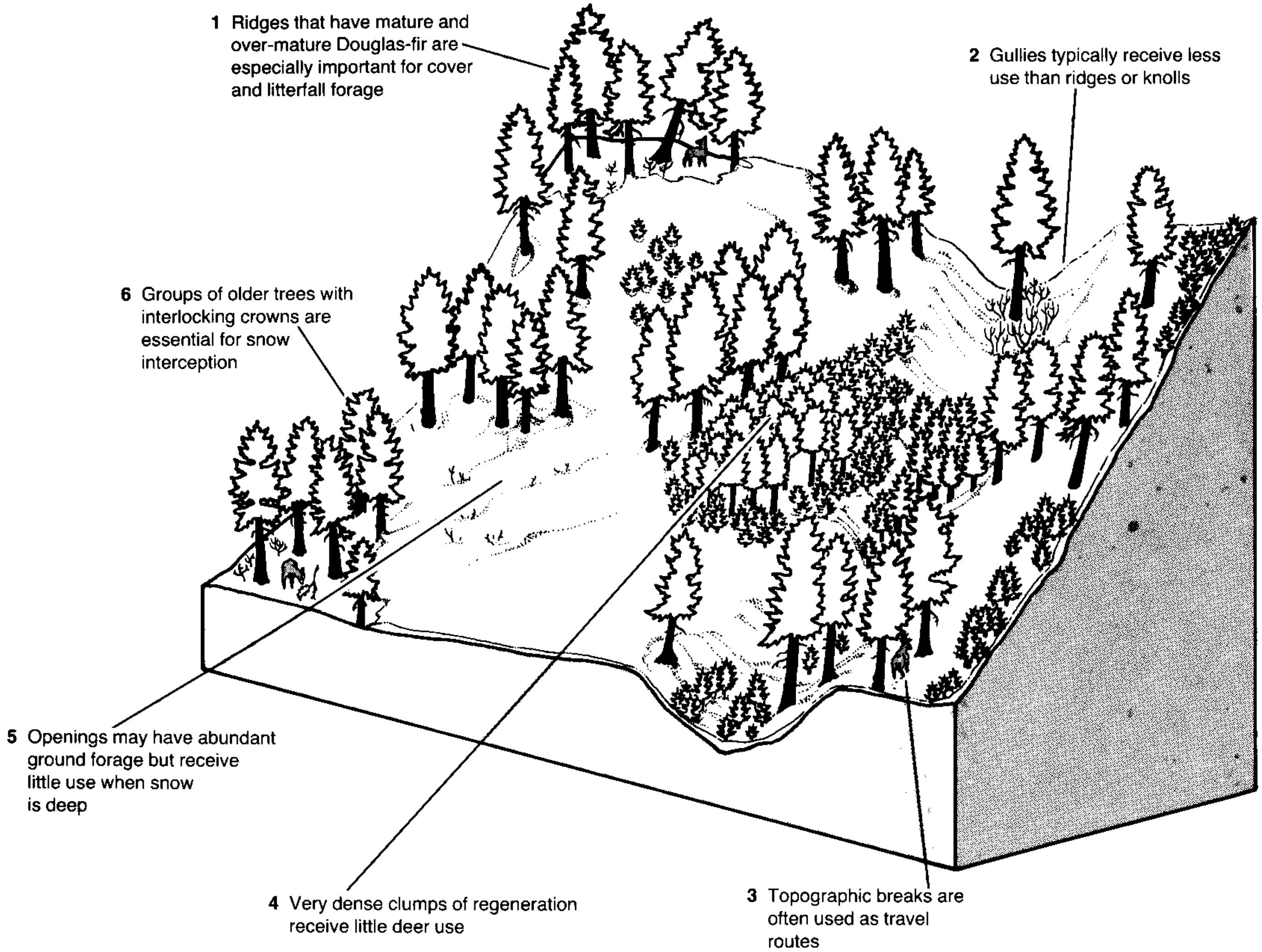


Figure 3: A depiction of microhabitats, which differ in value to deer. From Armleder *et al.* (1986). Reproduced with permission.

The portions of the Knife Creek block that are currently most suitable for mule deer winter range are depicted on a map in Appendix 2.

The optimum combination of cover and forage available on a winter range depends upon the snowpack prevailing on that winter range (Armleder *et al.* 1986). In the moderate snowpack zone, in which Knife Creek is located, an equal mixture of open-, moderate-, and closed-canopy conditions provide access to different habitats. Each habitat assumes a special importance as winter conditions change:

- open canopies provide ground forage but little cover, and are most valuable when snowpack is low or has been reduced by melting and sublimation;
- moderate canopies provide some ground forage, good litterfall forage, and good shelter, and provide habitat for most of the time;
- closed canopies provide little ground forage but very good shelter and litterfall forage, and are most useful immediately after or during snowfall.

These habitat types should ideally be arranged spatially to allow easy access from one type to another (Armleder *et al.* 1986), so that deer can find appropriate conditions for given weather conditions without having to travel long distances.

As discussed earlier, large old Douglas-fir are important to winter range -- their wide deep crowns are composed of stiff branches that effectively intercept snow and hold it off the ground. A clumpy arrangement of these large trees further increases their ability to intercept snow, since several interlocking crowns are more effective than the same number of trees uniformly arranged (Armleder *et al.* 1986). Litterfall is increased by the clumpy arrangement of trees, since their proximity increases the amount they bump into each other, resulting in the breakage of fine twigs and small branches (Waterhouse *et al.* 1991a).

5. Mule Deer Carrying Capacity and Census

Carrying capacity has been debated in wildlife management literature for generations, and continues to be a source of debate (Connolly 1981). Connolly said:

> "It should be possible to estimate carrying capacity from various habitat measurements, but so far no one has accomplished this on mule or black-tailed deer range."

Apparently there is general agreement that the principle is sound; the debate stems from the difficulty of counting deer and assessing whether herds are at, above, or below optimum density (Connolly and Wallmo 1981). People expect wildlife managers to measure the carrying capacity the range and herd size, and to demonstrate sustainable management. However, few mule deer populations are managed so intensively (Connolly and Wallmo 1981).

When viewed by a timber manager, who is completely invested in the concept of sustained yield, the lack of population targets for mule deer is frustrating. It is so apparently sensible that timber managers feel wildlife managers who fail to set such targets are dodging the issue for some other purpose. Why not simply set a target number of deer, estimate the carrying capacities for each winter range, do the arithmetic, and then manage the required area as winter range?

That which appears to be a simple exercise is actually extremely complex. Carrying capacity changes annually as a result of changes in climate, predation rates, human activity and other factors. Hebert and Beets (1990) state two separate management goals for mule deer in the Cariboo Region: harvest manipulation; and protection of winter range from disturbance and alienation. Opportunities to enhance habitat were considered (including the development of logging guidelines that would optimize cover and forage production), but the management plans did not include any reference to managing carrying capacity *per se*.

Accepting the foregoing discussion, the carrying capacity of the Knife Creek winter range clearly does not provide a useful model for managing mule deer. However, in order to contemplate the impact of silvicultural prescriptions on mule deer habitat, a method of relating the habitat effects to the target stand structure was desirable. A key component of carrying capacity is forage availability, which is influenced primarily by forest cover and structure as discussed above. An index of forage availability for the Knife Creek block of the Research Forest is developed below, and then used to examine the impact of various target stand structures on page 53.

a) Maximum Theoretical Forage Availability

Assumptions:

1. That mule deer eat Douglas-fir foliage only, since foliage comprises up to 89% of mule deer diet in a given month (Waterhouse *et al.* 1994).
2. That the maximum foliage litterfall comes from overmature even-aged stands on productive sites on flat ground, and was measured as 33.47 kg/ha/month (Waterhouse *et al.* 1991a).
3. That the maximum area that could support maximum litterfall is the total forested area, assuming that all stands could be grown to overmature even-aged pure Douglas-fir. Total forested area Knife Creek = 3,419 ha (Table 2).

Calculation **Maximum Theoretical Forage Availability(MTFA)**

MTFA = 33.47 kg/ha/month x 3,419 ha = 114,434 kg/month

b) Forage Availability

Assumptions

1. That Preferred Litterfall comes from Douglas-fir trees > 40 cm dbh (Dawson *et al.* 1990).
2. That the target stand structure for timber (B=18, D= 60, q=1.25 -- page 50) carries 44% of the stand basal area in trees >40 cm dbh.

Calculation **Forage Availability (FA)**

FA = MTFA x Preferred Litterfall

= 114,434 kg/month x 44% = 50,351 kg/month

It is therefore suggested that the forage availability, at regulated stand condition, is approximately 50 tonnes/month on the Knife Creek block. This estimate has been employed only as an index value, to model the impact of various target stand structures on winter range values (refer to page 53).

6. Implications to Forest Management

Armleder *et al.* (1989) conclude that a strategy to preserve stands for mule deer winter range without timber harvesting is a poor option. The rationale for this conclusion is that:

- the value of the standing timber precludes preservation of large blocks of old growth;
- insufficient winter range will be preserved to support populations during a severe winter
- old growth forests are not static, and slow-growing stands are threatened by insects and disease without management for replacement trees;
- the loss of preserved stands to catastrophic natural events could compromise an entire winter range.

Mule deer winter range should be managed according to a silvicultural system that creates stands with good vertical diversity, small gaps and clumps, and a continuous supply of large old Douglas-fir. Important topographic features should be recognized in prescriptions, such that ridges and topographic breaks provide sufficient cover and litterfall. Stands should be organized to provide a continuous flow of habitat values through time, in an appropriate spatial arrangement.

Armleder *et al.* (1986) suggested selection harvesting could be carried out on some winter ranges without detriment to mule deer, and proposed a methodology for identifying, evaluating, and developing mule deer winter range for timber harvesting. Generally referred to as "the handbook method," it has been adopted by the Ministry of Forests and the Ministry of Environment as the most suitable method of harvesting timber from mule deer winter ranges. Armleder *et al.* (1997) report that they were unable to detect a response in mule deer use after eight winters of tracking in seven blocks harvested by the handbook method.

Staff of the Ministry of Forests and Ministry of Environment evaluate cover on each winter range, as determined by crown closure and age class from forest cover maps (Mule Deer Winter Range Strategy Committee 1996). Those winter ranges where harvesting occurred by the diameter-limit method generally have too much low crown-closure habitat and insufficient moderate or high crown-closure habitat. This observation has caused government managers to defer additional timber harvesting in those winter ranges until the crown closure targets are satisfied. According to the Mule Deer Winter Range Strategy Committee (1996), the Knife Creek winter range has 32% high, 16 % moderate, and 55% low crown-closure conditions due to past diameter-limit cutting. The strategy therefore forces government managers to conclude that no harvest of Douglas-fir is currently available, except for salvage of mortality caused by bark beetles or other damage.

It is apparent to this author, however, that single-tree-selection management offers an opportunity to actively manage for mule deer habitat values, and to promote those values much more effectively than preservation or deferral could. Classical selection management, which is focused on managing stand structure towards a target condition, offers a framework to describe and achieve objectives on a forest estate. This thesis describes a working plan for stand and forest-level regulation to maintain mule deer winter habitat in Knife Creek in the short term, and improve the habitat over the long term.

FOREST MANAGEMENT

A. MANAGEMENT PHILOSOPHY

The mission of the UBC Faculty of Forestry is to serve the people of British Columbia through excellence in education and scholarship in forestry -- conservation, products, and production processes. The Alex Fraser Research Forest assists in attaining the mission of the Faculty by managing its forest lands for education, research, and demonstration in integrated forest resources management.

Education, research, and demonstration in integrated forest resources management are the primary objectives of the AFRF, and the highest priority must be given to creating and protecting opportunities for these activities. The forest will be managed on a sustained yield basis consistent with these objectives.

B. FOREST MANAGEMENT OBJECTIVES

The objectives of forest management on the Research Forest support the philosophy outlined above. The management objectives are:

- to provide opportunities for education, research, and demonstration in integrated forest resources management;
- to protect the soil of the Forest in all operations;
- to sustain or enhance the resources available on the Forest for
  - fish and wildlife habitat
  - timber
  - range and
  - recreation;

- to grow and harvest high quality, large diameter coniferous saw timber and veneer logs for sale within the local market;
- to regulate timber harvesting to provide the species and age composition of the forest that will ensure
  - vigorous and productive forests
  - a diversity of habitats
  - a diversity of product opportunities
  - an even or increasing flow of timber harvest through time

C. DIRECTION FROM HIGHER LEVEL PLANS

1. Cariboo Chilcotin Land Use Plan

The Knife Creek block of the Research Forest is contained within the Enhanced Resource Development Zone as designated by the Cariboo-Chilcotin Land-Use Plan (CCLUP) (Province of BC 1994). This designation is described as follows:

> "Management objectives and targets to be developed for these high-intensity lands will focus on enhancing or increasing the productive capability of natural resources for all uses. Forestry, mineral exploration and mining development, cattle grazing, tourism, wildcraft/agro-forestry, fishing, trapping and hunting are appropriate activities."
>
> "During the 90 day period following release of the plan, the forest industry and government will be challenged to set achievable, performance-based targets for increased sustainable productivity in this zone through intensive reforestation, spacing, pruning, thinning, and new harvest practices."
>
> "Efforts to enhance wildcraft/agro-forestry and fish and wildlife values in this zone will also be encouraged."

a) <u>Modified Harvesting</u>

The CCLUP implementation report (Province of BC 1995c) states that a proportion of the land base is available for harvesting only if management is modified to “more-sensitive practices." For the purposes of this Working Plan, modified harvesting is defined to be any practise that is imposed on timber harvesting in consideration of a non-timber resource. Harvesting on mule deer winter range is constrained to a low-volume selection management system for maintenance of mule deer winter habitat. All of the Knife Creek block is designated as highest use for mule deer winter range. All harvesting in the Knife Creek block is therefore modified for the purposes of the CCLUP.

2. Landscape Unit Plans

The Knife Creek block is located within the Williams Lake draft Landscape Unit. Landscape Unit plans have not yet been created, so the impact those plans will have on the Knife Creek block is unknown. The Williams Lake draft Landscape Unit contains many mule deer winter ranges, so this plan is expected to be compatible with the Landscape Unit Plan.

3. Management and Working Plan #2

Management and Working Plan #2 (Day 1997a) stipulates that winter range values on the Research Forest will be protected, and improved where feasible. The plan sets out a system of land-use zoning by compartments (see Appendix 5) which shows mule deer winter range as the highest priority for land use on all of the Knife Creek block. Under the strategy defined in the management plan, other land uses can go ahead provided they do not compromise the highest-priority use. Timber harvesting can therefore proceed on mule deer winter range if it is not detrimental to the winter range values.

The management plan calls for the development of mule deer winter range plans. This thesis is a winter range plan for the Knife Creek block as described in the Management and Working Plan #2. The winter range plan takes direction from the Management and Working Plan, and will guide the Forest Development Plan for Knife Creek.

D. FOREST ECOSYSTEM NETWORK

Forest Ecosystem Networks (FENs) are a means of protecting landscape level biodiversity. FENs are intended to provide important landscape features within managed forests, such as connectivity, refugia, and gene pool. FENs are a construct of even-aged forest management, and it is this author's opinion that they serve only a limited purpose in selection management in dry forests. If stands are being managed for continuous uneven-aged conditions, in the assortment of structures that occurred naturally on the landscape, then landscape-level biodiversity is protected without the implementation of FENs. In fact, reservation of land in a FEN may be contrary to providing natural conditions, since periodic disturbance is a driving feature in the IDF (refer to Figure 2).

Management and Working Plan #2 describes a FEN for the Knife Creek block, which incorporates only about 4.6% of the total landbase. Areas included in the reserve are; the IDF research reserve, Environmentally Sensitive Areas, unmerchantable or inoperable forest, riparian areas, wetlands, and open range. No linkages are provided, since the forest will be managed for continuous forest cover. A map of these reserves is shown below at Appendix 5.

