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ALTERNATIVE SILVICULTURAL AND HARVESTING SYSTEMS FOR SECOND-GROWTH FORESTS IN BRITISH COLUMBIA

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INTRODUCTION

Management of over 95% of forest land in coastal British Columbia (BC) is based on clearcutting (Sauder, 1988). The essentially exclusive use of this method has come under intense media, social, political, and professional scrutiny resulting in an ever increasing demand to employ alternative forest management practices based on partial cutting. Limited information about the application of alternative silvicultural systems in BC is available, and only recently have field trials of alternative methods been initiated. A major issue yet to be addressed is the design of commercially viable and environmentally acceptable harvesting systems required in the application of alternative silvicultural systems.

BC's Ministry of Forests, Economics and Trade Branch have initiated a project to develop a better understanding of alternative silvicultural systems, silvicultural treatments, and harvesting systems, and their application in second-growth coastal forests. The Ministry of Forests has contracted members of the Forest Operations Group in the Faculty of Forestry at the University of BC to investigate potential alternative silvicultural systems in second-growth coastal forests. The focus of the study is on integrating the choice of silvicultural systems and development of stand-level prescriptions with the design and operation of timber harvesting systems. The objectives of the project are to:

1. Identify alternative silvicultural systems applicable in the second-growth coastal forests of BC.

2. Specify forest harvesting systems required for implementation of individual treatments within the alternative silvicultural systems.

3. Establish field trials for three of the most promising harvesting systems.

4. Determine the production and costs associated with these harvesting systems.

The project is divided into two phases. In phase I, a review was completed of the literature on silvicultural and harvesting systems in coastal areas of the Pacific North West of North America. The goal was to identify the most promising combinations of silvicultural and timber harvesting systems for the second-growth coastal forests of BC. Phase I also included the identification of potential sites, sponsors, and equipment for field trials by surveying the forest industry and the BC Ministry of Forests. Phase II involves field trials of the silvicultural and harvesting systems identified in phase I.

The findings of phase I are presented in this report which is as organized as follows. First, a brief background section is presented to define various concepts and terminology used throughout the report. Second, alternative silvicultural systems that do not require clearcut harvesting are discussed including citation of the relevant literature, and the potential application of those systems in second-growth coastal forests of BC. Silvicultural treatments required to implement each system, are also described for the two biogeoclimatic zones considered in the study. Third, factors that influence the choice of harvesting systems for each type of cutting within a given alternative silvicultural system are discussed, and published trials of such systems are summarized. The report concludes with recommendations regarding appropriate technology for similar operations in BC including examples of equipment generally available on the coast suitable for consideration which are contained in Appendix A. Appendix B shows common rigging methods for skyline yarding systems.

BACKGROUND

This brief section is presented to serve as background to the report. To begin, second-growth forests are defined to provide context for the remainder of the discussion. Next, a general review of the silvics of the important tree species found within the two biogeoclimatic zones where second-growth coastal forest are concentrated is presented. Finally, definitions for important terms used in the report are offered to promote consistent interpretation by readers.

This study defines forests as second-growth if they are less than 150 years old. About 12% of the annual coastal harvest in BC is from second-growth forests, and within about 10 years harvests from these forests are expected to exceed 45% (Sauder, 1988). Second-growth forests originate from natural or man-made disturbances which result in essentially complete removal or destruction of the original stand. Two factors in particular are responsible for the creation of the bulk of existing, mature second-growth forests in BC. First, Europeans settlers in the 1840's inhabited the southern coast of BC, clearing or accidentally burning large tracts of forest. Second, in 1865 the government began issuing forest licenses and, like today, clearcutting was the preferred method of timber harvesting.

Most of the older second-growth forests are located in the CDF (Coastal Douglas-fir) and the CWH (Coastal Western Hemlock) biogeoclimatic zones in three areas:

1) Southeastern, and central Vancouver Island, where settlement and logging were largely responsible for cutting of the original forest: CDF biogeoclimatic zone, and dry, maritime subzones (CWHxm and CWHmm) of the CWH biogeoclimatic zone.

2) South of 51°N latitude on the mainland, where logging, uncontrolled fires and wind storms caused the cutting of much of the original forests: CDF biogeoclimatic zone, and dry, maritime subzones of the CWH biogeoclimatic zone.

3) Northern Vancouver Island, where a windstorm in 1906 blew down most of the original forests: medium to wet hyper maritime subzones (CWHmm and CWHwm) in the CWH biogeoclimatic zone.

Silvics of Important Species

The majority of the mature second-growth forests in the Coastal Douglas-fir (CDF) zone originate from logging at the turn of the century (Nuszdorfer et al., 1991). The Douglas-fir Zone has warm, dry summers and mild, wet winters, and is limited to southeastern Vancouver Island, several islands in the Gulf of Georgia, and a narrow strip of the adjacent mainland (see Figure 1). The CDF zone is approximately 8,500 km^2 in area. Williamson and Twombly (1983) stated that the Coastal Douglas-fir zone is one of the world's most productive forest types.

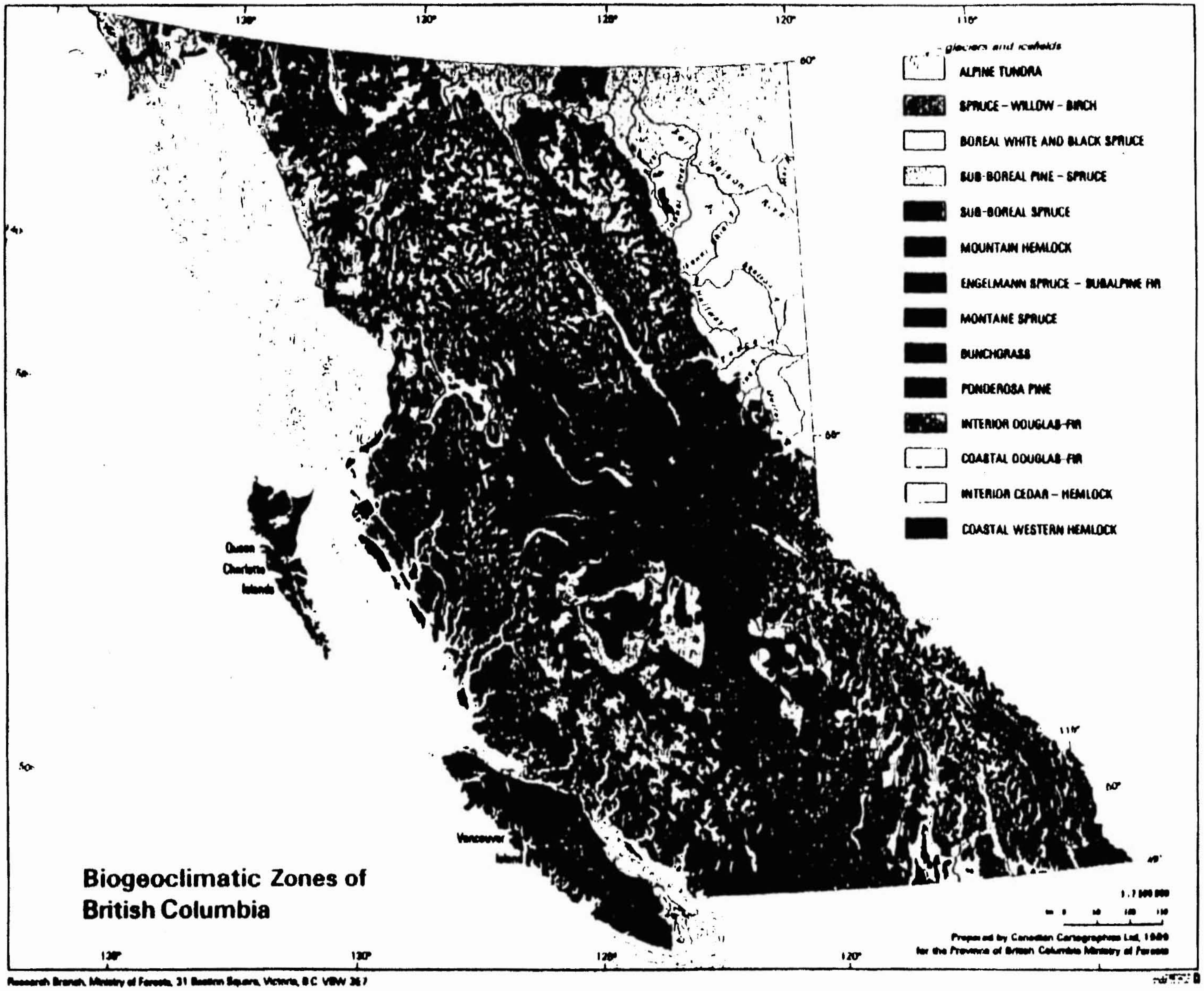

Figure 1. Biogeoclimatic zones of British Columbia (Meidinger and Pojar 1991).