E. FOREST INVENTORY

In 1993 the Vegetation Inventory Working Group established 93 plots on the Knife Creek block of the Research Forest. This was a pilot study of the provincial inventory system, which was under development at the time. The plots were established on a systematic grid at 600 m intervals. In this way, each plot represents approximately 36 ha. There are problems with the plots caused by the design of the study:

- the plots are point samples, with a small fixed-area subplot to tally small stems;
- the basal area factor (BAF) of the point samples differs between plots;
- the plots were installed and measured by more than one contractor.

In spite of the inherent problems, these plots represent the basis of an excellent Continuous Forest Inventory (CFI) system. Each plot has been described for soils and vegetation and had an ecological site assessment done. In addition the timber has been described, including five point samples, a fixed-area subplot, sample trees for height and age, and site-index trees. All of the plot data has been located, and captured into a database by Research Forest staff. A subset of the plots will be employed as the basis of a Continuous Forest Inventory for Knife Creek. The balance of the plots will be archived.

A Continuous Forest Inventory provides forest-level data on growth, stocking, health, and productive potential for the forest as a whole (Reed *et al.* n.d.). Thus CFI is a means of periodically assessing the impacts of management, and adjusting policy and procedures (Husch *et al.* 1972). CFI plots are generally located on a systematic basis, since stratification of the landbase at present cannot foresee how strata will change in the future (Husch *et al.* 1972) Some of the potential uses of CFI data (modified from Husch *et al.* 1972) are to:

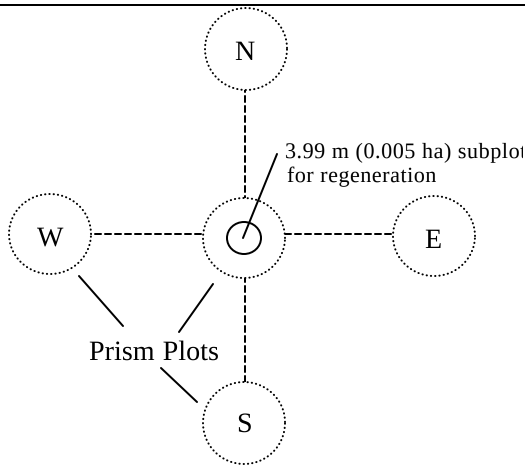
- provide inventory data for a sample of the land base to give statistical summaries;
- provide growth information for allowable annual cut (AAC) calculations;
- monitor the effects of silvicultural practices;
- provide inventory points with known stand structure for non-timber resources such as wildlife; and

- monitor stand development to determine timing of silvicultural treatments.

CFI therefore provides a perfect vehicle for adaptive management -- the periodic testing of working hypotheses so as to adjust management. The sampling is insufficient to provide stand-level data to support Silviculture Prescriptions. Instead, the CFI is intended to show the changes through time which result from various treatments. CFI therefore supports the development of Silviculture Prescriptions and aids in establishing Allowable Annual Cut levels. The CFI does not replace the need for detailed stand inventory in developing Silviculture Prescriptions. CFI plots receive the same treatment as the general landbase -- they are harvested and regenerated according to the standard prescriptions in force, without recognition of the existence of the plots.

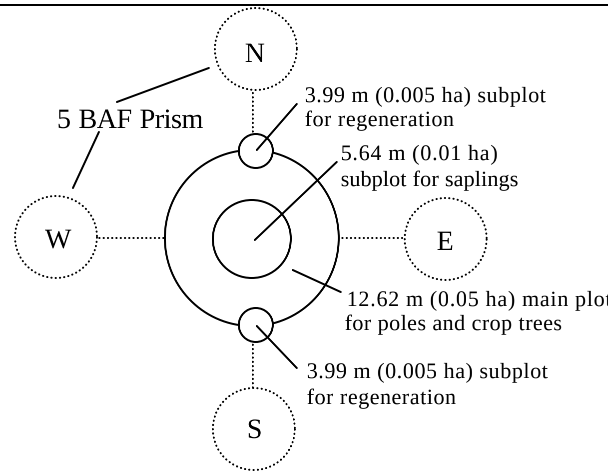
Selected plots will be remeasured in 1998 (subject to funding), five years after initial plot establishment. A detailed plan for the remeasurement project will be required, and should be completed in time to allow field work to begin in August. According to Husch *et al.* (1972), the plan should allow for the measurement of 0.03 to 0.1% sample (1.05 to 3.5 ha) of permanent plots. This indicates that between 21 and 70 plots (of 500 m^2 each) are required for the Knife Creek block. Some of the initial plots can be discarded if they are considered to be problematical, for instance falling on a road.

Figure 4 following contrasts the plots as established with a suggested format for remeasurement. The suggested format corrects the shortcomings of the initial installation, by establishing fixed-area plots instead of prism plots. Fixed-area plots sample small-diameter trees with greater accuracy than prism plots, and are therefore better for enumerating trees by size classes. Prism plots are more efficient for estimating stand volume than fixed area plots, since fewer trees need to be sampled. The nested subplots will allow sampling of all sizes without counting too many small trees.



1993 Installation: 93 clustered prism plots,

- sample for volume
- prism factor varies amongst plots
- sub-plots 25 m from main plot on cardinal directions
- one regeneration plot 50 m^2 (3.99 m radius)



1998 Remeasurement: 60 of 93 clustered plots,

- sample for stand structure and volume
- main plot 500 m^2 (12.62 m radius)
- one sapling plot 100 m^2 (5.64 m radius)
- two regeneration plots 50 m^2 (3.99 m radius)
- sub-plots 25 m from main plot on cardinal directions, 5 BAF prism

Figure 4: Transformation of Vegetation Inventory Plots to Continuous Forest Inventory Plots, at remeasurement.

REGULATION

Sustained yield is a goal of single-tree-selection management, both at the forest and the stand level (Baker *et al.* 1996). Sustained yield is provided at the stand level by regulating stand structure, and at the forest level by regulating the frequency of harvest in a given stand.

A. STAND LEVEL REGULATION

1. Stand Management Objectives

Managing mule deer winter range is achieved by managing stands of Douglas-fir to provide a continuous supply of large-crowned trees greater than 40 cm dbh, across the entire winter range. This goal is best achieved by:

- single-tree-selection management for large trees with wide and deep crowns;
- stand structures which hold most of the basal area in large trees;
- regeneration arranged in groups not exceeding half a tree-length in diameter;
- stocking control in all diameter classes to reduce the density to target levels before the onset of competition-induced mortality;
- reserves of approximately 10% of the residual basal area retained in trees greater than the maximum diameter class, to contribute biodiversity and amenity benefits;
- production of moderate-quality sawlogs from stand management;
- continuous forest cover on key topographical features;
- varying stocking through space and time to provide open-, moderate-, and closed-cover types for deer;

- maintaining representation of intolerant species in the landscape (aspen, birch and lodgepole pine) by varying from the target stand structure on occasion.

2. Stand-Level Biodiversity

Maintenance of stand-level biodiversity requires attention to three elements of stand structure; large trees, dead standing trees, and coarse woody debris. In concept, these three elements are a continuum of one element through time. If trees are allowed to grow to large sizes, to die and eventually fall to the ground, then they fulfill important ecological functions.

Wildlife trees (dead, dying, or decaying trees that fulfill some important need for wildlife) are an important component of stands and landscapes. They have special characteristics that provide habitat for a wide variety of organisms (Hunter 1990; Province of BC 1995b).

Hunter (1990) said:

> "Dying, dead, and down trees are important components of forest ecosystems, because during the process of death and decay they are inhabited by an extraordinarily diverse succession of organisms ranging from woodpeckers and other cavity-users, to myriad invertebrates, fungi, and micro-organisms."

Twenty-five species of birds in the IDFdk3 are cavity nesters (Waterhouse and Dawson 1997). Many other plants and animals are dependent on wildlife trees during some part of their life cycle. According to Hunter (1990) large snags are preferred to small snags by virtually all species. In addition, large snags are likely to last longer than small snags.

Wildlife trees eventually fall over and become decaying logs. Such coarse woody debris is important in dry ecosystems as habitat for many species. As the wood decays and becomes incorporated into the soil, it is an important contributor to good soil structure and moisture-holding capacity, as a site for nitrogen fixation, and for germination of regeneration (Hunter 1990).

Single-tree-selection management requires repeated harvest entries, so mortality is foreseen and trees at risk of dying are marked for cutting (Matthews 1991). Those trees that do die between entries must be cut at the next entry due to concerns for worker safety. Frequent cutting entries effectively eliminate dying and dead trees from stands unless their recruitment is actively pursued.

There are two methods available to recruit wildlife trees: dispersed reserves of candidate trees, or creation of wildlife tree patches. Wildlife tree patches are unharvested areal reserves, established during the preparation of stand prescriptions, which allow some portion of the stand to develop, free of harvesting disturbance. The current guidelines of the Ministry of Environment for Knife Creek require 12% of the land base to be reserved in wildlife tree patches, on a stand-by-stand basis. Dispersed reserves may contribute to the recruitment of wildlife trees under current guidelines.

Recruitment of wildlife trees requires two concurrent considerations: worker safety, and loss of timber yields. Current rules require that any wildlife tree that presents a hazard to workers (hazard trees) must either be felled or surrounded by an area within which no worker will enter. These "no work zones" have a radius of one and a half times the height of the hazard tree, so a single 30 m tall wildlife tree can occupy up to 0.6 ha. Clearly, dispersed reserves for wildlife trees will render a lot of each stand inoperable in consideration of worker safety.

Farnden (1997) compared the timber-yield impacts of dispersed reserves to wildlife tree patches, using computer simulation for spruce-subalpine fir forests. He concluded that three percent of the landbase in wildlife tree patches would recruit snags at the same rate as approximately 25% of stand basal area in dispersed reserves. Wildlife tree patches will recruit snags of all sizes, whereas dispersed reserves will recruit only large wildlife trees.

The strategy for maintenance of wildlife trees on the Knife Creek block will be twofold:

- maintain 12% of the land base in wildlife tree patches;

- allow approximately 10% of the residual basal area to achieve diameters greater than the indicated maximum, to provide large live trees for biodiversity and amenity benefit;
  - do not allow these dispersed large trees to become hazard trees.

Whenever possible, wildlife tree patches will be situated where they can be incorporated into other reserves, such as riparian management areas. Wildlife tree patches might also be located on topographical features important to deer, since very little cutting will be done on those positions, and dry ridges are of poor site quality for timber production.

It is expected that wildlife tree patches will move as time passes, when more suitable wildlife trees are found outside the designated wildlife tree patch. This will provide the recruitment to soil organic matter across the whole stand through time.

3. Target Stand Structure By BDq Regulation

Single-tree-selection management requires explicit description of the stand-structure objectives. Although alternative approaches are available, this thesis approaches stand structure regulation by BDq (Basal area, maximum Diameter, and diminution quotient) (Guldin 1991; Matthews 1991; Fiedler 1995).

Setting target stand structures is a design process that has two elements:

- the biological reality of site quality and silvical characteristics, which dictate the carrying capacity and therefore residual basal area (B); and
- the arrangement of trees into the type of stand that will meet the management objectives for the site (D and q), which is constrained by silvical characteristics.

In order to understand the complexities of stand structure regulation, this topic was first explored without considering the necessity of open-, moderate-, and closed-cover conditions.

Alternative stand structures were then explored to arrive at the best target stand structures for a mule deer winter range objective.

a) Target Stand Structure For Timber

(1) Residual Basal Area (B) = 18 m^2/ha (DBH>7.4 cm)

Residual basal area is the minimum density to be carried on a stand. It is sensitive to site quality, since higher-quality sites can support higher density.[10] As site quality declines, so must residual basal area. Residual basal area is also sensitive to silvical characteristics of tree species being managed, since tolerance to exposure and drought varies by species.

Using radial increment data developed from 794 trees on 39 plots, Day (1997b) took two different approaches to calculating residual density for Knife Creek.

1. Langsaeter's curve (as described by Lotan *et al.* (1988)) was fitted using regression techniques, and B-level stocking[11] from Langsaeter's curve was estimated to be 17.5 m^2/ha. Refer to further discussion of Langsaeter's curve starting on page 63.
2. A Gingrich Chart[12] was created for Knife Creek, using maximum density measured on the 39 plots as the reference level. Upper and lower limits of stocking as suggested by Long (1985) for even-aged stands were set -- 60% and 35% of maximum density respectively. Given the target maximum diameter and q-factor described below, the quadratic mean

[10] Density is the measurable quantity of trees on a given area, expressed as number of trees, basal area, volume, or various relative measures such as stand density index or relative density.
Stocking is the ratio of stand density to the density of the ideal stand, generally expressed as a percentage.
Reference Davis and Johnson (1987).

[11] B-level stocking is the first point of inflection on Langsaeter's curve, and indicates the onset of full site occupancy.

[12] Gingrich stocking charts were first described by Ginrich [sic] (1967), and are a simple expression of stocking as a proportion of a reference level. The chart displays the density of the stand by number of trees and basal area, and therefore implies the quadratic mean diameter of the stand.

diameter (QMD) is calculated as 28.4 cm. According to the Gingrich Chart (Figure 5) the residual basal area for a stand with 28 cm quadratic mean diameter is 17.85 m²/ha.

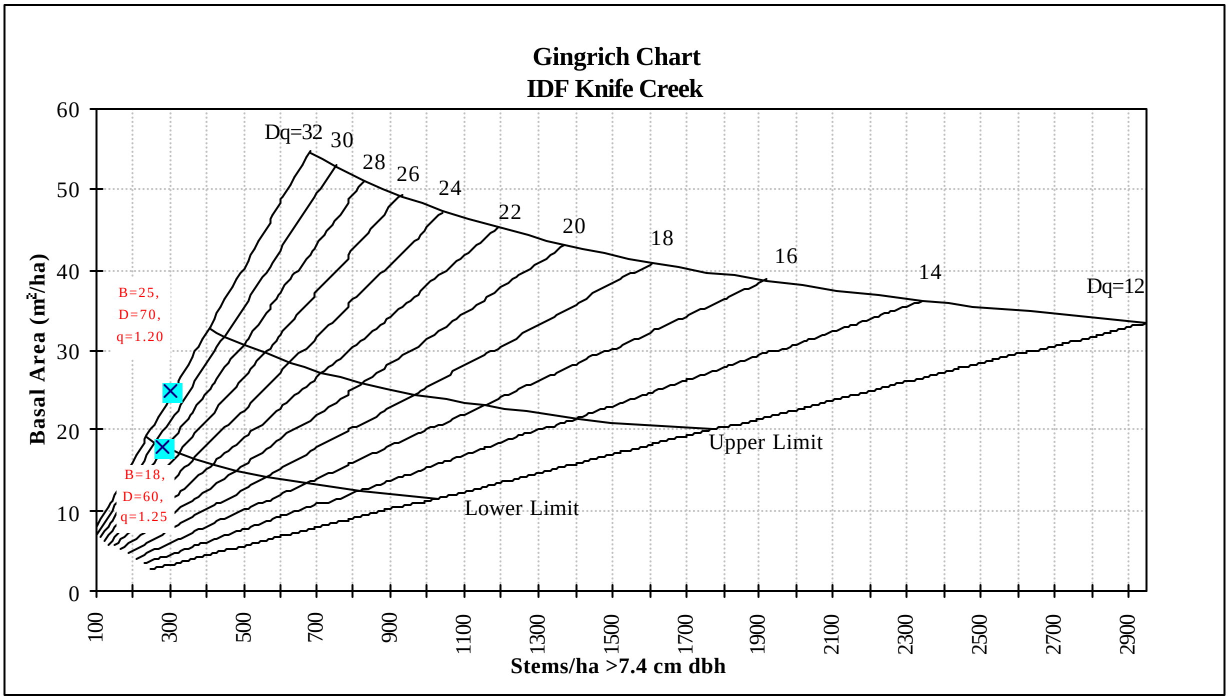


Figure 5: Gingrich Chart for Knife Creek after Day (1997b) indicating that the target stand for timber management (B=18, D=60, q=1.25) is at minimum stocking.