The coastal variety of Douglas-fir (*Pseudotsuga menziesii var menziesii*) is the most common species in the CDF zone. Western redcedar (*Thuya plicata*), grand fir (*Abies grandis*), Arbutus (*Arbutus menziesii*), Garry oak (*Quercus garryana*) and red alder (*Alnus rubra*) occur on most sites with Douglas-fir. Western hemlock (*Tsuga heterophylla*), bigleaf maple (*Acer marcophyllum*) and Sitka spruce (*Picea sitchensis*) are less common, occurring principally on wetter sites (Nuszdorfer et al, 1991). Douglas-fir is moderately shade tolerant, and less tolerant of shade than most of its associates, except for Sitka Spruce, bigleaf maple, and red alder (Hermann and Lavender, 1990). Coastal Douglas-fir is most shade tolerant in the seedling stage and can regenerate under both closed and partially open stands (Nuszdorfer et al, 1991). Douglas-fir responds favorably to overstory removal, provided it has not been suppressed (Hermann and Lavender, 1990). Western redcedar is very tolerant of shade, and responds well to removal of the overstory (Minore, 1990).

The stand structure of these forests is usually an even-aged continuous canopy dominated by Douglas-fir, with a component of alder, grand fir, redcedar, and western hemlock. The understory in drier areas is dominated by Douglas-fir seedlings, with some redcedar. In wetter areas the understory is usually dominated by redcedar and western hemlock. On wet sites Douglas-fir and alder regenerate in small gaps in the canopy resulting from the death of trees (Nuszdorfer et al., 1991).

The Coastal Western Hemlock (CWH) zone occurs from sea level to 900 m elevation, and covers much of Vancouver Island, the Queen Charlotte Islands, and the Coast Mountains (See Figure 1). The CWH is, on average, the wettest biogeoclimatic zone in BC, with cool summers (although hot dry spells are frequent), and mild, wet winters. The CWH zone is approximately 45,000 km^2 in area. Western hemlock is the most common tree species. Western redcedar occurs throughout the range south of 56°N latitude, and Douglas-fir is common on drier zones south of 53°N latitude. Bigleaf maple, western white pine (*Pinus monticola*), and grand fir are less common associates on drier sites. Red alder occurs on all disturbed sites. Sitka spruce (*Picea sitchensis*) is found occasionally on southern, low elevation, wet sites. Amabilis fir (Abies amabilis) is the most common associate in wet, upper elevations (Pojar et al., 1991). Western hemlock and amabilis fir are very shade tolerant, and respond well to release provided they were not subject to long periods of suppression (Crawford and Oliver, 1990; Packee, 1990).

Second-growth stand structure in the CWH is an even-aged continuous canopy of western hemlock, amabilis fir, redcedar, Douglas-fir, and Sitka spruce. The stands are not old enough to have developed multiple age classes, but most of the species are shade tolerant, and an uneven-aged stand structure will ultimately evolve if left untreated. The shade tolerant species can regenerate and grow into any position in the canopy after initial crown closure. There may be sufficient quantities of these trees to have a multi-storied, uneven-aged forest, but at early stages of development it is unusual. In a few cases, residual trees remain after a significant disturbance. Their death allows advanced regeneration of shade tolerant trees to be released which results in pockets of uneven-aged stands. In drier zones of the CWH, the forest canopy is dominated by Douglas-fir, western hemlock and redcedar. The understory contains western hemlock and redcedar only, unless an opening in the canopy has permitted the establishment of less tolerant species (Pojar et al., 1991).

The canopy of the low elevation wet zones of the CWH is dominated by western hemlock, redcedar, and in alluvial areas Sitka spruce may be present . The understory usually contains all three species. In wetter zones (and with increasing elevation) the forest canopy is dominated by western hemlock and amabilis fir, with decreasing quantities of redcedar and Sitka spruce (Pojar et al, 1991). The understory is dominated by western hemlock and amabilis fir. Hemlock seedlings on all zones often regenerate so densely (up to 10,000's stems per hectare) that no other tree species can compete resulting in almost pure stands of hemlock.

Definitions for Important Terminology

A **silvicultural system** is a planned program of silvicultural treatments during the life of a stand. It includes not only the harvest and regeneration, but also any tending operations or intermediate cuttings (Smith, 1986). Silviculture uses the *silvics* of the individual species to develop harvesting, regeneration, and tending methods to manage the forest. Silvics are the principles underlying the growth and development of single trees and of the forest as a whole (Smith, 1986). Silvicultural systems are named and classified according to the harvesting method used to remove the mature crop (BC Ministry of Forests, 1991). Silvicultural systems can be divided into two major groups: even-age, and uneven-age. The distinction between the two systems is based on the age class distribution within the forest stands. Even-aged forests typically are maintained by clearcutting, shelterwood, and seed tree silvicultural systems. Uneven-aged stands are maintained by selection silvicultural systems of which there are numerous variations (BC Ministry of Forests, 1991).

A **silvicultural prescription** is a schedule of silvicultural treatments required in the application of a chosen silvicultural system to a specific forest, stand, or management area.

A **silvicultural treatment** is an individual entry into a forest stand which involves killing and perhaps removal of growing stock, or some other activity such as planting, pruning, or fertilizing. Silvicultural treatments are the individual steps in the application of a silviculture system. Commercial cuttings are silvicultural treatments.

A **harvesting system** is a combination of equipment, labor, and operational procedures required to implement a specific silvicultural treatment which involves removal of growing stock. With the exception of some sanitation cuttings, timber harvesting operations are supposedly commercial, that is, they generated positive net cash flows.

ALTERNATIVE SILVICULTURAL SYSTEMS

Silvicultural systems are explained thoroughly in numerous textbooks (for example see, Smith 1986, or Daniel et al. 1979). There are four recent literature reviews of silvicultural systems with potential use in BC. Nelson et al. (1990) focused on alternative silvicultural systems with possible application in coastal old-growth stands. Weetman et al. (1990) did the same for the north central biogeoclimatic zones. Sanders and Wilford (1986) concentrated on alternatives for the management of unstable sites in the Queen Charlotte Islands. Standish (1989) focused on alternative silvicultural systems for use in streamside management zones and steep slopes on the coast. There is also a recently published computer-based annotated bibliography of partial-cutting methods in the Pacific Northwest (Daigle and Comeau, 1992). Finally, a recent review of the Silvicultural Systems Program of the BC Ministry of Forests (Smith, 1993) explores many of the issues concerning application of alternative silvicultural methods in the forests of British Columbia. None of these works have directed attention towards exploring alternative systems for second-growth coastal forests. In BC, nothing has been published on the design of harvesting systems needed to implement alternative silvicultural systems in second-growth coastal forests.

The following discussion of alternative silvicultural systems concentrates on systems with potential application in second-growth stands in coastal BC. Literature on field trials of alternative systems in forests with conditions similar to those found in coastal BC is cited when appropriate. The observations made are general in nature and are not meant to substitute for the stand- and site-specific judgments of foresters required in the development of prescriptions. The discussion concludes with a summary of the factors specific to biogeoclimatic zones, silvicultural systems, and treatments which affect the choice and employment of harvesting systems.

Thinnings are not included in the discussion of alternative silvicultural systems which follows. The literature on both pre-commercial and commercial thinning trials in the Pacific Northwest is voluminous and can be accessed through the textbooks cited above and the annotated bibliography of Daigle and Comeau (1992). The vast majority of published thinning trials are for early tending of even-aged stands destined for clearcutting. Consequently they do not represent treatments applied in alternative systems as defined here. While thinnings may be prescribed for stands managed using alternative silvicultural systems, their purpose and, therefore, design differ substantially from those used with clearcut management. The review of appropriate harvesting technology for implementing alternative silvicultural systems at the end of this report includes references to equipment trials in thinnings. Many of the operational conditions faced in commercial thinnings of any kind are shared by other partial cutting treatments, consequently, much can be learned by considering the findings from these trials of harvesting systems.

Definition: Alternative Silvicultural Systems

Silvicultural systems are usually named after the cutting method used to regenerate the stand. The *clearcutting method* involves the removal of the entire stand in one harvest with reproduction obtained artificially or by natural seeding (Smith, 1986). Alternatives to the *clearcutting method* involve leaving a portion of the forest stand intact at all times by employing "partial cuts". There are both even-age and uneven-age silvicultural systems which employ partial cuts and, in fact, partial cutting (thinnings) may be applied in treatments prior to the regeneration cut in the clearcutting method. The *shelterwood* and *seed-tree* silvicultural systems involve even-age management and employ partial cutting throughout the prescriptions. All uneven-age management systems use partial cutting exclusively. The choice between even- or uneven-age management for a given stand is based on management objectives and the reproductive and growth requirements of trees which vary by biogeoclimatic zone. These factors are summarized by Fowells and Means (1990).

EVEN-AGE MANAGEMENT

The forest stand structure of even-age management is relatively simple because the difference in age between the oldest and youngest trees does not exceed 20 percent of the rotation length (Smith, 1986). There are two even-age alternative silvicultural systems which employ partial cutting: the *shelterwood* and *seed tree* methods. Both have potential application in the second-growth forests of coastal BC.

Shelterwood

The shelterwood system involves gradual removal of the entire stand in a series of partial cuttings that extend over a fraction of the rotation (BC. Ministry of Forests, 1991; Smith, 1986). The shelterwood system provides constant cover to the regenerating forest under a partial canopy, which is subsequently harvested (Burns, 1983). The ultimate removal of the overstory permits the new stand to develop in the open as an even-aged stand. The shelterwood system is best implemented where the desired species are capable of regenerating under the "shelter" of overstory trees. Shelterwood harvests provide a micro-environment suitable for seedlings of intermediate shade tolerance by discouraging competition from undesirable shade intolerant species (Burns, 1983; Starker, 1970).

Regeneration cuttings in the shelterwood system can be arranged in time and space in various ways that can be categorized as follows: **uniform, strip, or group shelterwood** (Smith, 1986). The uniform method applies cutting over the entire forest. With strip shelterwood the forest is stratified into strips which become separate treatment areas.

Strips are cut sequentially in time so that cutting advances strip by strip across the forest. In group shelterwood cuttings are concentrated in patches which resemble small clearcuts.

The shelterwood method involves application of a series of partial cuts of three types (Smith, 1986). Occasionally it is necessary to prescribe a **preparatory cut** to promote the development of vigorous seed-bearing trees, encourage the decomposition of unfavorable humus and promote wind firm trees (Smith, 1986; BC. Ministry of Forests. 1991). These cuttings remove undesirable species and malformed or diseased trees and, consequently are often economically marginal (Figure 2A). If stands are relatively young, these objectives can be achieved during pre-commercial and commercial thinnings. The second type of cut is called the **regeneration cut** in which trees are harvested in order to open up the forest floor to light and encourage regeneration of the desired species (Figure 2B). Residual trees provide seed for regeneration, shelter for seedlings, and grow in size for the final harvest. This cut should be planned to coincide with good seed crops of desired species. The third type of cutting is called the **removal cut**. In this entry the mature trees remaining after the regeneration cut are harvested to release the advance growth established after the previous cut. This may be done in one or more treatments (Figure 2). The shelterwood silvicultural system has applications in both the CDF and CWH biogeoclimatic zones.

CDF Biogeoclimatic Zone

The shelterwood system of management has application on the drier sites in the CDF zone where Douglas-fir is the species of choice. Douglas-fir is more shade tolerant on such sites and the competition is less from moisture demanding species like red alder, hemlock, and red cedar.

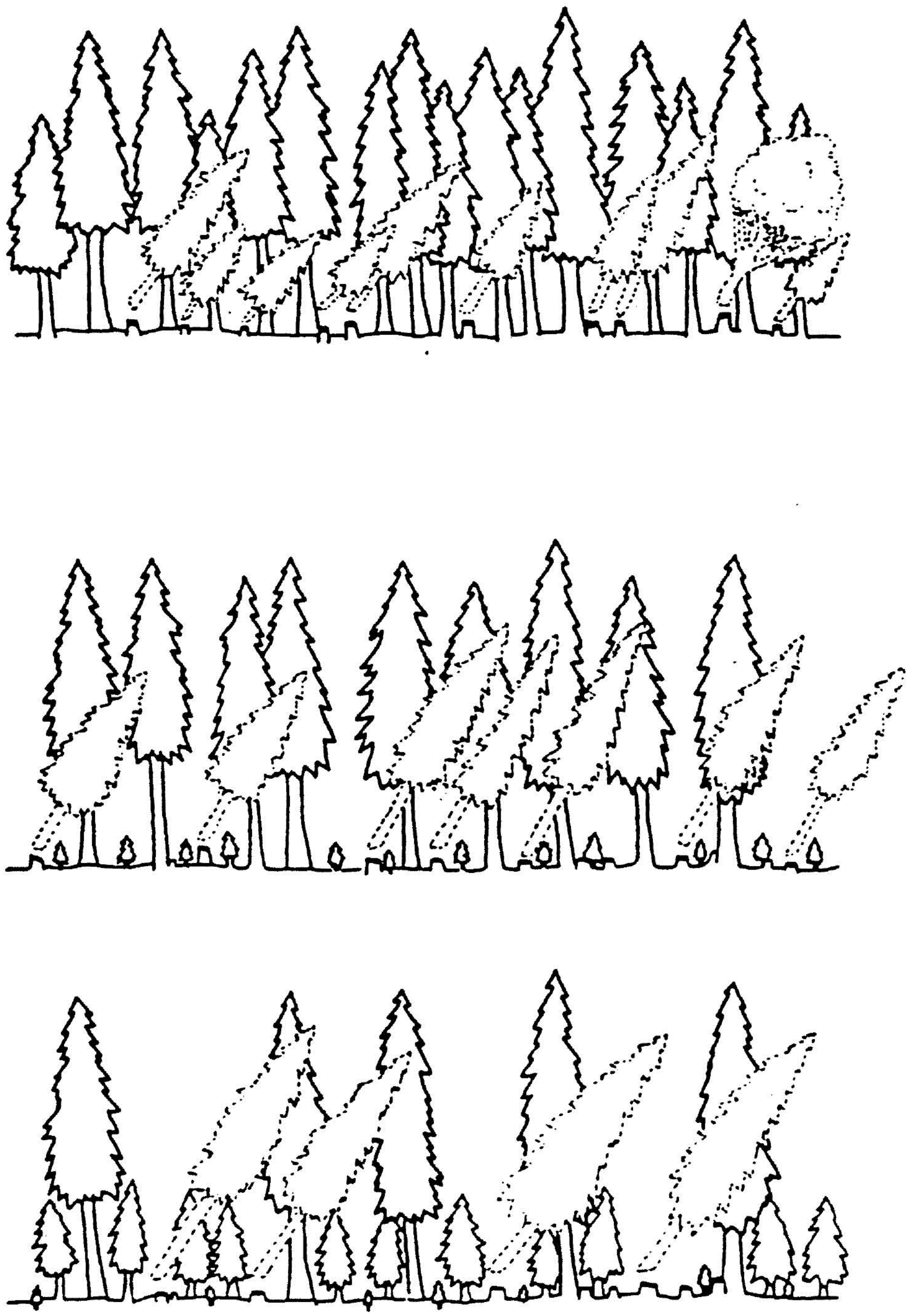

Figure 2. Shelterwood System (BC Ministry of Forests, 1991).