(2) <u>Maximum Diameter (D) = 60 cm dbh</u>

Since the stand management objectives require that a significant component of the trees in a stand be large and old, large maximum diameters are inferred. Fiedler (1995) recommends that maximum diameter should be set either at the size where growth slows, or beyond which few trees grow.

- Data reported by Day (1997b) indicate that diameter growth of Douglas-fir at Knife Creek slows down between 50 and 60 cm dbh.
- Few trees at Knife Creek grow beyond 60 cm dbh -- generally less than 10 trees/ha constituting about 10% of the stand basal area.

Sixty centimetres therefore seems to be a suitable target for maximum diameter. A basal area reserve of 2 m^2/ha greater than 60 cm dbh is instituted, to recruit large green trees for biodiversity and amenity benefits (as recommended by Fiedler (1995)).

(3) Diminution quotient (q) = 1.25

High q-factors concentrate stocking in small diameter classes, while low q-factors concentrate stocking in large diameter classes (Daniel *et al.* 1979; Fiedler 1995). Low q-factors produce better volume growth, since increment is being concentrated on larger stems (Marquis 1976; Leak 1976). Dry forests managed by uneven-aged methods typically employ very low q-factors to avoid overstocking and stagnation, which could accompany higher q-factors (Becker 1995). Since the stand management objectives for Knife Creek require large trees to provide forage and cover, a low q-factor is desirable. Use of a low q-factor on the first harvest in an unregulated stand invites over-cutting, however, and many authors suggest using a slightly higher q-factor in the first entry (Marquis 1976; Daniel *et al.* 1979; SIWG 1992; Fiedler 1995). By process of design, and considering the factors discussed above, a q-factor of 1.25 was selected.

b) Discussion of Target Stand Structure

The three descriptors of stand structure (**B**, **D**, and **q** described above) combine to describe a unique target stand structure (Figure 6). **B** sets the minimum basal area, or the total space under the curve. **D** and **q** together describe the shape of the curve; the combination of the two establishes the quadratic mean diameter (QMD) of the stand. Higher **D** and lower **q** cause QMD to increase. For the stand structure described above (**D** = 60, **q** = 1.25), QMD is 28.4 cm. Changing **B** will move the curve in Figure 6 in the y-axis; changing **D** will stretch or shrink the curve in the x-axis; changing **q** will change the slope of the curve.

As time passes, the number of trees stays the same (except in the smallest diameter class) and the diameter increases. Thus the curve in Figure 6 shifts right, increasing the number of trees in each diameter class. Harvesting should then reduce the number of trees in each class to the appropriate level as set by **B**.

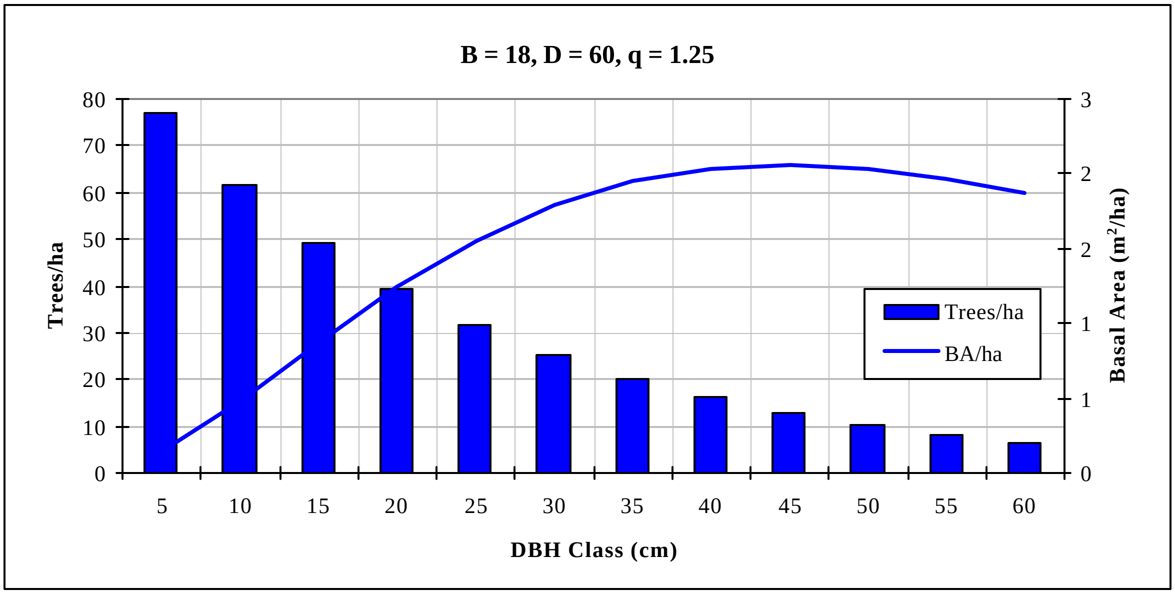


Figure 6: Target stand structure for Knife Creek, given a timber management objective.

Selecting an appropriate target stand structure has implications to growth and yield, and to attainment of management objectives. An understanding of the silvics of the species being managed is critical to selecting target structures that are sustainable. In this author's opinion, the "natural" stand condition (as defined by existing conditions) is not appropriate guidance for establishing target stand structures. Overstocking of saplings and poles results from lack of disturbance, and creates a false standard for target stand structure. Instead, the target stand structure is designed, based upon a knowledge of growth and yield and silvics, and a clear statement of management objectives.

c) Designing Target Stand Structure for Mule Deer Cover

Target stand structures must provide three different levels of cover for deer: open, moderate, and closed cover. The impacts of target stand structure on forage was analysed, based upon the forage availability calculated on page 34. The critical assumptions in this analysis are:

1. trees under 40 cm dbh do not contribute to litterfall forage significantly (Dawson *et al.* 1990);
2. high cover results in higher litterfall than moderate cover (in a ratio of 1.5:1) because high cover forests are more heavily stocked and therefore more likely to shed foliage through abrasion during wind events;
3. low-cover stands provide no litterfall useful to mule deer, since the deer cannot use the area during periods of deep snow;
4. low, moderate, and high cover equals understocked, stocked, and overstocked on the Gingrich chart shown at Figure 5 above.

The simple model developed therefore compares forage availability under a variety of target stand structures, which is thought to be a useful measure of the impact of stand structure on carrying capacity. The results of the model are shown below in Table 5 and Figure 7.

Table 5: Index of forage availability, as affected by target stand structures and Residual Basal Area (RBA). The base value for the index is the estimated forage availability of the target stand B=18, D=60, q=1.25.

D, q-factor	**Nominal QMD (cm)**	**BA% >40 cm**	Index of Forage Availability By RBA Class					
			15	**20**	**25**	**30**	**35**	**40**
70, 1.2	32	0.6	0.0	1.3	1.3	1.3	2.0	2.0
60, 1.25	28	0.4	0.0	1.0	1.0	1.0	1.5	1.5
50, 1.35	24	0.2	0.0	0.5	0.5	0.8	0.8	0.8
40, 1.45	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0

30, 1.75	16	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15, 2.25	12	0.0	0.0	0.0	0.0	0.0	0.0	0.0

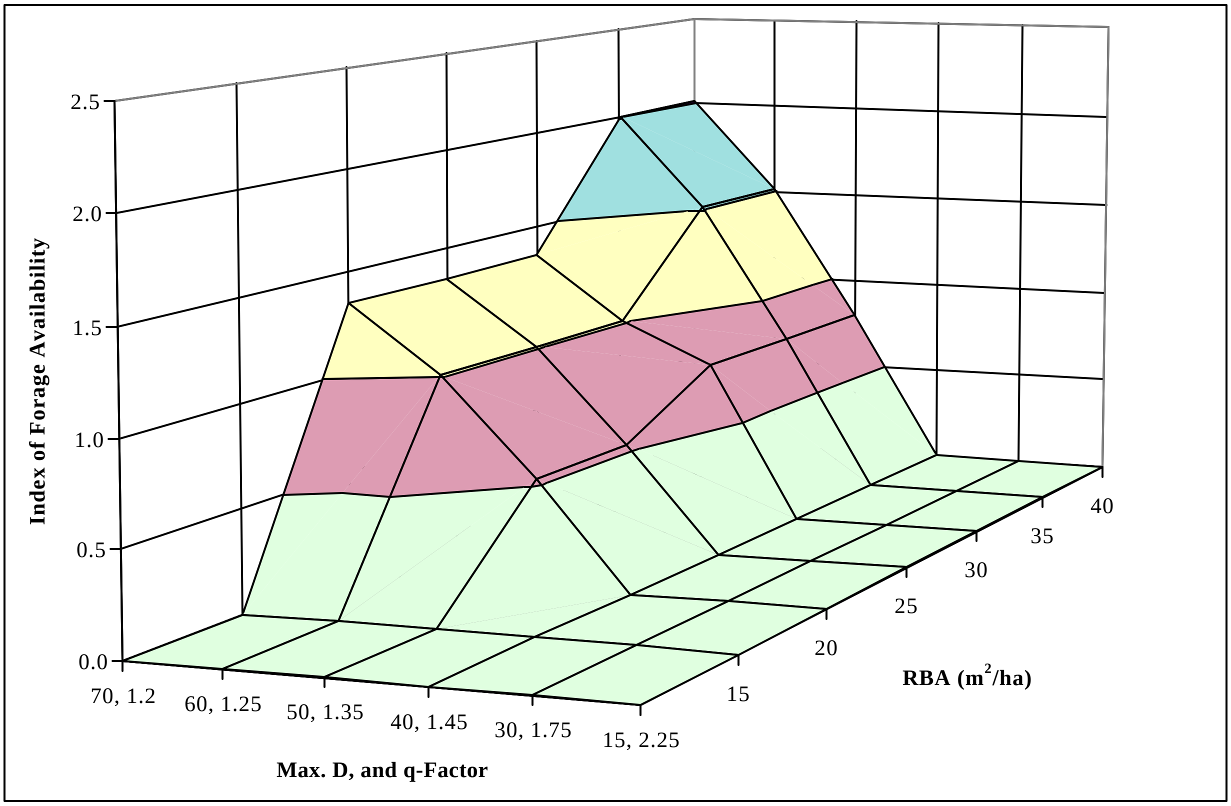


Figure 7: The impacts of target stand structure on an index of mule deer forage availability, suggesting that increasing RBA and Maximum Diameter improve forage availability.

An analysis of the impact of target stand structures upon forage availability index suggests that higher basal areas, higher maximum diameters, and lower q-factors will improve the forage availability without limit. Of course the ecology of the site and the silvics of Douglas-fir limit the ability of a particular site to support forest cover, and stands at Knife Creek rarely support more than 40 m^2/ha of basal area.

Taking the foregoing into consideration, two different target stand structures have been chosen:

- Moderate to High Cover: B=25, D=70, q=1.2
- Low to Moderate Cover: B=18, D=60, q=1.25

The lower cover target will fluctuate through time between low and moderate cover; the higher cover target will fluctuate between moderate and high. In this way the cover class of a given stand at any point in time will depend upon time since the last harvest entry. There is some risk entailed that regeneration will grow poorly in the moderate- to high-cover stand, since density will be relatively high at all times. This will require monitoring after harvest has been implemented and time has passed.

4. Stocking Control

The arrangement of stocking by diameter class (D and q) is essentially a design process that describes the physical qualities of the stand required to meet management objectives. The level of stocking to be carried in the stand is, however, a biological or ecological interpretation. Davis and Johnson (1987) state that:

> "The actual growth achieved in a given site is determined by the amount, kind, and distribution of trees currently on the site. Changing the character of this vegetative growing stock is the principal way foresters manipulate and control growth and yield."

Failure to adequately manage stocking puts management objectives at risk. Carrying too little stocking means lost productivity (in terms of timber production) and reduced wood quality. Carrying too much stocking also means lost timber productivity due to stagnation and mortality. More importantly, stands grown under intense competition have reduced vigour and are therefore more susceptible to insect or disease attack (Boyce 1961; Furniss and Carolin 1980; Larsson *et al.* 1983; Carlson *et al.* 1985; Entry *et al.* 1991; McDonald 1991). In addition, closely grown trees are slender and small-crowned, and have high risk of damage due to wind or heavy snow (Herman and Lavender 1990).

In a retrospective study conducted in the IDF, it was found that regeneration was rarely lacking 8 to 15 years after harvesting (Day 1996a; Catton 1997). Stocking control was, however, a more critical problem. In nine stands examined by Day (1996a), the residual growing stock varied from 25 to

83% of the pre-harvest condition, and response of the residual stand therefore varied widely. In the extreme cases, it was estimated that a 13% removal could be taken every 12 years, but a 75% removal could be taken once every 83 years.

Many authors cite control of stocking as being the principal decision in stand management (Marquis 1976; Long 1988; Lotan *et al.* 1988). While regeneration is a critical factor in single-tree-selection management (Davis and Johnson 1987), regeneration success alone is not a good reflection of success of stand prescriptions. It is quite possible to develop good regeneration and growth of small stems by highgrading a stand (cutting the best and leaving the worst). Regulation of stand structure and control of stocking ensures that stand growth is maintained and management objectives are met (Hann and Bare 1979).

Dry Douglas-fir forests of the interior of British Columbia have had a history of highgrading. Harvesting did not seek to regulate stand structure; instead harvesting simply removed timber. This highgrading was made possible by the abundance of advanced regeneration that allowed heavy cutting to leave a regenerated stand. Highgrading entries are dysgenic[13] (Howe 1995), and leave an inappropriate stand structure composed of low-vigour and low-quality trees, which are susceptible to insect and disease attack. Such stands are not capable of growing at a rate that maximizes site productivity. Appropriate stand structure targets and stocking control ensure harvesting will meet management objectives and maximize growth, and rigorous attention to stocking control is critical.

Stand growth is maximized when a stand is fully stocked, but below the level where suppression and mortality commence. There is a range of stocking that produces the maximum stand growth (Daniel *et al.* 1979; Lotan *et al.* 1988). Growing a stand at the lowest stocking that still captures all the

[13] Dysgenic: having to do with or causing degeneration in the type of offspring produced. Gage Canadian Dictionary, 1983.

growing space (B-level Stocking) maximizes both stand growth and individual tree growth (Daniel *et al*. 1979; SIWG 1992).

The stocking chart developed by Day (1997) and presented in Figure 5 (page 51) remains largely untested. Research is required to examine the impact of levels of growing stock on growth.

5. Regeneration

According to Leak (1976), the fundamental theory that underlies selection management assumes that a population subject to consistent mortality and recruitment rates will settle to a stable age distribution. In single-tree-selection management, mortality is supplied by cutting, and recruitment must be ensured by providing the required environment, seed bed, and seed supply.

Periodic regeneration (subsequent to harvesting) is a requirement of single-tree-selection management (Daniel *et al.* 1979; Matthews 1991; Becker 1995), because regeneration feeds the lower end of the diameter distribution (Leak 1976). It is a critical assumption in single-tree-selection management that regeneration is in place; failure to ensure regeneration threatens the sustainability of the prescription (Marquis 1976; Davis and Johnson 1987).

Linhart and Davis (1991) described the wide genetic variability of Douglas-fir, and showed that variability to be important among groups of trees within stands. They recommended that care be taken to preserve a wide genetic base in Douglas-fir by ensuring regeneration results from many parents.

Seed supply at Knife Creek is generally good. Fair cone crops are frequent, and bumper crops occur approximately five to eight years apart (from the author's personal observations). Single-tree-selection management ensures ample cone production from many parents, and good distribution of seed. Careful marking can maintain the genetic qualities of stands by marking poor-quality trees for cutting, therefore allowing the best phenotypes to produce seed.

A reasonable seedbed (refer to page 13) is generally available without disturbance, since the dry forest soils have very thin moder and mor-moder humus forms, which act as litter. Some level of canopy retention promotes superior germination and survival in all climates tested by Ryker (1975) and Burton (1996).