Shelterwood has limited application on wetter sites in the CDF zone, although may be used effectively to reduce competition from red alder. Red alder has very rapid juvenile growth rates, and can easily overtop and suppress Douglas-fir seedlings (Hermann and Lavender, 1990) in large openings. Red alder is shade intolerant and, consequently, competes poorly under a closed canopy. Shelterwood management allows the more shade tolerant Douglas-fir to regenerate and compete against alder. The presence of some alder is beneficial to Douglas-fir because of its nitrogen fixing capabilities (Hermann and Lavender, 1990). Lack of nitrogen in Douglas-fir forests has been shown to be the greatest limitation to growth (Miller et al., 1986).

Where shelterwood management is appropriate in the CDF zone, preparatory cuts should remove most of the undesired species, and all the malformed and diseased trees. However, vigorous, well developed dominant or co-dominant redcedar or western hemlock trees may be left to ensure a diversity of species and timber products. According to Kellogg et al. (1991), Seidel (1983), and Williamson (1973), the regeneration cut should remove 60% to 70% of the mature trees to ensure adequate regeneration of Douglas-fir. Douglas-fir's tolerance to shade in the seedling stage enables it to establish in the understory after the regeneration cut (Hermann and Lavender, 1990; Seidel, 1983; Smith, 1986; Starker, 1970; Williamson and Twombly, 1983). Douglas-fir seedlings regenerate best in exposed mineral soil, which sometimes necessitates additional ground disturbance (site preparation) apart from what results from logging (Minore et al., 1977). Alternatively, artificial regeneration may be used (Hermann and Lavender, 1990; Hobbs and Owston, 1985; Minore et al., 1977; Williamson, 1973). The mature Douglas-fir left in the overstory as a source of seed generally responds well to the increased growing space (Williamson, 1973).

The final cut must be delayed until the Douglas-fir seedlings are 60-100 cm tall, at which point they are less susceptible to damage from logging during the removal cut (Tesch, 1985). Logically, the greatest damage to advance growth occurs on skid roads or yarding corridors where essentially 100% mortality can be expected (Minore et al., 1977; Tesch, 1985; and Tesch et al., 1986).

The major disadvantage to the shelterwood system is the potential for windthrow after the preparatory and seed cuts (Hermann and Lavender, 1990; Seidel, 1983; Williamson and Twombly, 1983; Williamson, 1973). Regeneration mortality and loss of productivity may occur if the initial harvests are not planned and executed carefully (Tesch, 1985; Tesch et al., 1986). As with all partial cutting, shelterwood management in Douglas-fir is more costly than clearcutting because of increased planning and administrative costs and higher logging costs (Mann, 1985).

CWH Biogeoclimatic Zone

In the drier subzones of the CWH zone shelterwood management could also be used. In this case a more mixed stand would result comprised of hemlock, Douglas-fir, and redcedar. The shade tolerance of hemlock and redcedar make them ideal species for regenerating under a partial canopy (Harris and Johnson, 1983; Minore, 1990; Packee, 1990). In fact, Williamson and Ruth (1976) report that too many western hemlock seedlings (over 30,000 stems/hectare) regenerated after shelterwood treatments, almost completely dominating the understory. Hemlock can regenerate in mineral soil or in the humus layer, which gives it a tremendous advantage over its competitors (Harris and Johnson, 1983). Hemlock seedlings respond to almost any opening in the canopy and generally as the intensity of cutting increases (bigger openings) the quantity and vigor of hemlock seedlings increases (Franklin et al., 1983; Harris and Johnson, 1983; Williamson and Ruth, 1976). Hemlock is capable of prolific seed crops on a regular basis, and increased light penetration to the forest floor causing even the slightest increase in soil temperature will trigger the germination of hemlock seed (Packee, 1990, and Williamson and Ruth, 1976).

Establishing redcedar and Douglas-fir on drier CWH sites requires some treatment designed to reduce the competition from the more vigorous hemlock. Redcedar is tolerant of shade, but not to the extent as hemlock, and redcedar has considerably slower growth rates, especially at the seedling stage (Minore, 1990). Redcedar germinates best in mineral soil, and will thrive well in cooler micro-climates under a relatively closed canopy. With increasing overstory removal, redcedar is less able to compete with hemlock seedlings. If redcedar is already established in the understory, it will respond favorably to overstory removal, especially if the advance growth is thinned at the same time as overstory removal. The preparatory and regeneration cuts should provide some site disturbance and the use of conservative regeneration cuts will intensify potential redcedar regeneration in drier CWH zones. Shelterwood treatments designed to favor Douglas-fir should be essentially the same as the CDF zone, except that some precommerical thinning may be required to eliminate hemlock and cedar competition after the removal cut to ensure adequate stocking of Douglas-fir seedlings. The regeneration cut should remove at least 60%-75% of the canopy, because Douglas-fir is less shade tolerant than hemlock and redcedar.

For the wetter subzones of the CWH zone, hemlock, amabilis fir, and Sitka spruce could be managed using shelterwood. Hemlock and amabilis fir are two of the most shade tolerant species in coastal BC (Crawford and Oliver, 1990; Packee, 1990). Opening the canopy would stimulate the growth of both species, however, heavier removal of the overstory would favor hemlock (Crawford and Oliver, 1990; Williamson and Ruth, 1976). Both species are capable of germinating in a variety of seedbeds. Hemlock has better seed crops than amabilis fir, so regeneration cuts should be planned around crop years for amabilis fir to promote balanced species composition.

Packee (1990) showed that the hemlock seedlings respond best to overstory removal before they have reached a height of 1 m. The final harvest can be scheduled when the majority of the seedlings reach this height.

Sitka spruce is not wide spread in the CWH zone and is restricted to alluvial soils near creeks, streams or rivers, and close to the sea where moist maritime air and fog provide moisture during the summer growing season (Harris, 1990). Spruce is intermediate in shade tolerance and thrives in open conditions and under limited partial shade (Farr and Harris, 1971; Harris and Johnson, 1983; Harris, 1990). Farr and Harris (1971) showed that Sitka spruce would only regenerate after at least two thirds of the canopy was removed. Sitka spruce seedlings will regenerate in organic matter provided the underlying mineral soil has sufficient nutrients to support tree growth (Harris and Johnson, 1983; Harris, 1990). The best seedbed is a mixture of mineral soil and organic matter. The use of clearcutting for artificial and natural regeneration of Sitka spruce has generally failed, because of the spruce weevil (*Pissoides strobi*) (Harris, 1990). The weevil attacks and disfigures spruce growing in direct sunlight. Consequently, successful management of this species requires the maintenance of partial shade for as long as possible during the development of the stand. This makes shelterwood an ideal choice.

There are substantial problems associated with the use of shelterwood management in the CWH zone. All the species mentioned, with the exception of Douglas-fir, are shallow rooted. This predisposes stands to windthrow especially after the regeneration cut. In addition, all species mentioned, again with the exception of Douglas-fir, have thin bark, and are extremely susceptible to scarring from falling and yarding or skidding operations. Hemlock, amabilis fir, and Sitka spruce are hosts to many fungal diseases capable of entering wounds from stem and root damage. Caccavano (1982) showed damage and mortality due to stem injury in thinned mixed stands of Douglas-fir and hemlock increased significantly when a higher component of hemlock was present. Special care must be exercised during the regeneration cut to minimize damage to seed trees.