Seedlings are generally abundant under partial canopies, within several years of disturbance at Knife Creek. Some exposure is required to allow seedlings to grow, but too much exposure appears to be detrimental. When openings are created in a stand, protected positions near stumps or debris appear to be most favourable for regeneration. As seedlings develop into saplings, increasing amounts of exposure are necessary for good growth.

Given the target stand structures discussed above, sufficient advanced regeneration generally exists before the first harvest on a site. Protection of regeneration during harvesting should usually provide enough ingress into a stand to provide for sustainable stand structures. In fact, overstocking is a much greater concern than regeneration failure at Knife Creek.

6. Topographic Features

Particular topographic features have critical importance to mule deer, as discussed on page 31. South- and west-facing slopes, ridges, and topographic breaks play a key role in mule deer ecology; maintaining forest cover on those features is critical. Conversely, gullies and cool slopes have limited value to mule deer, whereas those positions have higher timber productivity.

Management objectives will be achieved by considering topographic position in the marking guide (page 79). Trees on positions important to deer will have a higher priority as leave-trees during marking. In addition, important topographic positions will be considered as good locations to place wildlife tree patches, which will be reserved from harvesting.

B. FOREST LEVEL REGULATION

Forest regulation is a concept of organizing a forest estate to provide an even flow of forest products (Davis and Johnson 1987). The desire for even flow comes from the historical European concepts of forestry, and was imported to North America by early foresters who were trained in Europe (Davis and Johnson 1987). Regulation of timber harvest is desirable for a number of biological, social, and economic reasons (Davis and Johnson 1987). These are:

- to create a stable basis upon which to plan business;
- to ensure approximately equal expenses and receipts from year to year;
- to facilitate improved forest health and fire protection, as the forest is kept vigorous and well distributed in size and condition;
- to incorporate wildlife, range, and recreation uses into the harvest planning on a rational basis;
- to provide continuity of jobs in harvesting and silviculture.

Full regulation is an ideal condition that will probably never be attained, but which provides a standard by which management progress can be measured. The ideal is a forest in which size and age classes grow at rates and are represented in proportions that provide approximately equal annual or periodic yields of the desired products, in perpetuity (Davis and Johnson 1987). Hence forest regulation is the planned approach to sustained yield.

Strategies for forest regulation are numerous (Davis and Johnson 1987), but fall into two broad categories: area control, and volume control. Area control achieves a fully regulated forest in one rotation or cutting cycle, but does not provide an even harvest flow from year to year until regulation is achieved. Volume control provides a uniform volume harvest, but delays attainment of regulation (Davis and Johnson 1987) beyond the first rotation or cutting cycle.

The objectives of management for the Alex Fraser Research Forest (described on page 39) include maintenance of an even or increasing flow of timber. This objective is primarily financial -- to allow relatively stable revenues to support the operation of the Research Forest. This suggests that volume control would be the best method of achieving regulation. However, a rapid approach to regulation at Knife Creek is necessary to improve stand vigour and promote forest health, which suggests that area control would be the preferable method of achieving regulation.

Forest regulation for the Knife Creek block will be achieved by area control with a volume check. Such hybrid approaches are supported by Davis and Johnson (1986) as being a framework for considering the complexities of setting allowable harvest rates in order to make decisions. The steps employed are:

- calculate an annual allowable harvest by area;

$$\frac{\text{Productive Area (ha)}}{\text{Cutting Cycle (yrs)}} = \text{Allowable Cut (ha / yr)} \qquad \text{Equation 1}$$

- calculate yield functions for the Knife Creek block which consider the growth and mortality rate of stands before harvest, and the response of stands to density reduction (see Appendix 10);
- employ Atlas[14] to schedule individual blocks (cutting units) for each year so as to provide a relatively even flow of timber volume from year to year.

1. Growth and Yield

Growth is the change of tree and stand volume with time; yield is the standing volume of a tree or stand, that is, the accumulation of growth (Oliver and Larson 1996). Volume growth varies with stand structure, site quality, and species (Oliver and Larson 1996), and yield is a function of growth rates and time since disturbance.

[14] Atlas is a geographically explicit simulation model developed by John Nelson, UBC Faculty of Forestry, Vancouver BC.

a) Comparing Uneven-aged With Even-Aged Management

The comparison of growth and yield between even-aged and uneven-aged stands is a common topic in the literature. Uneven-aged stands are not as productive as even-aged stands late in the rotation when the even-aged stand is fully stocked with large trees. However, the productivity of the uneven-aged stand exceeds the even-aged stand during stand establishment (Oliver and Larson 1996). Baker *et al.* (1996) cite other authors who report that cubic volume yields of loblolly and shortleaf pines are highest for intensively managed even-aged plantations, whereas sawtimber volumes are highest for intensively managed uneven-aged stands with high stocking. Larger trees and better-quality bottom logs result from single-tree-selection management (Baker *et al.* 1996, citing other authors).

In his review of the French and German literature, Bugnot (1997) found that both uneven-aged stands (under single-tree-selection management) and even-aged stands have about the same productivity, given the same site quality. Again the question of value weighs in favour of single-tree-selection management, since Bugnot (1997) cites reports showing 19-24% better financial yields compared to even-aged management. More of the production is composed of large trees, and bottom logs are of high quality, because as small trees they grew slowly in the understory.

The comparison of productivity between even-aged and uneven-aged stands is of great interest, as is shown by the amount of debate it receives. Largely, however, the question is academic, since the use of a given silvicultural system is generally a function of management objectives and silvics. Volume production is only one objective in forest management, and the use of single-tree-selection management at Knife Creek is based upon habitat values for deer and the silvics of the Douglas-fir growing there. Having chosen single-tree-selection management, however, it is comforting to know that it probably does not entail a reduction in sawlog volumes, and it probably affords an increase in value compared to even-aged management.

b) Review Of Growth And Yield Basics

In an uneven-aged stand, most of the volume growth occurs on trees exposed to direct sunlight; trees in the lower strata only grow after a disturbance and before the overstory becomes very dense (Oliver and Larson 1996). Prolonged absence of disturbance will cause trees in the understory to lose vigour, and render them incapable of rapid growth when release happens.

Growth is a function of density. Very low densities result in site productivity being lost to non-crop vegetation, whereas very high densities result in competition-induced mortality and consequently reduced productivity. Clutter *et al.* (1983) describe the general relationship between stand density and net growth as a smooth curve, similar in form to that described by Langsaeter (as discussed by Lotan *et al.* 1988). Langsaeter's hypothesis stated that there is a wide range of densities within which growth is equal. Recent work has generally discredited that hypothesis, in that points of inflection and a plateau probably do not exist (K.L. O'Hara, U. of Montana, Missoula, pers. comm., Nov. 1997). Curtis *et al.* (1997) report results from spacing studies in coastal Douglas-fir that discredit Langsaeter's hypothesis. Nyland (1996) suggests that the widely held axiom still holds -- density does not influence gross growth over a wide range. However, he suggests that net yield is more sensitive to density.

All authors agree that there is a density above which volume growth declines. Clearly the general form of Langsaeter's curve still applies. As density increases so does growth until competition for resources becomes detrimental to all trees, and then growth declines. Langsaeter's curve and its points of inflection may not exist; none-the-less there is a range of density around an optimum that can be estimated using two points, representing the management zone for stand density.

According to Clutter *et al.* (1983), harvest is sustainable if net growth plus ingrowth is harvested at each time period. The resulting equilibrium between harvest and growth maintains a stationary growing stock reserve from period to period. For any given [cutting cycle and] level of reserve growing stock (B-level stocking) there is an associated sustainable harvest (Clutter *et al.* 1983).

Stand growth has four components, as defined by Husch *et al.* (1972):

- growth -- the periodic increase in diameter and height (or volume) of trees which existed on the site before the first measurement (sometimes termed *upgrowth* in uneven-aged stands, to describe the movement between diameter classes);
- ingrowth -- the number or volume of trees periodically growing into [measurable] size;
- mortality -- the number or volume of trees which die and are not harvested;
- cut -- the number or volume of trees that are felled or salvaged (regardless of whether they are utilized, as in pre-commercial thinnings);
- cutting is therefore sustainable if it equals the sum of growth and ingrowth less mortality.

Growth and yield of uneven-aged dry Douglas-fir stands is complex. Variability in stocking, site quality, and disturbance history complicates the measurement of growth. Unregulated stands with trees of different sizes growing at different rates cause difficulty in measurement. The wide range of structures encountered in unregulated stands is an uncontrollable variable. Theory and approaches developed in even-aged forests do not apply to uneven-aged stands. Age is a poor predictor of tree size, and the traditional measure of site quality (site index at a reference age) is not available (Johnstone 1985; Monserud 1987).

c) <u>Growth And Yield For Dry Douglas-Fir In British Columbia</u>

Dry Douglas-fir forests contribute only about 7% of the total allowable annual cut (Johnstone 1985) and occupy about 5% of the total provincial land base (BC Ministry of Forests 1994). Because of the complexity of the issue and the relatively low strategic importance of the problem, growth and yield of dry forests in British Columbia has historically received an “appalling” lack of attention (Johnstone 1985).

Since the province has not yet published growth data for dry Douglas-fir forests, there is very little information available for estimating growth and yield of uneven-aged stands. Some studies have been undertaken, however, and are worth review.

Bonnor (1991) summarized stem-analysis data from three different sources, and estimated volume growth equations. His equation for undisturbed IDFdk stands used trees/ha as the independent variable, was based upon 38 samples, and had an R^2 value of 0.60. He estimated the maximum volume growth to be 5.34 m^3/ha for stands of 1400 stems/ha (>9 cm dbh). Unfortunately there is no indication of how those stems are distributed in terms of stand structure.

Korol (1985) examined the relationships between soil moisture and growth of Douglas-fir. She calculated growth rates as high as 9 to 11 m^3/ha/year for stands of 300 m^3/ha. These very high growth rates were received skeptically (Peter Marshall, UBC Faculty of Forestry, pers. comm.) but the relative differences in growth rate due to density are of interest. Korol’s (1985) findings support the contention that density control will have a significant impact upon growth in dry Douglas-fir stands. Korol’s data was used in Bonnor’s (1991) study described above.

Marshall and Wang (1996) and Marshall (1997) describe the remeasurement results of six permanent sample plots located on the Knife Creek block. They report volume growth ranging from 3.3 to 4.4 m^3/ha/year; the best volume growth was measured on plots with a predominance of larger trees (>20 cm dbh). Mortality averaged 1% of the stems annually. These six plots sample a range of stand structures, and stand quadratic mean diameters (all stems >1.5 m tall) vary from 9.66 to 22.73 cm. Compilation of 1997 remeasurements will result in additional information becoming available in 1998.

Marshall and Bugnot (1997) report early results from a study of pre-commercial thinning of dry Douglas-fir 30 years after diameter-limit cutting at Knife Creek. On spaced plots (over a four year period), basal area growth averaged 0.86 m^2/ha/year, ingrowth averaged 13 trees/ha/year, and mortality averaged 0.03 m^2/ha/year. Unfortunately, the results are only applicable to stands of similar structure and density.

Data collected by this author (Day 1997b) have been used to validate the model FVS (Forest Vegetation Simulator). FVS is in development as a stand model for British Columbia, based upon the model Prognosis. The British Columbia version is in beta-testing. Model runs were made[15] to estimate the impact of stand structure on volume growth, after the methods described by Farnden (1997). The model runs indicate that the best volume growth (9 m^3/ha/year) will be achieved by stands of very small mean diameter and very high residual density (12 cm and 40 m^2/ha respectively). The results are contradictory to the PSP results reported by Marshall and Wang (1996), and contrary to the relationships between stand structure and growth as described by this author (Day 1997b). On that basis the results of FVS have been discarded. Calibration of the model for local data may, however, improve the validity of the estimates.

d) Stand Table Projection

Growth estimates for the Knife Creek block can be developed using the traditional method of stand table projection as described by Husch *et al.* (1972) and Clutter *et al.* (1983). Stand table projections are a direct estimate of stand growth based upon data collected from the stands being considered (Husch *et al.* 1972). Stand table projections require diameter growth information, a present stand table, a local volume table, and estimates of ingrowth and mortality (Husch *et al.* 1972). Because

[15] The financial support of the Ministry of Forests, Forest Practices Branch and the technical support of J.S. Thrower and Assoc. is gratefully recognized.

the estimates of the components of growth are retrospective, the underlying assumption is that the future will follow the past. This may be problematic, since growth, mortality and ingrowth are all likely to change with the passage of time. Stand table projections are therefore only useful for short range forecasting (Marshall and LeMay 1995).

A stand table projection for Knife Creek has been developed for undisturbed stands only. Development of the model will be completed outside this thesis. The model, which still requires validation, employed the following data:

- ten-year diameter growth data from 794 trees on 39 plots in four different blocks (from Day 1997b), presented in Appendix 8;
- local height table derived from 195 trees in three different stands in Knife Creek, summarized in Appendix 9;
- volume equations from Watts (1983) also shown at Appendix 9; and
- estimates of ingrowth and mortality from Marshall and Wang (1996) and Marshall and Bugnot (1997).

A sample run of the stand table projection for undisturbed stands is included at Appendix 10. This model will be validated for forest structures represented in the diameter growth data. Inventory plots will be stratified, and average stand tables will be produced for input to the model. In addition permanent sample plot data will be input, and model results will be compared to actual remeasurement data.

A critical consideration is the expected reaction of a given stand to harvesting. Clearly stands that have not been disturbed are overstocked, and therefore presumably not growing to their full potential. It is conservative to estimate that a stand will continue to grow at current rates after cutting, but data on response to cutting similar stands are unavailable. Two approaches to this problem will be examined: basal area growth is assumed to continue at current rates after harvest; and basal area growth is primarily a function of site quality, so the results of Marshall and Bugnot (1997) can be imputed to any stand that is appropriately stocked. The remaining calibration and validation of the model will be completed outside this thesis.

2. Forest Structure

a) Current Condition

The Knife Creek block is a product of the past history of harvesting (as discussed earlier). A map showing the harvest history of the block is shown at Appendix 3. In total, 70% of the Knife Creek block has been harvested, and two-thirds of that is considered to have been severely altered in terms of stand structure. The road density exceeds optimum in some parts of the area. Much of the diameter-limit cut areas from the 1960's have now been juvenile spaced, in an effort to restore stand structure to a productive condition. Six hundred and fifty hectares of pre-commercial thinning have been accomplished since 1984.

b) Target Condition

The target condition for the Knife Creek block is:

1. all stands in an uneven-aged condition;
2. a presence of seral species such as lodgepole pine, white birch, and aspen retained on the landscape;
3. an equal mixture of high-, moderate-, and low-cover conditions throughout the landscape, with the high cover emphasized on south- and west-facing slopes;

4. mule deer ranging across the forest on average or milder winters, but utilizing primarily the south and west slopes during severe winters;
5. permanent access to allow harvesting, salvage, research and education throughout the forest;
6. distance between roads not less than 800 m;
7. harvesting occurring each year on stands dispersed across the forest;
8. all stands stocked appropriately and approaching target diameter distributions, with vigorous and well distributed regeneration;
9. stands composed of vigorous trees and able to withstand periodic epidemics of bark beetles or defoliators.

3. Cutting Cycle

According to Davis and Johnson (1987) the cutting cycle is the cornerstone of the management prescription. The cutting cycle is a function of the level of residual growing stock and the basal area growth rate (Matthews 1991). Day (1997b) found that periodic basal area growth in Knife Creek averaged 4.2 m^2/ha per decade in unregulated stands (without considering mortality). Marshall and Wang (1996) found basal area growth in Knife Creek (considering mortality) to be 3.4 m^2/ha per decade in unregulated stands. Marshall (unpublished data, 1997) has found average growth rates of 8.3 m^2/ha per decade in thinned stands at Knife Creek.

Short cutting cycles require large felling areas to produce a small volume (Matthews 1991), but ensure the salvage of mortality and more constant control over stocking. Long felling cycles, on the other hand, reduce the area of each compartment and thereby improve the economic efficiency of the harvest (Matthews 1991). Longer cycles increase the risk of loss through mortality and reduce the stocking control exerted. Matthews (1991) also states that long cycles with small compartments favour more light-demanding species, because of relatively more intensive cutting.