Open conditions that follow partial cuts can stimulate the development of epicormic shoots in mature Sitka spruce trees. Epicormic shoots can cause serious defects in lumber and reduced pulp quality. Farr and Harris (1971) showed that 62% of mature Sitka spruce developed epicormic shoots after a regeneration cut, and that epicormic branching was positively correlated with thinning intensity. The most important problem in the CWH zone is the presence of dwarf mistletoe (*Arceuthobium tsugense*) in hemlock. This pathogen increases mortality, decreases growth, provides an entry for disease and lowers wood quality.

Trials of Shelterwood

The only published studies of trials of shelterwood in conditions similar to those in coastal BC are from the Pacific Northwest of the United States. The findings from the most informative studies on shelterwood management in Douglas-fir and hemlock forests are summarized in Table 1 and 2, respectively. Residual damage, seedling mortality, and harvest intensity columns indicate whether the author discusses these factors in depth. The comments column provides additional information from the studies.

There have been at least three attempts of shelterwood cutting in second-growth coastal Douglas-fir forests in BC. Fletcher Challenge Canada Limited has an ongoing shelterwood operation on Quadra Island. Shortwood Thinning Limited has performed several shelterwood regeneration cuts on Saltspring Island. In both cases the decision to use shelterwood was based on the need to incorporate aesthetic concerns raised by residents of the Gulf Islands in the Gulf of Georgia. Shelterwood harvests have been conducted since 1960 on Tree Farm #1, owned and operated by Tom Wright. Mr. Wright, former Dean of Forestry at the University of BC, began shelterwood harvests out of personal interest, and was searching for methods of securing natural regeneration. There are no published results from any of these operations.

The BC. Ministry of Forests intends to use shelterwood management in an area near Roberts Creek (Sechelt), with operations expected to begin in late summer of 1993. Local residents and cottage owners had serious reservations about clearcut harvesting in the area, and the impact on water quality and aesthetics.

Table 1. Summary of four shelterwood trials in Douglas-fir forests of the US Pacific Northwest.

Author(s)	Residual Damage	Seedling Mortality & Damage	Harvest Intensity	Comments
Minore et al. (1977)	No	Yes	Yes	Compared regeneration success between shelterwood and clear-cutting in South Western Oregon.
Seidel (1983)	Yes	Yes	Yes	Shelterwood should not be used where the risk of blowdown is excessive. Residual stocking of 20-60 stems/ha recommended.
Tesch et al. (1986)	Yes	Yes	Yes	Felling and yarding responsible for 41% of seedling mortality. Seedlings 60 cm to 100 cm had highest survival rates.
Williamson (1973)	No	Yes	Yes	Mineral soil exposure of at least 25%, and residual stocking of 9 to 17 m2 resulted in highest regeneration stocking.

Table 2.
Summary of two shelterwood trials in western hemlock forests of the US Pacific Northwest.

Author	Residual Damage	Seedling Mortality & Damage	Harvest Intensity	Comments
Farr and Harris (1971)	No	Yes	Yes	Compared a control plot to 66% thinned plot. Sitka spruce regenerated only in thinned plot, and were considerably smaller than hemlock regeneration. Improved growth rate in residuals, but 62% of Sitka spruce developed epicormic branches.
Williamson and Ruth (1976)	No	Yes	Yes	Hemlock seedling stocking increased, and average seedling height decreased with higher harvest intensities (lower residual basal area). 45,700 seedlings/ha where measured 5 years after the initial cut.

A shelterwood regeneration cut and a commercial thinning trial have resulted in successful natural regeneration in the CWH zone. Both are located in drier subzones. First, MacMillan Bloedel Limited developed a program in the late 1980's near Stillwater (Paradise Valley), to test the feasibility of alternative silvicultural systems, such as shelterwood. They have gained valuable experience in the implementation of these systems from this trial. Second, Western Forest Products attempted a commercial thinning, which resembled preparatory cuts in a shelterwood system. In the 1950's near Jordan River a low intensity thinning (25% removal), resulted in exceptional regeneration of western hemlock, and high annual increment on residual trees. The results from these trials have not been published either.

In an effort to promote the use of alternative silvicultural systems, the BC. Ministry of Forests in Duncan have tendered contracts to harvest two Small Business Forest Enterprise Program (SBFEP) blocks based on shelterwood systems. One is located near MacKay Lake, in Cassidy, and the other at Mount Prevost, near Duncan. These blocks are expected to be harvested in the summers of 1993 and 1994.

Seed tree

The seed tree silvicultural system (see Figure 3) involves removal of all but a few seed or crop trees which are left standing singly, or in groups to furnish seed to restock the cleared area (Burns, 1983; Smith, 1986). After a new crop is established the seed trees may be removed in a second cutting or left indefinitely.

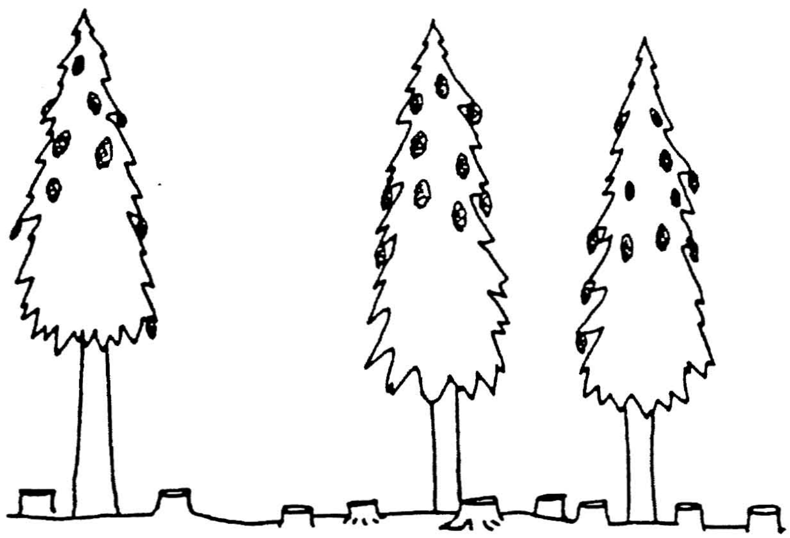

Figure 3. Seed Tree System (BC Ministry of Forests, 1991).

CDF Biogeoclimatic Zone

The seed tree method is appropriate in stands of Douglas-fir that have been thinned throughout their lives, and have developed substantial wind firmness in individual trees (Williamson and Twombly, 1983). Older stands that have not been thinned and are subject to more than 80% removal of the forest stand are at great risk to windthrow (Hermann and Lavender, 1990; and Williamson and Twombly, 1983).

The regeneration cut (initial harvest) resembles a heavy shelterwood regeneration cut removing 80% or more of the stand. Wide openings facilitate the establishment of less shade tolerant trees such as alder and maple which compete aggressively with Douglas-fir seedlings. Consequently, there is a strong possibility that precommerical thinning would be required some time after the regeneration cut. Soil disturbance tends to favor the establishment of red alder (Hermann and Lavender, 1990) and, therefore, should be minimized. If a removal cut is planned it should be executed in a similar fashion to the removal cut in shelterwood management. Removal cuts in seed tree management provide the opportunity to thin the developing advance growth during a commercial operation. Control of this activity requires careful planning and supervision of skid road or yarding corridor location, and felling procedures.

CWH Biogeoclimatic Zone

Hemlock, redcedar, Sitka spruce, and amabilis fir, are shallow rooted trees, and are susceptible to windthrow (Crawford and Oliver, 1990; Harris, 1990; Minore, 1990; Packee, 1990). This fact alone effectively excludes seed tree management from consideration in the CWH zone. In wetter zones with Sitka spruce, and where windthrow is not a potential problem, seed tree is feasible. However, the risk from weevil damage associated with the increased level of direct sunlight compared to shelterwood makes seed tree management a poor choice.

Trials of seed-tree silvicultural systems

There are no published studies on the application of seed tree management under conditions similar to those found in coastal BC.

Two unpublished trials of the seed tree system were located. A seed tree system was attempted by H.R. MacMillan (MacMillan Bloedel Ltd), near the Copper Canyon, Vancouver Island, BC, in the early 1950's. All the residual trees blew over, and seed tree management has not been attempted since in that area. MacMillan Bloedel Limited successfully implemented a seed tree silvicultural trial in the late 1980's on their private woodlot in Paradise Valley near Stillwater, BC. Thirty trees per hectare were left as crop trees for seed sources.

UNEVEN-AGE MANAGEMENT

Uneven-age silvicultural systems create stands in which three or more age classes are intermingled (BC. Ministry of Forests, 1991; Gibbs, 1976; Smith, 1986). Uneven-aged stand structure is usually accomplished by so-called "diameter distribution harvests", where cutting removes a fixed percentage of trees in all diameter classes at each entry. Smith (1986) explains the ideal diameter distribution for uneven-aged stands as follows,

> "Since it requires many saplings to cover the space eventually occupied by a single mature tree, the distribution should approximate the smooth, 'reverse J-shaped' curve (Figure 4A). This curve really represents the collective total of the diameter distributions of a series of little even-aged, pure groups of trees covering equal areas and separated by equal intervals of age (Figure 4B)".

Development of a reverse J-shape diameter distribution requires the application of either the group or single-tree selection system.

Selection silviculture shouldn't be confused with ***selective*** harvesting. Selective logging is the unregulated harvest of valuable trees, with little regard for ecological or silvicultural principles. Selective logging is not recommended for second-growth coastal forests. It is essentially ***high grading.*** There were optimistic attempts to implement selective logging in the Pacific Northwest in the early 1930's, the planning and implementation of these harvests are outlined in Kirkland and Brandstrom (1936) and English (1929). The consequence of these trials were disastrous, resulting in the conversion of high quality old growth forests, to low vigor stands of poor quality. The dangers of selective logging in BC are outlined in Whitford and Craig (1918).

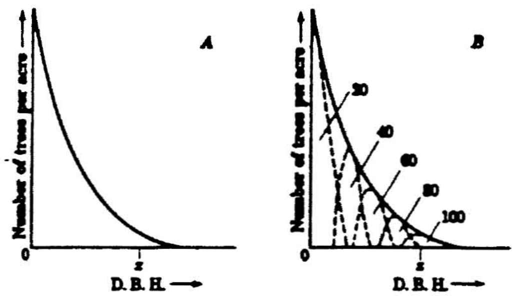

Figure 4. Uneven-aged diameter distributions, a) the distribution curve of an all-aged stand of 1 acre containing sufficient trees in each diameter class to produce an unvarying number of trees of optimum size (of diameter x or larger) at rotation age, b) a balanced uneven-aged stand of the same diameter distribution may be composed of five age classes, each occupying an equal area, with 100 year rotation. (Smith, 1986).

Selection Systems

Selection systems involve the removal of mature and immature trees, either as single scattered individuals, **Single Tree Selection**, or in small groups, **Group Selection**, at relatively short intervals. The entries are repeated indefinitely, which leads to the continuous establishment of regeneration, and maintenance of an uneven-aged stand (see Figure 5). Factors that effect the choice of either single or group selection cutting are (BC. Ministry of Forests, 1991):

1. Existing and desired species composition.
2. Seed bed and growing requirements.
3. Potential for windthrow.
4. Development of competitive species.
5. Sensitivity of soil to repeated entry.
6. Potential spread of pathogens.

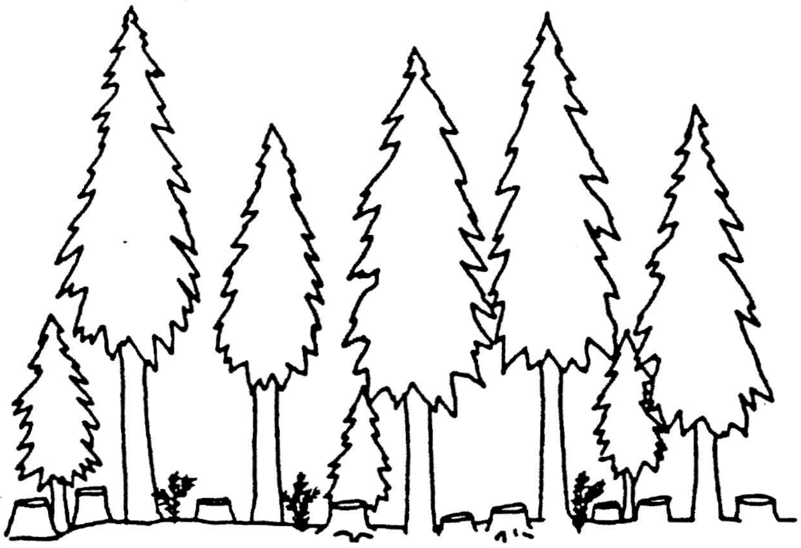

Figure 5. Selection System (BC Ministry of Forests, 1991).

Single Tree Selection

Single tree selection involves the removal of single trees from the stand with the objective of maintaining the reverse j-shaped diameter distribution (BC. Ministry of Forests, 1991; Burns, 1983; and Marquis, 1976). In mixed stands, single tree selection promotes the development of the most shade tolerant species present in the forest.

CDF Biogeoclimatic Zone

Single tree selection is not the preferred method for maintaining a continuous uneven-aged forest of Douglas-fir. The single tree system does not provide favorable light conditions for intermediate shade tolerant coastal Douglas-fir (Burns, 1983). Poor Douglas-fir regeneration results in the forest being converted to more shade tolerant trees, such as redcedar and hemlock (Isaac, 1956). If these species are acceptable substitutes for Douglas-fir, individual tree selection could be used.

CWH Biogeoclimatic Zone

Hemlock, redcedar, and amabilis fir are very shade tolerant, and single tree selection is a favorable method of maintaining a continuous uneven-aged forest dominated by these species (Marquis, 1976). Under limited light conditions created by single tree removal, amabilis fir and redcedar compete well for growing space with hemlock. Douglas-fir and Sitka spruce cannot compete for light with the other tree species, and eventually disappear from the stand. In drier zones, the forest canopy would be dominated by hemlock, redcedar, and a small component of grand fir. The wetter sites would be dominated by hemlock, amabilis fir, and redcedar.

Removing single tress reduces the chance of windthrow in comparison to other partial cuts because the openings are generally small so the wind doesn't penetrate the canopy. Moreover, the wide range in size of residual trees helps shield the more windthrow-prone trees. This is particularly important in this zone given most of the species are shallow rooted. A disadvantage to individual tree selection is the high residual basal area and associated risk of logging damage to residual trees. This is especially problematic in this zone because the majority of species are thin-barked and, therefore, predisposed to damage. Single tree selection can promote the spread of dwarf mistletoe in hemlock forests, so if control of this parasite is important, single tree selection is probably not appropriate.

Group Selection

Group selection can be used to maintain more of the light-demanding species compared to individual tree selection by removing trees in clumps (BC. Ministry of Forests, 1991). In tracts of timber where trees are large, the clumps may exceed 1 hectare in area, thus resembling small clearcuts. Group selection provides easier access for harvesting operations, and may result in less damage than in single tree selection. The difference between clearcutting and group selection, is that group selection creates a balance of age and size classes in a mosaic of small continuous even-aged groups throughout the forest rather than a single, large even-aged stand.

CDF Biogeoclimatic Zone

Douglas-fir is intermediate in shade tolerance and may regenerate in the small openings created in the application group selection management. Other shade intolerant species would regenerate and provide competition to Douglas-fir seedlings if the opening size were too large. Some site disturbance maybe necessary to initiate germination of Douglas-fir seed. Precommerical and commercial thinning in these clumps may be necessary to control species composition and competition.