Figure 5 (page 51) indicates that the upper limit of stocking for the target stand is approximately 32 m^2/ha. Given a residual stocking of 18 m^2/ha, the stand can therefore recover approximately 14 m^2/ha of basal area before the onset of competition-induced mortality. Using the data cited above from Marshall (unpublished data 1997) for managed stands in Knife Creek, basal area was estimated to grow at a rate of 8.3 m^2/ha per decade. A cutting cycle of 17 years was therefore indicated.

The cutting cycle was increased to 20 years to recognize several factors:

- Marshall's data are from plots that do not include any voids, and therefore overestimate growth at the stand level;
- the relatively long cutting cycle will allow some mortality, which is not recognized in Marshall's data;
- average diameter growth ranges between 1.2 and 2.5 cm/decade in Knife Creek in unmanaged stands -- a 20 year re-entry period will allow more trees to pass into the next diameter class between entries;
- recruitment of snags and coarse woody debris will be enhanced by a slightly extended cutting cycle; and
- the exposure requirements of interior Douglas-fir indicate that a longer cutting cycle may be beneficial.

4. Allowable Annual Cut

The Allowable Annual Cut for the Knife Creek block is calculated on the basis of cutting equal areas each year, in order to achieve stand structure regulation across the forest in the shortest time possible. Given a net productive area of 3,418 ha from Table 2 and a cutting cycle of 20 years, the Allowable Annual Cut is calculated according to Equation 1 (page 61) as

$$\text{Net Productive Area} \div \text{Cutting Cycle} = 3{,}419 \text{ ha} \div 20 \text{ years}$$

$$\text{AAC} = 170.9 \text{ ha/year}$$

A volume check will be carried out during the summer of 1998, to attempt to rationalize the annual volume harvest as described earlier.

PRESCRIPTIONS

A. PRE-COMMERCIAL THINNING

Herring *et al*. (1977) first recognized pre-commercial thinning (also known as juvenile spacing) as a means of rehabilitating stands after diameter-limit cutting in the Cariboo Region. Stands that have been diameter-limit cut generally have low quadratic mean diameter, and poor spatial distribution of growing stock. Density is generally low in layers[16] one and two but excessive in layers three and four. The Ministry of Forests retains the financial burden of pre-commercial thinning any areas that were harvested before the creation of the Research Forest and exceed maximum density of 2000 stems/ha in layer three. The Williams Lake Forest District has been very supportive by allocating sufficient resources to carry out this important work over the past ten years.

Thinning is a normal part of single-tree-selection management; all stands harvested will have some component of thinning in non-commercial sizes, to ensure that all components of the stand have space to grow. The investment will be greatly reduced compared to the current expense of about $400/ha (including project establishment and administration), because much less cutting will be required. In the future, spacing will be done at the time of harvest or shortly after, perhaps in conjunction with quality slashing[17].

The objectives for pre-commercial thinning in Knife Creek are to:

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[16] Layers are used in describing structurally complex stands in British Columbia, and are defined as:
Layer 1 -- dbh ≥ 12.5 cm; Layer 2 -- 7.5 cm ≤ dbh ≤ 12.4 cm; Layer 3 -- 0 cm < dbh ≤ 7.4 cm; Layer 4 -- height ≤ 1.3 m.
For more detail, refer to Table 10, Appendix 6.

[17] Quality slashing is an activity that follows logging, to reduce slash depths and cut sub-merchantable trees damaged during harvesting operations.

- retain sufficient growing stock in layers one and two to declare the stand stocked according to the stocking chart (Figure 5 page 51);
- reduce the density of over-stocked layers, by keeping the most vigorous trees at appropriate inter-tree distances (deduced from the stocking chart, Figure 5 page 51);
  - layer 1 3.5 m (0.5 - 5 m allowable range)
  - layer 2 3.1 m (1.5 - 5 m allowable range)
  - layer 3 & 4 2.7 m (1.5 - 3.5 m allowable range)
- develop the natural clumpiness which exists in unlogged stands by allowing wide tolerances, so that spacers can cut low-vigour trees and leave vigorous trees without penalty;
- allow sufficient growth that the next entry will generate merchantable sawlogs;
- begin developing target stand structures.

Research Forest staff, working in co-operation with Harold Armleder, have developed "clumpy spacing" prescriptions. The objective of the prescriptions is to leave residual stocking in groups of close spacing, and create space outside the groups to provide resources to trees within the groups. A hallmark of these prescriptions is their low residual density when compared to standard spacing prescriptions. To date, the implementation of the prescriptions has been difficult, because the instructions for the spacing contractor have been complex. Work continues to reduce the complexity of the instructions.

Spacing prescriptions benefit from a close examination of stand structure, so as to set the most appropriate cutting objectives. Pre-spacing surveys include either fixed-area plots or a point sample to allow construction of a full stand and stock table. Information on species composition is important because it allows the prescription to consider salvage of mature lodgepole pine left in the first cutting, and retention of hardwoods for biodiversity. The Gingrich Chart developed by Day (1997) is extremely useful in setting target densities for each stand. Stand and stock tables should be compared to target stand structures (Appendix 7) to illustrate thinning priorities.

Spacing prescriptions include the retention of unspaced reserves, which generally consist of a 30 m wide strip spanning the spacing unit. These unspaced reserves provide hiding cover for deer and moose, and retain habitat for a variety of other species such as snowshoe hare and red squirrels (Waterhouse *et al*. 1990). Wildlife trees are identified by a stand survey, and unspaced zones are established to protect them.

Blocks to be spaced are separated in space and time, so that contiguous areas of spacing do not exceed about 50 ha. This has benefits for wildlife and fire protection. Five years is about the minimum time that should elapse before an adjacent unit can be spaced, since that interval allows the depth of spacing slash to reduce, and crown growth to reduce the "open" nature of the treated stand.

Pre-commercial thinning is typically carried out with chainsaws, but brush saws may also be used. Significant training is necessary for each spacing contractor, because the prescriptions are quite different from the standard prescription in the Williams Lake Forest District.

B. HARVESTING

The success of any partial-cutting operation depends upon the union of many things: an appropriate prescription; intelligent layout which facilitates logging; good marking which meets the prescription within the practicalities of the logging; willing and trained loggers who understand the prescription; and active supervision which addresses problems as they arise. This section describes methods to be used in establishing and implementing harvesting prescriptions.

1. Cruising To Assess Stand Structure

Cruising on public land in B.C. at present is primarily focussed on evaluation of the timber to be cut, and estimation of the cost of harvesting operations. A typical cruise is done by point sampling, and only measures six to ten trees per plot. Plots are located and compiled on the basis of forest cover types. In order for a cruise to provide the information required to assess stand structure, more trees should be sampled, and the sample should include all diameters. The cruise should be compiled by treatment unit rather than timber types.

Cruising at Knife Creek should follow the standards shown below. Plot areas and layers discussed are further described in Appendix 6.

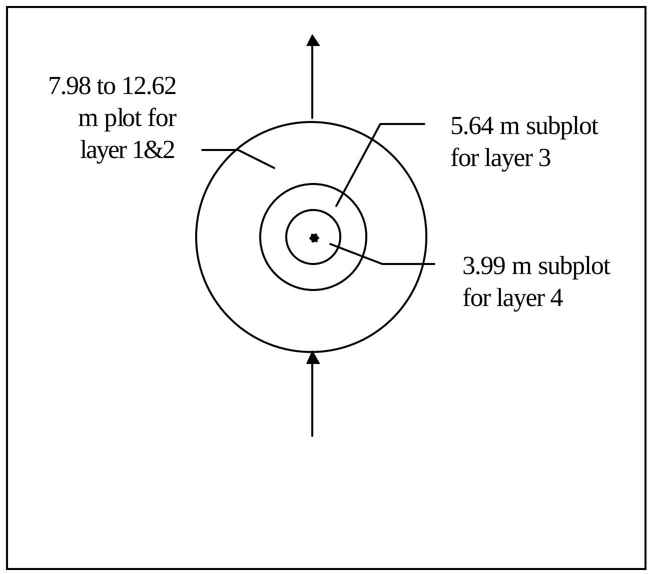

Figure 8: Cruise-plot layout for stand structure assessment at Knife Creek.

- Fixed radius plots, to sample 3-5 % of the cut block, on a systematic grid;
- Main plot from 7.98 - 12.62 m radius (layer one and two) depending upon distance between plots -- larger plots are preferred because they are more likely to sample big trees;
- Nested sub-plots of 5.64 m radius for layer three trees and 3.99 m radius for layer four trees;
- Sample heights of trees throughout diameter distribution to verify height/diameter relationships, which will vary with site quality and density;
- Tally trees by 5 cm diameter classes (Appendix 6) and vigour classes described in Table 7 (page 81).

Cruise results should be compiled according to normal fixed-area plot compilation procedures, except compilation should include all stems. The stand table from the cruise compilation can then be entered into a spreadsheet application that compares the existing stand table to the target-stand condition, and allows analysis of prescriptions. These spreadsheets can be quite sophisticated, such as Uneven95, written by John Przeczek, RPF[18]. A simpler spreadsheet, devised by the author, has been used to examine stand structure, and to help to set the marking guide for the stand. An example of that spreadsheet is included at Appendix 7.

2. Layout

Designing and locating boundaries, skid trails, and landings is a critical to a successful logging operation, particularly in partial-cutting prescriptions. Boundaries must be located so that timber is not isolated. Landings, roads and skid trails are permanent features in single-tree-selection management, so they must be placed to minimize environmental impact and future maintenance requirements. Access must occupy as little ground as possible, since it is a permanent withdrawal from the productive landbase.

Single-tree-selection management requires repeated entry into each stand. The cutting cycle for the Knife Creek block has been set at 20 years. A permanent network of trails will therefore be developed in each cut block. Soils of the Knife Creek block are typically fine-textured (Silt Loam to Silty Clay according to the Canadian System of Soil Classification), and have high or very high hazard for soil compaction. In addition, the soils have shallow forest floors, and are therefore sensitive to forest floor displacement. Site degradation by compaction is therefore expected if logging does not recognize

[18] Interior Reforestation Co. Ltd., Cranbrook, B.C.

the sensitive nature of the soil. Harvesting can be planned in such a way as to reduce the negative impact of trail development on productivity.

1. Designate trails. Laying out and marking trails for logging contractors significantly reduces trail density (Nyland 1996).
2. Minimize trail density. Current harvesting methods and practises require trail spacing not more than 30 m apart. Trail density can be reduced as local contractors become more familiar with this prescription, and as logging equipment continues to develop.
3. Minimize trail width. Ensure loggers stay on one track, keep the trails as straight as possible, and employ skidding equipment that is as narrow as is practical.
4. Protect the soil. Harvesting in winter when the soil is frozen greatly reduces compaction and displacement. Similarly, using slash from limbing and topping to provide a carpet on which machinery can run also protects the soils.

Trail layout also has a significant impact on damage to residual trees. Each time logs being skidded must be turned, they rub or bump against residual stems and cause wounds. Trail junctions must meet at a narrow angle, preferably less than 35° (Przeczek 1995). More than one trail should not join the main trail at a common junction, since such junctions create large voids in the stand. Trails should not curve except over very long distances, since trees on the inside of curves will always be rubbed.

3. Marking

Marking is "...the mechanism that facilitates the regulation of ... partial cutting..." (Anderson and Rice 1993). Marking therefore applies the stand management objectives to the stand as it exists at the present time (Day 1996 b). It is particularly important in the first entry into a stand, because of the large number of stems and wide range of quality and vigour in the unmanaged stand (Fiedler 1995).

Single-tree-selection management can be dysgenic if care is not taken to make qualitative decisions in favour of leaving the best trees and cutting the worst (Howe 1995). According to Howe (1995), dysgenic effects can be avoided if:

- regeneration is episodic, and widely separated in time;
- final cutting removes the oldest individuals, not the fastest-growing; and
- trees of poor form, vigour, and health are removed from each age class at each entry.

Marking is not a new practise in British Columbia. Benteli (1955) describes a study he conducted of marked Douglas-fir stands in the dry Douglas-fir forests from Penticton to Clinton. His report pointed out many flaws in the marking as it was practised at that time, and generally concluded that the lack of well-defined silvicultural objectives resulted in highgrading. Soon after the publication of Benteli's report, the BC Forest Service published a stand treatment guide, but marking was gradually replaced by diameter-limit cutting due to expense (Vyse *et al.* 1991). Expense, however, is relative to benefit, and if a simple objective (retain 40% of the stand volume) can be achieved without marking, then marking will certainly fail. However, when complex objectives dictate that particular types of trees need to be retained, the benefits of marking will justify the expense.

Faller's selection as currently practised in the Cariboo Forest Region is not sufficiently responsive to prescriptions, and will no longer be used on the Research Forest. Logging contractors operate in a competitive environment, which dictates that they find the most efficient way to complete the task at hand. In single-tree-selection management, the issues of tree selection and protection of the residual stand are very important silviculturally, but are costly in terms of a logging operation. The logger's interests will frequently be at odds with the prescription, so the prescription must be clearly defined for the logger by Research Forest staff. Finally, marking provides an opportunity for a prescription to be implemented and verified before the trees are cut; success or failure of a prescription is therefore less subject to the whims of the logging contractor. These reasons dictate that the choices not be left to the faller.

The marking described below costs about $1.00/m^3, and undoubtedly entails greater logging and layout costs. In this author's opinion, however, the additional costs are offset by improved growth and quality of the residual stand. This opinion has not been substantiated by research, but it is striking that the Cariboo is lagging behind other regions in BC in moving to marking for partial cutting. To this author's knowledge, no other first-world jurisdictions allow faller's choice logging.

a) Marking Guides and Tree Classification

Marking guides provide a tree classification system to assist qualitative decisions (Anderson and Rice 1993), as well as quantitative guidance for a given stand (Marquis 1976; Guldin 1991). Tree classification interprets management objectives, the silvics of the species, and the ecology of the site. A tree classification for Knife Creek is shown below in Table 6. Marking should select leave trees in the A and B classes, and concentrate harvesting in the C and B class.

Tree vigour and diameter are used as a surrogate for tree age when marking. Marking the youngest trees in each diameter class is the best practical means of avoiding dysgenic selection. Classification of trees by their vigour is relatively simple, given some experience. Schmidt *et al.* (1976) provide qualitative criteria for identifying vigorous Douglas-fir, and those descriptions are presented in Table 7 with some modification to localize the criteria to Knife Creek.

Table 6: Tree classification for timber marking on mule deer winter range.				
Class		**Species**	**Values**	**Future**
Habitat	**A1**	Douglas-fir.	Currently or potentially providing good cover and forage. Located on important topographic features.[19]	Poor to Good vigour and low risk[20].
	A2	Douglas-fir.	Currently providing good cover and forage.	Good vigour and low risk.
	A3	Douglas-fir.	Currently providing good cover and forage.	Poor vigour and low risk.
	A4	Douglas-fir.	Potentially providing good cover and forage.	Good vigour and low risk.
Timber	**B1**	Any species.	Neither currently nor potentially providing good cover and forage but with good timber potential.	Good vigour and low risk.
	B2	Any species.	Neither currently nor potentially providing good cover and forage but with good timber potential.	Poor vigour and low risk.
Risk	**C**	Any species.		Poor vigour and high risk.

[19] Ridges, terrain breaks, south- or west-facing slopes have high value to mule deer. Refer to page 31.

[20] Risk is defined as the likelihood of the tree dying before the next entry.

Table 7: Vigour classification by qualitative descriptions for interior Douglas-fir (after Schmidt *et al.* 1976).