CWH Biogeoclimatic Zone

Regeneration of alder and Douglas-fir can be established in the drier subzones of the CWH zone using the group selection method provided the openings are large enough. However, development of hemlock would generally be favored by group selection. Artificial regeneration or scarification may be necessary to ensure desired stocking levels of Douglas-fir.

The application of group selection in the wetter subzones would almost certainly lead to stands dominated by hemlock, amabilis fir, and redcedar. Provided the opening sizes were large enough, Sitka spruce could be encouraged in the lower elevation, wetter zones. The same comments made for shelterwood management in these areas apply.

Too large an opening would lead to windthrow problems, and potential overstocking of Sitka spruce, and unacceptable levels of weevil damage. Increased opening size will result in high stocking of hemlock, with a small to moderate component of Amabilis fir and redcedar. To achieve a larger component of redcedar and Amabilis fir, blocks should be small, and harvests scheduled to coincide with prolific seed years for either species. Some pre-commercial thinning may be necessary to regulate stand density and species composition, especially if other treatments are scheduled. In very dense stands that are common after hemlock stands are treated (Williamson and Ruth, 1976), pre-commercial thinning may be prohibitively expensive.

Trials of the selection system

While there are some informal trials of cuttings which are referred to as "selection" such as Merv Wilkson's tree farm near Ladysmith, BC. and Fletcher Challenge Canada Limited on Quadra Island, none of these trials can really be considered true selection management. There are apparently no published trials of selection management in Coastal British Columbia.

SILVICULTURAL OBJECTIVES AND THE IMPACTS ON CHOICE AND EMPLOYMENT OF HARVESTING SYSTEMS

The primary purpose of this report is to identify promising harvesting systems for use with alternative silvicultural systems, and, more specifically, in the application of individual silvicultural treatments. Commercial timber harvesting is in fact the most commonly employed tool of the forest manager and should be viewed as an integral part of forest management, not simply an end in itself. The choice and employment of a given harvesting system for a particular cutting involves matching silvicultural objectives or requirements with harvesting system capabilities. With partial cuttings this process is more complicated for primarily two reasons. First, there are residual trees which ideally are left undamaged and/or advanced growth which is also left undisturbed or carefully thinned. Second, if the stand is to be regenerated naturally, the soil and light conditions after harvesting must be appropriate for the establishment of the desired species.

Tables 3-5 were constructed as a means for systematically addressing the requirements of each of the silvicultural systems and individual treatments discussed in the previous sections. The tables are organized as follows. General silvicultural observations are listed in the first four columns by management system, cutting type (treatment), and biogeoclimatic zone. The items listed are those which have a major and direct impact on the choice of harvesting system. The factors were derived from the previous, detailed discussion on silvicultural and are generally a function of the original stand conditions, the type of cutting, and the desired results of the cutting with respect to stand and soil conditions. These are linked to the columns listed under operational impacts on the right-hand side of the table which represent the translation of the silvicultural objectives into operational variables and dictate or affect the following:

1. Choice of equipment.
2. Stand level planning.
3. Scheduling of activities seasonally and sequentially.
4. Procedural guidelines for each logging phase.
5. Drainage-level planning.
6. Economics.

The scales used in the tables are general. The idea is to help direct consideration of harvesting systems to an appropriate class rather than to specify explicitly the type of equipment. The contents of the tables are described in more detail in the following sections and a more complete discussion of the six factors listed above is also provided.

Table 3. Silvicultural treatment and operational parameters for the shelterwood system

	Silvicultural Objectives				Operational Impacts					
Silvicultural Treatment	Basal Area Removed	Residual Basal Area	Advanced Growth Protection	Desired Soil Conditions	Average Volume per Tree Removed	Quality of Timber Removed	Volume per Ha Removed	Potential Residual Damage	Advanced Growth Disturbance	Soil Scarification
	1	2	3	4	1	1	1	2	3	4
Commercial Thinning & Preparatory Cut										
CDF zone	Low	High	Not Important	Not Important	Low - Medium	Low	Low	High	Not important	Not Required
CWH zone	Low	High	Not Important	Not Important	Low - medium	Low	Low - medium	High	Not important	Not required
Regeneration Cut										
CDF zone	Medium	Medium	Some concern	Exposed mineral soil	Medium - High	Medium	Medium	Medium	Passive protection	Required
CWH zone	Medium	Medium	Some concern	Undisturbed	Medium	Medium	Medium	Medium	Passive protection	Not required
Removal Cut										
CDF zone	High	NA	Very important	Undisturbed	High	High	Medium	NA	Active protection	Not required
CWH zone	High	NA	Very important	Undisturbed	High	High	Medium	NA	Active protection	Not required

Table 4. Silvicultural treatment and operational parameters for the seed tree system

	Silvicultural Objectives				Operational Impacts					
Silvicultural Treatment	Basal Area Removed	Residual Basal Area	Advanced Growth Protection	Desired Soil Conditions	Average Volume per Tree Removed	Quality of Timber Removed	Volume per Ha Removed	Potential Residual Damage	Advanced Growth Disturbanc e	Soil Scarification
	1	2	3	4	1	1	1	2	3	4
Commercial Thinning										
CDF zone	Low	High	Not Important	Not Important	Low - Medium	Low	Low	High	Not important	Not Required
Regeneration Cut										
CDF zone	High	Low	Not important	Exposed mineral	Medium	Low - High	High	Low	Not important	Required
Final Cut										
CDF zone	Low	NA	Very important	Undisturbed	High	High	Low	NA	Active protection	Not required

Table 5. Silvicultural treatment and operational parameters for the selection system

	Silvicultural Objectives				Operational Impacts					
Silvicultural Treatment	Basal Area Removed	Residual Basal Area	Advanced Growth Protection	Desired Soil Conditions	Average Volume per Tree Removed	Quality of Timber Removed	Volume per Ha Removed	Potential Residual Damage	Advanced Growth Disturbance	Soil Scarification
	1	2	3	4	1	1	1	2	3	4
Single Tree										
CDF zone	Low	High	Very important		Low - High	Low - High	Low	Medium	Active protection	Required
CWH zone	Low	High	Very important		Low - High	Low - High	Low	High	Active protection	Not required
Group Selection										
CDF zone	Low	High	Very important		Low - High	Low - High	Low - Medium	Low	Passive protection	Required
CWH zone	Low	High	Very important		Low - High	Low - High	Low - Medium	Medium	Passive protection	Not required

HARVESTING SYSTEMS

This section of the report concentrates on harvesting systems used in the application of specific silvicultural treatments within a chosen alternative silvicultural system. First, a brief discussion on harvesting systems is presented followed by a more detailed analysis of the major operational considerations important in the choice and employment of logging equipment. Next, published field trials of promising harvesting systems are reviewed, and when possible, categorized by silvicultural treatment. A more technical treatment of available or suitable harvesting equipment is given in Appendix A. Typical rigging configurations for skyline yarding are given in Appendix B. Site specific terrain and other factors dictate the preferred rigging method for skyline systems, therefore, a detailed treatment of this component of cable harvesting is not included in the report. Finally, each silvicultural treatment for the four silvicultural systems shown in Tables 3-5 is discussed separately and recommendations for the most promising harvesting systems are given. Differences regarding the choice of harvesting system between the two biogeoclimatic zones are discussed for each treatment.

LINKING SILVICULTURE AND HARVESTING

The following discussion assumes that the reader has a basic knowledge of common timber harvesting systems. A comprehensive treatment of timber harvesting systems is provided by Conway (1982). The primary objective of the following sections is to identify the most promising harvesting systems to employ in the application of individual silvicultural treatments for each of the four silvicultural systems listed in Tables 3-5. The discussion includes comments regarding the advantages and disadvantages of each harvesting system in each application as well as observations concerning specialized planning or operational problems.

In the final section on silviculture six factors were listed which categorize the major impacts various silvicultural objectives can have on the choice and employment of harvesting systems. The following is a more detailed explanation of these six factors. While these items are discussed separately below, it is important to keep in mind that they are considered simultaneously when designing a harvesting system and planning its deployment and operation.