Characteristic	Good Vigour	Fair Vigour	Poor Vigour
Crown Class[21]	Dominant or Codominant.	Codominant or Intermediate.	Intermediate or Suppressed.
Live Crown Ratio	> 40%	20 - 40%	< 20%
Crown Shape	Pointed to rounded.	Rounded to flat.	Flat or spike-topped.
Crown and Foliage	Dead branches rare. Foliage moderately dense or better.	Occasional dead branches. Foliage moderately dense.	Dead branches frequent. Foliage thinning to sparse.
Bark	Dark bark plates at base are broad with well-exposed new bark between. Upper bole -- ¼ or more of tree height light grey and smooth.	Less exposed new bark between plates. Upper bole -- less than ¼ of tree height light grey and smooth.	No new bark exposed between plates. Upper bole -- dark grey rough bark for entire stem.
Insects or Disease	Free of damage.	Light damage.	Moderate to heavy damage.

b) Mechanics of Marking

The residual stand should not be composed of "left-overs" (Fiedler 1995), so marking should focus on the residual trees. Ideally leave-trees should be marked. Efficiency and cost, however, dictate that marking should be conducted in whichever manner is fastest. Stands can be marked by mark-to-leave, mark-to-cut, or a combination of the two. It is critical for communication with loggers that paint colour is consistent, and the following protocol has been adopted at the Research Forest:

- Cut -- Orange paint in a ring at breast height plus a stump mark;

[21] Crown class should be considered relative to the immediate neighbours, not to the entire stand. Hence dominance can be expressed by trees of any height.

- Leave -- Blue paint on four spots evenly spaced around the tree at breast height plus a stump mark.[22]

Use of two colours facilitates complex marking rules, such as "Cut all the pine except those marked with blue, and leave all other species except those marked with orange." Trees should be marked at the stump to allow assessment of the marking status after the tree has been cut. The stump mark should be a short vertical stripe on the down-hill side, starting below stump-height and extending up above the level of the falling cut.

Rub trees should be designated at any place where trails turn, to protect the residual stand from skidding damage. The rub trees are simply marked as leave trees (blue paint), then re-marked for removal after the skidding is finished.

Marking is challenging work, and should be conducted by well-qualified staff. Staff should be conversant with cruising and silviculture, and should be familiar with logging operations, particularly falling and skidding. Following is a discussion of the necessary steps for marking a stand.

Lay out and flag permanent skid trails to access 100% of the block. Trails should be at or slightly below the density specified in the prescription, straight, and parallel. Trail junctions should be less than 35° angles to allow logs to turn without undue damage to the residual stand.

A marking tally[23] is useful to guide the marking if the harvest will approach the target stand structure. Frequently, however, the first harvest will concentrate on other issues -- species composition or health. In these cases, a marking tally is not very useful because the markers approach residual basal area before marking for structure can be considered. Instead, a post-marking re-cruise is more

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[22] Trees marked-to-leave should be marked as inconspicuously as possible, since the resulting stand will have every tree marked.

[23] Traditionally two markers are accompanied by a tally person, who notes the marking status, species and diameter class of each tree in the stand. This allows the markers to compare their progress towards the prescribed stand, and continuously adjust their marking.

efficient, since it is simply a matter of returning to the cruise plots and noting the marking status of each tree in the plot.

Two or three markers should work together as a team to mark the space between each pair of trails. If a tally is being kept, two markers and a tally-person work together. Markers assess each tree for vigour, form, quality, ability to withstand the post-harvest environment, contribution towards the target stand, and falling difficulty. Trees that need to be felled in a particular direction to avoid stand damage can be marked for directional falling. Such a tree is marked with a vertical arrow on the side to which the tree must be felled. Trees along the trails are assessed for likelihood of skidding damage, and rub trees are marked as necessary (particularly at trail junctions), with the intent that they will be cut on a final "clean-up" pass. Periodically the markers must pause to ensure that the target residual basal area is being marked. This is generally done using a prism (4 or 5 m^2/ha Basal Area Factor). Farrar (1996) recommends that 3-5% of the cut be allocated for marking damaged trees after logging is nearly complete (refer to page 84 for further discussion of damage to residual trees).

4. Logging Guidelines

a) Logging Contractors

Although faller's selection logging has been underway in the Cariboo Region for nearly 20 years, the prescriptions and objectives under this plan are sufficiently unusual that problems will be encountered. Selection of a logging contractor is the most critical decision. Production should not be more than four or five truck loads (150 to 200 m^3) per day. Careful training of the contractor is important to ensure that the objectives and marking are understood. This approach to harvesting is sufficiently different from standard Faller's Selection logging that all members of the logging crew will require training. The critical concepts for each member of the crew are:

- the contractor should have a willing attitude, appropriate equipment, and a low-production operation;
- fallers must ensure directional falling in lead[24] to the trails, protect the residual stand by topping and limbing in the bush, and work to cut difficult trees;
- skidder operators must stay on the trails, and work to protect the residual stand on every trip.

Logging a block typically takes four or more stages. The loggers first fall the timber on the trails. In the second and third stages they cut about half the volume on each trail. On the fourth stage they return to cut the damaged and problem trees. The skidder removes the felled wood after each stage while the faller works on another trail.

Research Forest staff have discussed the potential of implementing a system of quality-based payment for logging contractors, as has been adopted for other silvicultural contracts in British Columbia. Such a system would reward high-quality and penalize low-quality work. Currently payment is based entirely upon production levels, and higher production equates to higher pay rates despite accompanying quality problems.

Clearly a lot of training is required for fallers, skidder operators, and contractors before there is a sufficient pool of contractors willing and qualified to do this type of logging. Training for loggers is a high priority, and should be initiated before the year 2000.

b) Damage To Residual Trees

Logging damage is a feature of selection cutting, but the levels of damage are controllable. Nyland (1996) suggests that work practices substantially influence the extent of damage. Crew training, use of special practices, proper supervision, and choice of equipment are key components to minimizing

[24] Falling in lead entails directing the tree so it will easily move into the skid trail when pulled by the skidder, with minimum damage to residual trees.

damage. The logging crew is the critical element in reducing damage, and careful work habits must be promoted (Nyland 1996).

Three types of damage are recognized:

Top Damage -- falling trees break the top or shear the branches from a leave-tree. Top damage is worst in cold winter weather when branches are frozen. This type of damage can be reduced by careful directional felling, and felling in multiple stages so that new holes open up for difficult trees.

Basal Scarring -- skidding equipment or moving logs bump or rub against a tree and remove bark and sometimes wood from the butt log. Broken wood weakens the tree, and damaged bark allows stem-rotting pathogens to enter the tree and cause decay. Basal scarring is worst during the spring and summer when the sap is up, and least during the winter. Careful falling to put trees in lead to the trail is critical, but the attitude of the skidder operator is most important.

Root Damage -- repeated traffic either compacts the soil around roots, or mechanically damages roots by breakage or abrasion. This type of damage is least on frozen soils, and worst when soils are wet. Logging in winter on snow or frozen soil, logging on dry ground, or using a mat of limbs and tops all reduce the level of damage. Restricting machinery to dedicated skid trails will also reduce the amount of unnecessary damage. Root damage will cause a loss of vigour, and may create entry points for decay-causing pathogens. It is this author's opinion that root damage is a primary cause in unexplained mortality of spruce after partial cutting.

(1) <u>Work Habits to Reduce Damage</u>

The logging crew can have a very significant effect upon the amount of damage done to the residual stand. Figure 9 depicts some of the critical activities that reduce damage, and more methods are discussed in Table 8.

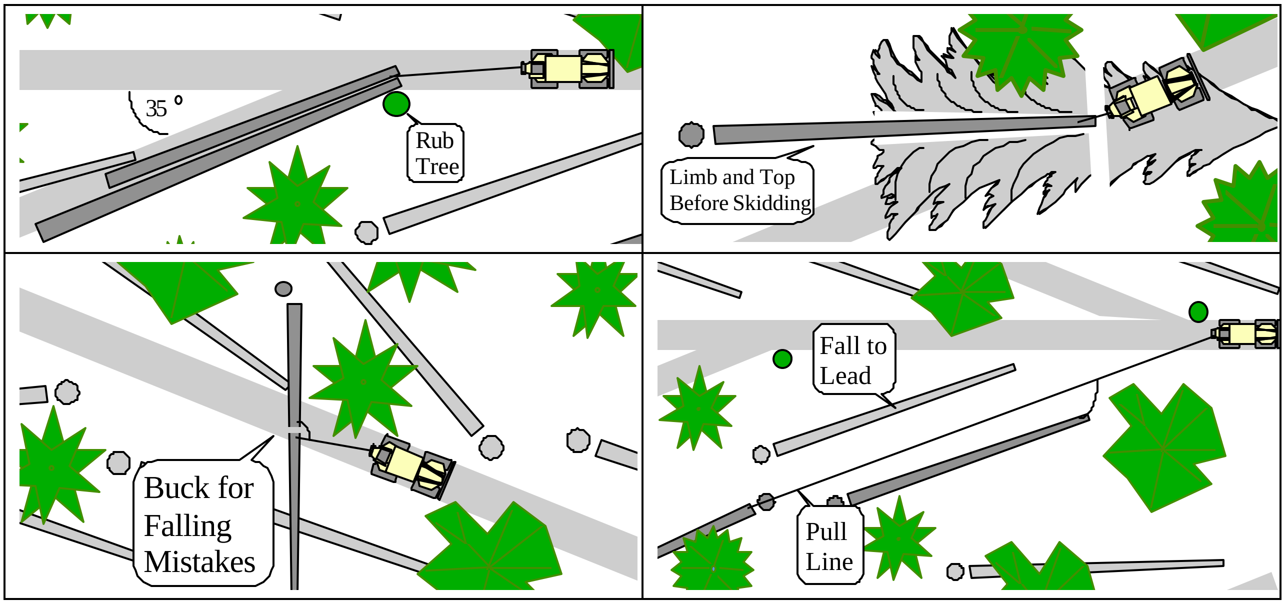

Figure 9: Work practices to reduce damage to the residual stand (After Przeczek 1995).

Table 8: Work habits that will reduce residual-stand damage during logging.

Falling

1. fall to lead for the skidder -- trees should be felled at an angle of about 35° or less to the trail;

2. accept that not all trees will reach the trail, and the skidder operator will have to pull the mainline off of the trail;

3. stop falling when wind velocity makes it uncertain that you can put your tree where you want it;

4. top and limb every felled tree;

5. buck those trees which do not fall in lead with the trail;

6. protect the residual stand according to the following priorities
- marked trees
- well-formed poles and saplings
- regeneration;

7. fall in multiple stages to improve the falling opportunities and reduce damage and breakage

8. work co-operatively with the skidder operator to ensure safety and efficient logging with minimum damage;

9. get assistance from the skidder to winch or push dangerous trees -- do not leave hang-ups;

10. consider using a block and tackle, pry-bars or other felling aids to fall problem trees in the final falling stage;

11. walk away from problem trees until the supervisor can discuss the problem and either change the marking or suggest alternatives -- do not cut trees contrary to their marking status until approved by the logging supervisor;

12. discuss concerns or ideas with the contractor and the supervisor to improve the results.

Skidding

1. use small- to medium-sized skidding equipment;

2. prefer crawler tractors to rubber-tired skidders, if stumping trails is possible;

3. keep the skidder on the trails and follow the same track every trip;

4. place debris or cull logs on inside of corners and on low sides of trails;

5. work co-operatively with the faller to ensure safety and efficient production with minimal damage;

6. watch the corners of the blade and wheels on trail-side trees;

7. be prepared to pull mainline up to 30 m;

8. carry a maximum of three chokers;

9. do not skid whole trees -- skidding should always be done by tree-length (limbs and tops removed) or log-length;

10. trees which have not been felled to lead should be bucked to shorter lengths before skidding;

11. drive in the trail backwards, or turn around at trail junctions -- do not back off the trail;

12. do not push trees together to facilitate skidding;

13. pass the mainline on the correct side of all trees between the skidder and the log -- stop winching if the cable is rubbing on a leave tree;

14. use a snatch block at an intermediate tree to angle the mainline for particularly difficult skidding problems;

15. discuss concerns or ideas with the contractor and the supervisor to improve the results.

(2) Damage and Decay

Despite the best efforts of personnel to reduce logging damage, some will occur. It is important to consider the results of the damage that does occur, and develop a strategy to minimize its impact.

Top damage is the most critical type of damage, since the resulting wounds appear to be very attractive to bark beetles, based upon informal observations by the author. Scars in the upper bole had a higher incidence of infection by decay fungi (Craig 1970). A tree with a broken top or limbs sheared off will not contribute well to the desired stand, and should be cut.

Basal scarring is of less concern than top damage, since Douglas-fir are quite resistant to decay after injuries (Craig 1970). Craig (1970) found that over 60% of the scars sampled in the central Cariboo were infected with decay fungi, and showed that decay will account for 1-5% of the gross volume of scarred Douglas-fir. Craig's (1970) study sampled from a wide geographic area, and concluded that moister regions had significantly higher rates of volume loss than drier regions. The central Cariboo was the moistest region studied. Decay and resin-soaked wood caused by wounds result in loss of volume and quality in the bottom log -- the most valuable portion of the tree. The losses in value are therefore greater than the decay volume alone would indicate.

Trees of small diameter at the time of logging will have only a small volume of rot. Decay resulting from basal scars only affects the wood that exists at the time of injury (Craig 1970; Allen and White 1997), and does not expand into new stemwood over time.

Craig (1970) does not distinguish between the incidence of infection and the incidence of decay. This is an important consideration, since a scar may be infected but the tree resists decay. Allen and White (1987) report that 88% of wounds on western larch result in decay, while only 7.8% of scars on lodgepole pine result in decay. Aho *et al.* (1983) suggest that trees with resinous wood (including lodgepole pine and Douglas-fir) are less-readily infected by decay fungi than trees with non-resinous wood (true firs and hemlock). The exception to their rule of thumb is the spruces, which despite being resinous are very susceptible to infection by decay fungi. The author's experience suggests that the incidence of decay associated with scars on Douglas-fir is relatively low, based upon observations of fire-scarred trees after cutting. This supposition requires verification -- it is important to find out the incidence of decay associated with logging scars at Knife Creek, since the management implications are significant.

Douglas-firs that have basal scars should preferably be cut, but can be left with little risk of attracting bark beetles, based upon informal observations of the author.

Until further information is available, the following guidelines are offered based upon local experience and three pertinent reports (Craig 1970; Aho *et al.* 1983; Allen and White 1997):

- large scars are more likely to cause decay than small scars;
- scars that gouge the wood are more likely to cause decay than scars which do not;
- a scar on a large tree will cause much greater volume loss to decay than a similar scar on a small tree;
- wounds in contact with the ground are more likely to result in decay than higher wounds, and the decay progresses more rapidly;
- decay is established relatively quickly, and 5% losses can occur in just 10 years;
- scarred Douglas-fir may be left;
- scarred pine may be left;
- scarred spruce should be cut.

(3) Addressing Damage During Harvesting

Residual trees should be protected by careful logging practices (page 86). Not all trees can be protected in this way, however, and damage will occur. Damaged trees should be addressed by re-marking the stand for a final clean-up pass before logging is complete. Farrar (1996) recommends that 3 to 5% of the harvest be retained unmarked until this final cleanup pass, to hedge against overcutting the prescription at the end of the logging. Any trees that have significant top damage should be cut, since such damage is apparently very attractive to Douglas-fir bark beetles. In addition, Craig (1970) found scars in the upper bole had a higher incidence of infection by decay fungi. Spruce with basal scars or root damage should be cut. Lodgepole pine or Douglas-fir that have large (more than 30% of their circumference) or gouged basal scars should be removed if the stand density will allow their removal.

Since damage to residuals can be attractive to bark beetles, monitoring of selection cutting is important for several years after logging. Routine bark beetle detection and management activities as described by Day (1997a) are sufficient to manage outbreaks resulting from selection harvesting.

RESEARCH AND EXTENSION

A. RESEARCH NEEDS

The following list of research projects is ranked from highest to lowest strategic importance for the Research Forest.

1. validation of the Stand Table Projection model.
2. calibration and validation of the Stand Table Projection model for stands after cutting
3. quality-based payment for logging contractors
4. growth response to density control
5. shelter and/or exposure requirements of Douglas-fir seedlings and saplings
6. incidence of decay associated with logging scars for all tree species present in Knife Creek.
7. impact of levels of growing stock on growth, to validate the stocking chart
8. impact of target stand structures on snow interception, thermal and hiding cover
9. impact of target stand structures on rooted forage and litterfall forage
10. links between stand density, tree vigour and Douglas-fir bark beetles
11. inventory methods for uneven-aged stands
12. site quality description for uneven-aged stands
13. the impact of density control on soil moisture
14. cost/benefit analysis of marking vs. faller's selection
15. economic analysis of integrated timber and mule deer management
16. maximum density relationships in different biogeoclimatic conditions

B. DEMONSTRATION AREAS

Following is a list of demonstration projects that will support implementation of this plan. The list is presented in order of priority for establishment.

1. examples of stands cut to differing stand structures and residual basal areas
2. stands which have been marked for cutting
3. demonstration plots for cruising
4. demonstration plots for Continuous Forest Inventory
5. comparison of stands with and without density control

C. EDUCATION PROGRAMS

Following is a list of education programs that are necessary to implement this plan. The list is presented in order of priority for establishment.

1. selection cutting for fallers and skidder operators
2. timber marking
3. stocking, vigour, and stand management
4. prescribing for drybelt-fir spacing
5. clumpy spacing for contractors and for spacers
6. single-tree-selection management for managers
7. training in single-tree-selection management for wildlife biologists
8. mule deer ecology for foresters

SUMMARY

This thesis lays out a working plan for the Knife Creek block of the Alex Fraser Research Forest. It is a complex forest, over which complex management objectives are laid. Silviculture is employed as a means of achieving those complex objectives. The Research Forest is managed for research, education, and demonstration of integrated resource management. The Knife Creek block is 3,419 ha of forested public land, which is zoned as having mule deer as the highest priority for land use. The forest of the Knife Creek block has been severely degraded, in terms of its ability to provide mule deer winter range values, by past diameter-limit cutting.

Douglas-fir is the leading species on the Knife Creek block, and is the primary regeneration species. It grows naturally in uneven-aged stands, in which succession was primarily driven by fire and insect attack. Changes in the natural disturbance regime have allowed succession to proceed to un-natural ends, such that stand structures have changed, and stand densities have increased. These changes probably result in mortality of large trees due to Douglas-fir bark beetles; they certainly increase the potential for stand-replacing fires. Both of these results suggest an increasing risk of losing significant parts of the winter range, and provide ample rationale for active management of the stands at Knife Creek.

Mule deer are dependent upon Douglas-fir forests in the Cariboo Forest Region. These forests provide snow interception and forage as litterfall from large Douglas-fir trees. Douglas-fir foliage is the large majority of the winter diet for deer at Knife Creek. Maintenance of a continuous supply of large old trees is considered to be critical for maintenance of mule deer populations. Single-tree-selection management is a logical method for providing the conditions required by mule deer in the winter on dry winter ranges.

Single-tree-selection management is a method that retains continuous forest cover. It maintains representatives of all age and size classes, from very large to very small trees in each stand. Management of drybelt stands has been gradually moving closer to single-tree-selection management over time, through periods of diameter-limit cutting and faller-selection methods.

Single-tree-selection management for Knife Creek entails forest-level and stand-level regulation to ensure sustainability. Forest-level regulation is aimed at ensuring relatively even and sustainable flows of timber products, and is chiefly driven by the calculation of Allowable Annual Cut. Forest-level regulation is severely hindered by lack of information on growth and yield of drybelt Douglas-fir. In order to establish regulation and reduce losses due to over-stocking, this plan sets AAC on the basis of area control, whereby an equal area is harvested each year. The AAC is set as 170.9 ha based upon a twenty-year cutting cycle. A volume check will be carried out to define the harvest queue (order of harvest) for the first and subsequent periods using the Atlas model. Anticipated yields will be calculated by a stand table projection model, which has been built but remains unvalidated. Validation work and calibration for stands after cutting will be completed outside this thesis.

Stand-level regulation is defined by the BDq method. Several critical features of stand-level regulation are described:

- two distinct target stand structures, dependent upon location in the winter range:
    - Low to Moderate cover -- B=18 m^2/ha, D=60 cm, q=1.25;
    - Moderate to High cover -- B=25 m^2/ha, D=70 cm, q=1.2;
- retention of 10% of the residual basal area in trees larger than the maximum diameter;
- wildlife tree patches comprising 12% of each cutting unit to provide for stand-level diversity, located on critical topographic features such as ridges and grade breaks.

Stocking is controlled according to a Gingrich stocking chart, which has been built for Douglas-fir in Knife Creek. The chart defines a working range for stand density based upon data collected by the author for an earlier paper. Use of the chart facilitates the planning of density control through pre-commercial thinning (in the case of degraded stands) or selection cutting. The stocking chart needs further validation work to verify the upper and lower limits of density.

Stands will be marked for harvest according to the marking guide provided, which discriminates between trees by their ability to provide mule deer habitat, their vigour, and their risk of loss. Logging for this prescription is sufficiently different from standard faller's selection that significant training and supervision of loggers are required. Guidelines are presented which will aid contractors to understand the requirements of logging contracts, and show fallers and skidder operators how to minimize damage during logging operations.

The prescriptions for stand treatment are supported in this plan by methodologies for cruising and stand structure analyses. Cruising will be by fixed-area plots, rather than by point sample. All layers of the stand will be cruised, to provide complete information on stand structure.

A continuous forest inventory program is described which will support the implementation of this plan through adaptive management. CFI plots will also provide a framework for future research projects, and provide a statistical summary of the condition of the forest through time.

This thesis is not framed as an adaptive management problem. None-the-less, continuous monitoring of results and refinements to methods are required to ensure its success. This plan will be successful if mule deer continue to find suitable winter range at Knife Creek, and if the Research Forest derives sufficient revenue to continue stewardship of the forest.

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APPENDICES

APPENDIX 1: FOREST COVER TYPES BY SPECIES AND AGE

APPENDIX 2: FOREST COVER CURRENTLY MOST SUITABLE FOR MULE DEER WINTER RANGE.

APPENDIX 3: HISTORY OF DISTURBANCE BY LOGGING TYPE.

APPENDIX 4: AREAS WHICH HAVE BEEN PRE-COMMERCIALLY THINNED.

APPENDIX 5: FORESTED ECOSYSTEM NETWORK AND COMPARTMENTS FOR THE KNIFE CREEK BLOCK.

APPENDIX 6: DETAILS FOR CRUISING AND INVENTORY.

Table 9: Fixed-area plots for use in cruising and inventory on the Knife Creek block.

Radius (m)	Area (m^2)	Area (ha)	Plot Multiplier
3.99	50	0.005	200
5.64	100	0.01	100
7.98	200	0.02	50
9.77	300	0.03	33.33
11.28	400	0.04	25
12.62	500	0.05	20

Table 10: Canopy layers, diameter classes and class limits for surveys on the Knife Creek block.

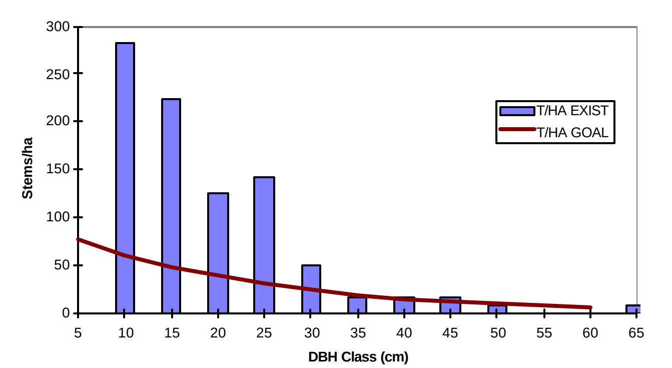
Layer	DBH Class (cm)	Class Limits (cm)
4 (Regeneration)	--	<1.3 m height
3 (Advanced Regen.)	0	0-2.4
3	5	2.5 - 7.4
2	10	7.5 - 12.4
1	15	12.5 - 17.4
⇓	20	17.5 - 22.4
	25	22.5 - 27.4
	30	27.5 - 32.4
	35	32.5 - 37.4
	40	37.5 - 42.4
	45	42.5 - 47.4
	50	47.5 - 52.4

	55	52.5 - 57.4
	60	57.5 - 62.5

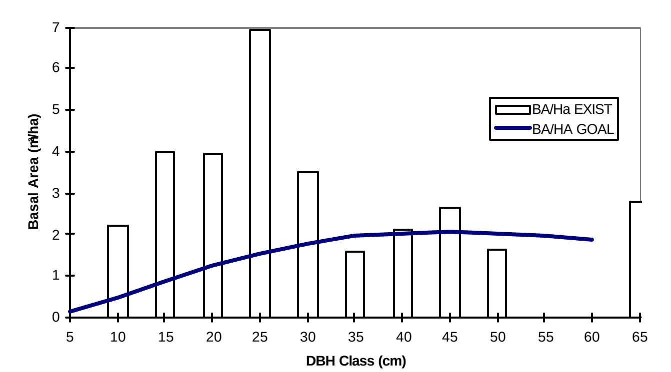
APPENDIX 7: SAMPLE STAND STRUCTURE ASSESSMENT SPREADSHEET.

Silviculture Prescription															
MarkEx Block		Plot Radius	7.98		#plots	6									
		Plot Area Ha	0.02												
LAYER	DIAM	CRUISE			STRUCTURE GOAL		TARGET STAND		SURPLUS		MARKING TO LEAVE				
	CLASS						B =	18							
							D =	60							
							q =	1.25							
	DBH	Tally all Plots	T/HA EXIST	BA/Ha EXIST	T/HA	BA/HA	T/HA GOAL	A/HA GOA	T/HA CUT	BA/HA CUT	Leave/Cut	Leave	Cut	T/HA Marked	BA/HA Marked
3	5				12	0	77	0							
2	10	34	283	2	9	0	62	0	222	2	0.28	1	4	71	1
1	15	27	225	4	7	0	49	1	176	3	0.28	1	4	56	1
1	20	15	125	4	6	0	39	1	85	3	0.46	1	2	62	2
1	25	17	142	7	5	0	32	2	110	5	0.29	1	4	35	2
1	30	6	50	4	4	0	25	2	25	2	1.02	1	1	50	4
1	35	2	17	2	3	0	20	2	-4	0	-5.68		0	17	2
1	40	2	17	2	2	0	16	2	0	0	33.51		0	17	2
1	45	2	17	3	2	0	13	2	4	1	3.48		0	17	3
1	50	1	8	2	2	0	10	2	-2	0	-5.12		0	8	2
1	55		0	0	1	0	8	2	-8	-2	-1.00		0	0	0
1	60		0	0	1	0	7	2	-7	-2	-1.00		0	0	0
1	65	1	8	3					8	3	0.00		0	8	3
	TOTAL		883	29	54	3	359	18	609	14				342	20

Stand Table And Target Stand Structure



Stock Table And Target Stand Structure



APPENDIX 8: RADIAL GROWTH REGRESSION RESULTS, ALL STANDS KNIFE CREEK.

Data used in this analysis were collected by the author, and methods are described in an earlier report (Day 1997b). Four separate stands were sampled, measuring 10-year radial growth from 794 trees on 39 plots. None of the stands sampled had been disturbed in the previous 20 years.

The objective of this analysis was to determine a function to estimate radial growth from parameters which could be easily measured or estimated for any given stand. Regression analyses were performed using Microsoft Excel 5.0. Although the R^2 value for the regression is relatively low (R^2 = 0.299), each term of the regression is significant, as shown in Table 11.

Table 11: Coefficients for the multiple regression of radial growth for Knife Creek.

Term	**Co-efficient**	**Description**	**Significance**
Int.	1.231	Y-axis intercept	$p<0.01$
X1	-0.025	Basal Area Above -- represents the competitive position of the tree	$p<0.01$
X2	-1.44×10^{-6}	DBH^4 -- the fourth term in a polynomial function	$p<0.05$
X3	1.81×10^{-4}	DBH^3 -- the third term in a polynomial function	$p<0.05$
X4	-7.31×10^{-3}	DBH^2 -- the second term in a polynomial function	$p<0.05$
X5	0.102	DBH -- the first term in a polynomial function	$p<0.10$
X6	-8.13×10^{-3}	Basal Area -- the total basal area of the plot	$p<0.01$

The regression only explains 30% of the variation in the data. There are two reasons for the unexplained variability, as represented by a high residual sum of squares:

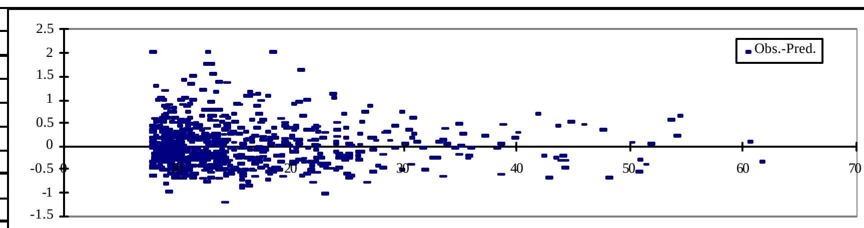
- first, diameter growth is highly responsive to density, and stand density outside the measured plots probably affects the diameter growth of trees within the plots;
- second, there are four different blocks combined in the data, introducing some unquantified site effects.

Data were combined for all four blocks, to provide one model for all site types and stand structures. One single equation is therefore required. The regression results are shown in Table 12. The predicted values are compared to the measured radial increment graphically in Figure 10 and Figure 11. When the blocks are grouped according to stand structure (two undisturbed blocks apart from two diameter-limit cut blocks), R^2 values are reduced. That is to say, the regression equation is a better fit for all blocks combined than it is for each stand structure condition sampled.

One troubling result is the few predicted values that are lower than any actual values. These results are on relatively small trees on undisturbed blocks, and describe trees on plots of very high basal area. It is suspected that the extremely low estimates of growth are an artifact of combining all blocks in one equation. This result is a cause for caution in the application of the results.

Table 12: Summary output from MS Excel, showing results of multiple regression for radial increment (R^2 = 0.299, n = 789).

SUMMARY OUTPUT	
Regression Statistics	
Multiple R	0.546687697
R Square	0.298867438
Adjusted R Square	0.293487904
Standard Error	0.468032795
Observations	789



ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	6	73.01932037	12.16988673	55.55638335	3.55351E-57
Residual	782	171.3007732	0.219054697		
Total	788	244.3200935			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.000%*	*Upper 95.000%*
Intercept	1.230773581	0.297551987	4.136331249	3.91129E-05	0.646678037	1.814869126	0.646678037	1.814869126
X Variable 1	-0.02532177	0.003118965	-8.118644371	1.82876E-15	-0.031444309	-0.01919923	-0.031444309	-0.01919923
X Variable 2	-1.4366E-06	6.48565E-07	-2.215050077	0.027044086	-2.70974E-06	-1.63469E-07	-2.70974E-06	-1.63469E-07
X Variable 3	0.000181067	7.96303E-05	2.273838572	0.023245938	2.47519E-05	0.000337381	2.47519E-05	0.000337381
X Variable 4	-0.007314913	0.003313247	-2.207777891	0.027549325	-0.013818827	-0.000810998	-0.013818827	-0.000810998
X Variable 5	0.101905921	0.054348498	1.87504575	0.061158889	-0.004780363	0.208592205	-0.004780363	0.208592205
X Variable 6	-0.008133769	0.002987249	-2.722829563	0.00661675	-0.013997749	-0.00226979	-0.013997749	-0.00226979

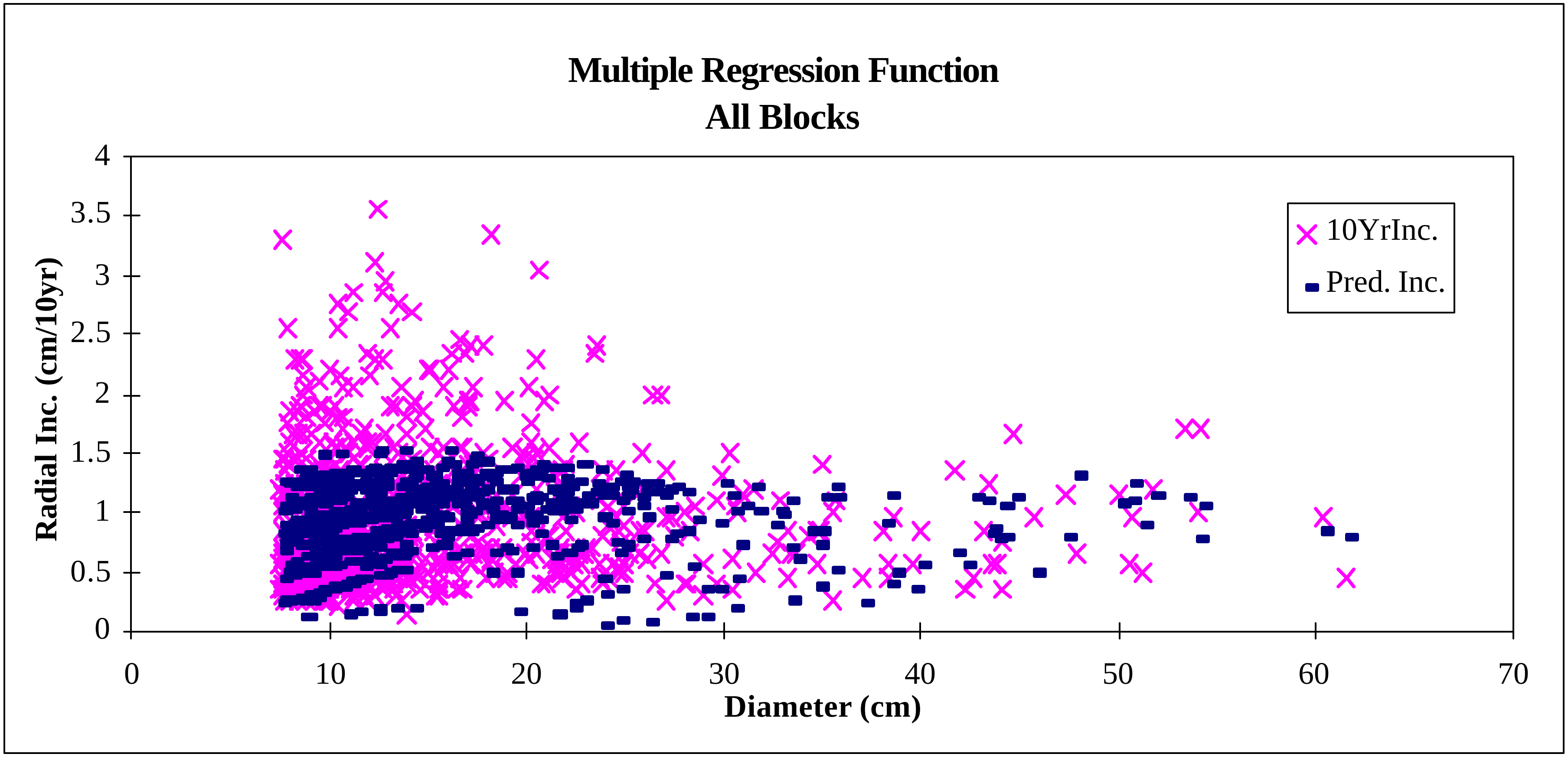


Figure 10: Multiple regression of radial increment; results for all blocks comparing predicted to measured values from Knife Creek.

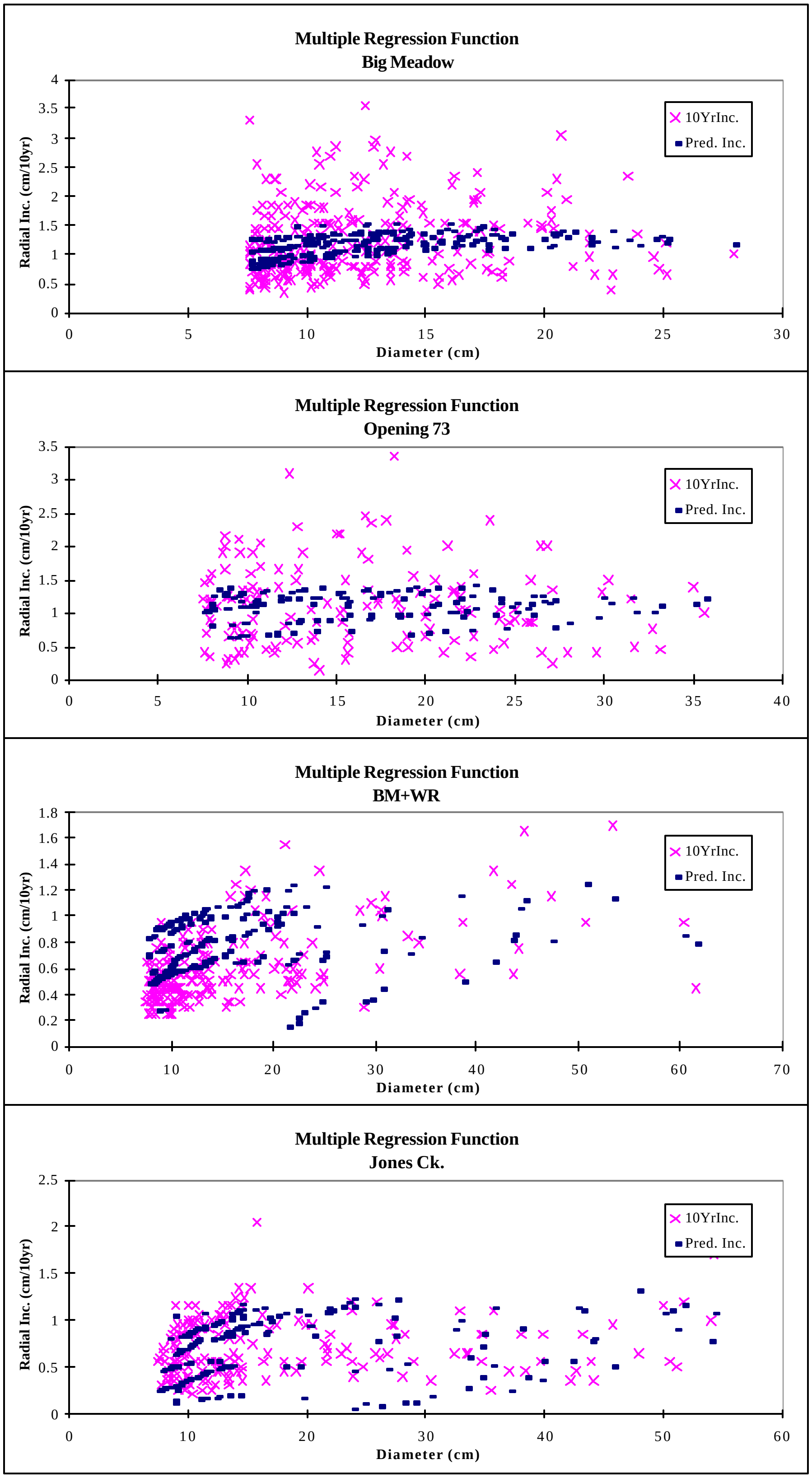
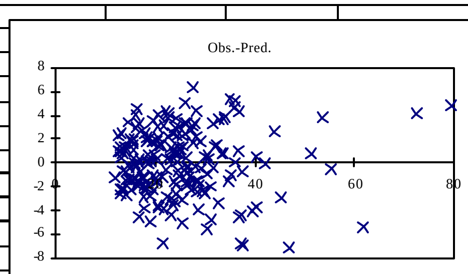


Figure 11: Multiple regression of radial increment; results comparing predicted to measured growth for each block from Knife Creek.

APPENDIX 9: LOCAL VOLUME TABLE, KNIFE CREEK.

Regression analyses from Microsoft Excel 5.0 examined the relationship between height and diameter for 195 Douglas-fir trees on three blocks in Knife Creek. Results of the analyses are shown below (Table 13). The resulting function is depicted in Figure 12, and employed in the development of the local volume table shown in Table 14.

Table 13: Summary output from MS Excel, showing results of linear regression for tree height (R^2 = 0.706, n= 195).



SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.840797156							
R Square	0.706939857							
Adjusted R Square	0.70542141							
Standard Error	2.71916113							
Observations	195							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	3442.333205	3442.333205	465.5678895	2.47923E-53			
Residual	193	1427.01059	7.393837253					
Total	194	4869.343795						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.000%*	*Upper 95.000%*
Intercept	-18.02505113	1.722096553	-10.46692248	1.36083E-20	-21.42159418	-14.62850807	-21.42159418	-14.62850807
X Variable 1	11.74649027	0.544398116	21.57702226	2.47923E-53	10.67275742	12.82022312	10.67275742	12.82022312

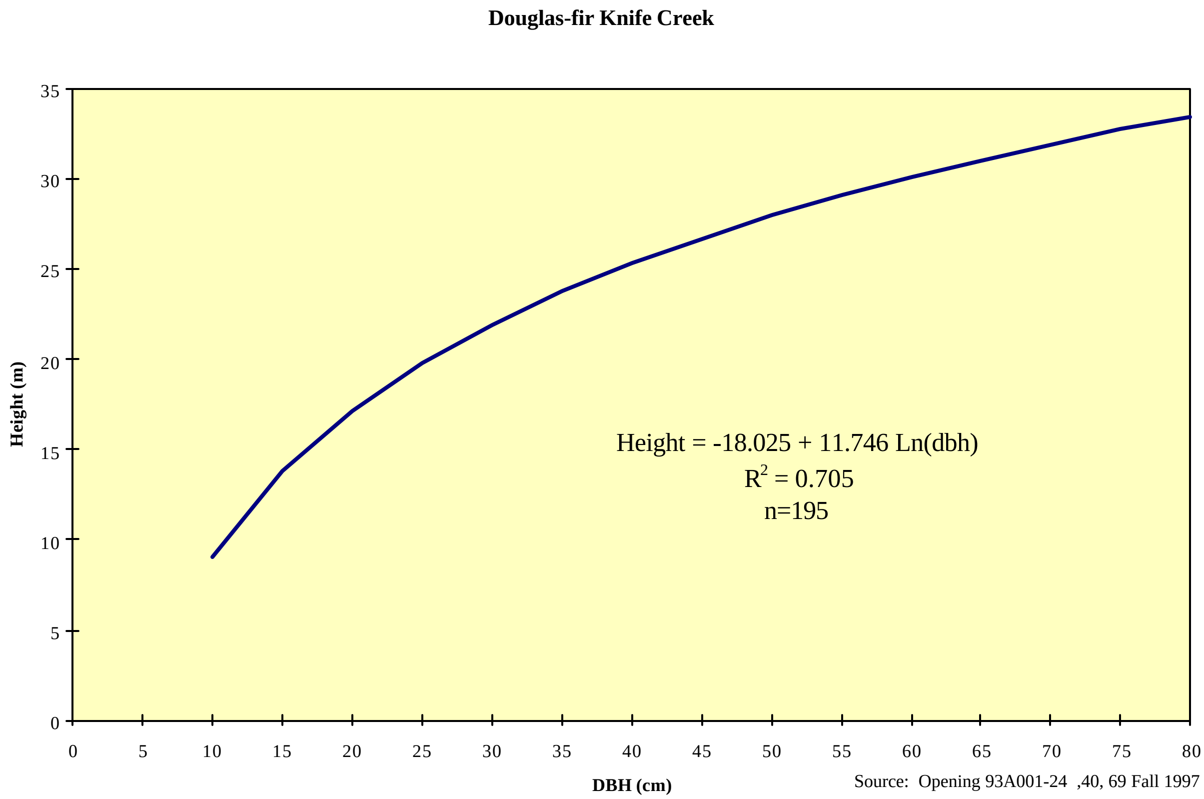


Figure 12: Local height curve for Douglas-fir at Knife Creek.

Table 14: Local volume table for Douglas-fir at Knife Creek.

DBH (cm)	Height (m)	Total Volume (m^3)[25]	Notes
0			
5			
10	9.02	0.03	
15	13.79	0.10	
20	17.16	0.21	
25	19.79	0.36	
30	21.93	0.55	
35	23.74	0.79	
40	25.31	1.08	
45	26.69	1.41	
50	27.93	1.78	
55	29.05	2.20	
60	30.07	2.66	
65	31.01	3.17	
70	31.88	3.73	
75	32.69	4.33	
80	33.45	4.97	
85	34.16	5.66	Extrapolation
90	34.83	6.40	Beyond
95	35.47	7.18	Height
100	36.07	8.01	Data

[25] Volume equation from "Whole Stem Cubic Metre Volume Equations, 1976" as reproduced in Watts (1983). Douglas-fir (All Ages) Forest Inventory Zone D to I inclusive [Knife Creek is in FIZ G].
Log Volume = -4.383102 + 1.742940 log DBH + 1.156410 log Height

APPENDIX 10: KNIFE -- STAND TABLE PROJECTION MODEL FOR KNIFE CREEK

Knife Creek Block

Stand Table Projection Model

Uneven-aged Douglas-fir

Period (yrs) =	20	(Must Be <= 40)
Min. DBH =	10	
DBH Class Width =	5	
Max. DBH =	65	

Diam. Growth Coefficients	Intercept	1.23077
BA Above	x1	-0.02532
DBH^4	x2	0.00000
DBH^3	x3	1.81E-04
DBH^2	x4	-7.31E-03
DBH	x5	1.02E-01
Plot BA	x6	-8.13E-03

				Present					Trees Moving DBH Classes				Future				
DBH Class (cm)	Total Vol. (m^3/tree)	Periodic DBH Increment (cm)	Movement Ratio	Number (stems/ha)	Basal Area (m^2/ha)	BA Above (m2/ha)	Total Volume (m^3/ha)	Expected Mortality (stems/ha)	0 Classes	1 Class	2 Classes	3 Classes	Number (stems/ha)	Basal Area (m^2/ha)	Total Volume (m^3/ha)	Periodic Volume Growth (m^3/ha)	Periodic Annual Inc. (m^3/ha/yr)
10	0.03	1.84	0.37	99	0.78	36.60	3	31	43	25	0	0	99	0.78	3	0.00	0.00
15	0.10	1.79	0.36	83	1.46	35.82	8	21	39	22	0	0	64	1.14	6	-1.75	-0.09
20	0.21	1.58	0.32	69	2.16	34.36	14	14	37	17	0	0	59	1.87	12	-1.92	-0.10
25	0.36	1.45	0.29	57	2.81	32.20	20	9	34	14	0	0	51	2.52	18	-2.13	-0.11
30	0.55	1.55	0.31	48	3.38	29.38	26	6	29	13	0	0	43	3.01	24	-2.83	-0.14
35	0.79	1.95	0.39	40	3.83	26.01	32	4	22	14	0	0	35	3.35	28	-3.94	-0.20
40	1.08	2.62	0.52	33	4.17	22.18	36	2	15	16	0	0	29	3.60	31	-4.85	-0.24
45	1.41	3.44	0.69	28	4.40	18.01	39	1	8	18	0	0	24	3.86	34	-4.72	-0.24
50	1.78	4.20	0.84	23	4.52	13.61	41	1	4	19	0	0	22	4.23	38	-2.69	-0.13
55	2.20	4.64	0.93	19	4.56	9.09	42	0	1	17	0	0	20	4.76	44	1.85	0.09
60	2.66	4.36	0.87	16	4.52	4.52	43	0	2	14	0	0	19	5.50	52	9.15	0.46
65	3.17	2.93	0.59		0.00	0.00	0	0	0	0	0	0	14	4.59	44	43.88	2.19
				514	36.60		303.74	91					480	39.21	333.78	30.04	1.50