Choice of Equipment

The first and most important decision regarding design of a harvesting system for a particular cutting is the choice of the type and size of equipment. The first issue which must be addressed is whether a ground-based system can be used or if a cable or aerial system is required. Ground-based systems are almost invariably less expensive, however, there are both physical and environmental limitations to their use. Rubber-tired vehicles for both mechanical felling and skidding are generally limited to slopes less than 35%. Tracked felling and skidding equipment can operated on slopes up to 50%. Cable or aerial systems must be used on slopes greater than 50%.

On slopes of less than 50% cable or aerial systems may also be required if the soils are particularly sensitive. Sensitive soils are typically shallow, and easily exposed and eroded in areas with high rainfall which includes most of coastal BC. In addition, cable or aerial systems which provide full suspension of the logs or trees during transport may be needed as ground-lead or partial suspension systems such as highlead can produce unacceptable soil disturbance. In very flat terrain so-called "low pressure" ground-based skidding equipment may be usable such as wide-tired skidders or wide-tracked vehicles.

The existing road network must also be considered when choosing equipment. Road location dictates maximum yarding or skidding distances as well as landing areas which limits the use of some equipment. Much of the second-growth timber in BC occupies sites logged originally using railroads and steam- or diesel-powered yarders. The use of old railroad beds on these sites can help reduce development costs. Use of actively maintained roads is obviously prudent. However, the original road networks were designed for harvesting systems suited for large, old-growth timber and short yarding distances (close spacing). Smaller timber size and current environmental regulations concerning area disturbed may preclude use of at least some portions of both the actively maintained and deactivated sections of the original road network.

Once the decision has been made to use ground-based, cable, or aerial systems, the next issue is the size of equipment and any other special considerations such as maneuverability. The size of equipment required depends on the weight of the loads which are a function of the size of the timber. The equipment chosen must be capable of handling the largest timber to be taken in the cutting. In addition, in most of the cuttings shown in Tables 3-5, cable systems must be capable of lateral yarding. This almost always requires the use of a carriage with special capabilities which limits the choice of cable operations to some type of skyline system. Exceptions to the requirement of lateral yarding are discussed in the section on equipment trials.

Stand-level Planning

Stand-level planning, also referred to as engineering, represents the development of a specific plan of operation for the harvesting system chosen for a given cutting block. This process requires the careful consideration of what is feasible and preferred with respect to the operation of the equipment. The activity involves a substantial amount of field work and leads to the determination of block boundaries, the location of spur roads, landings, skid roads, and yarding corridors and, in the case of cable systems, the rigging method. The time and effort required for this planning exercise increases substantially for partial cuts for numerous reasons (Kellogg et al., 1991). Aerial logging systems are especially complicated and require much more planning than ground-based or even skyline systems independent of the type of cutting (Burke et al., 1973; Moore, 1991).

Scheduling of Operations

Some silvicultural objectives associated with alternative management systems may place additional demands on the scheduling of harvesting activities. Soil moisture conditions can vary considerably on individual sites, and this can affect the ability to produce the desired seedbed as well as the potential for soil compaction, disturbance, and erosion. The existence of residual trees also leads to heightened concern for management of felled inventory in the interest of controlling the build-up of insect populations as well as other biotic pathogens. Seasonal weather patterns with respect to wind and precipitation may place additional restrictions on the scheduling of aerial logging operations. Finally, stem injury to residual trees can be diminished if operations are timed to coincide with favorable bark conditions, that is, when sap flow is at a minimum (Aho et al., 1983; Maxwell and Oswald, 1975). The timing of felling and skidding or yarding operations dictates the scheduling of all other activities like road building, loading, and trucking, all of which must be coordinated in the development and execution of any harvest plan.

Drainage-level Planning

Drainage-level planning involves primarily two concerns. First, the location and economically optimal spacing of major haul roads must be determined, and second, treatment units must be scheduled for harvest in both time and space. Partial cutting involves the removal of lower volumes per hectare compared to clearcutting which increases the fixed cost of road construction per unit volume. This requires wider spacing of haul roads to minimize total harvesting costs, although variable skidding and yarding costs also increase which have the opposite effect on road spacing. Problems with the scheduling of treatment units (cutblocks) are usually less difficult when partial cutting is used because aesthetically these cuts are less offensive. This means issues like green-up periods and other adjacency constraints probably do not apply which permits progressive cutting. In any case, drainage-level planning issues are significantly different for alternative silvicultural systems compared to clearcutting.

On-site Work Procedures

Some silvicultural objectives may require the use of special on-site work procedures in various phases of timber harvesting. For instance, depending on the density of residual trees, so-called "whole-tree" and even "tree-length" harvesting systems may be prohibited. In this case either "log-length" or "shortwood" systems may be required. Clearly this affects the choice of equipment in the first place, but it also influences stand-level planning, and the preferred work methods employed in each phase. Two other examples are when thinning of advance growth or soil scarification are desired. In these cases falling methods, either manual or mechanical, and skidding or yarding procedures may be modified to produce the required results.

Finally, logger training requirements are different for partial cutting compared to clearcutting, and the success of partial cuts with respect to damage to residual stems and advance growth, and economic viability depends heavily on loggers having the right attitude, training, and supervision (Aho, et al. 1983; Goetz, 1987; Kellogg et al. 1986; Maxwell and Oswald, 1975). Considering that nearly all timber harvesting in coastal BC at this time is based on clearcutting, it is not unreasonable to expect a substantial logger training effort will be required to successfully implement any partial cutting.

Economics

Finally, and perhaps most importantly, the use of partial cutting will involve different costs compared to clearcutting and in most cases will be more expensive. The size and quality of timber taken in many of the cuttings listed in Tables 3-5 are significantly lower than if the stand were clearcut. This increases the variable costs of harvesting and, in many cases, lowers the gross value of products coming from the operation with the obvious combined effect on the overall profitability. The volume removed per hectare will always be lower with partial cutting which leads to higher fixed costs per unit volume for a given area. In addition, the productivity of all phases of harvesting is lower when there are residual trees. Care must be taken not to damage these trees which slows operations, and because lower volumes are taken per hectare, more terrain must be covered to accumulate the same volume which increases cycle times. Finally, all aspects of planning are more time consuming and costly when partial cuts are used.

EQUIPMENT TRIALS IN PARTIAL CUTTING

Most of the literature describing studies of equipment trials in partial cutting do not give sufficient information to classify the silvicultural treatments according to the scheme used in this report. The majority of the treatments are commercial thinnings in young stands planned for clearcutting at rotation age. These trials are included in the review because the operational conditions are similar to those of all treatments employing partial cutting. The following review is organized by major type of harvesting system rather than by silvicultural system and treatment as was done in the review of alternative silvicultural systems. The literature review is restricted to cable systems in partial cuttings of any kind in Canada and the United States, logging of any kind in second-growth stands of coastal British Columbia, and ground-based logging in partial cuttings on steep terrain in western Canada and the United States, or where direct comparisons to cable yarding were made.

Cable Yarding

Published trials of cable yarding systems in partial cuts have been restricted to skyline systems. These systems have two characteristics which are essentially prerequisites for operating in partial cuts: lateral yarding capability, and full or nearly full suspension of logs during yarding. The use of carriages permits the former, while the skyline itself allows the latter. There are some general accounts of the use of these systems most of which contain some reference to employment in partial cutting (Studier and Binkley, 1974; Binkley, 1981; Burke et al. 1973; Carvell, 1984; Kellogg, 1983). LeDoux and Brodie (1982) evaluated various combinations of silvicultural treatments for thinning and harvesting equipment using computer simulation and concluded that through prudent choice of harvesting system financial returns can be increased. Making cable yarding economical is one of the predominant themes in the literature on these systems.

The majority of published trials on skyline yarding is in commercial thinnings. In most cases the studies were done in young stands (less than 50 years old) of Douglas-fir under even-age management (clearcutting or shelterwood). The thinnings concentrated on the removal of low vigor, intermediate or surpressed stems at high risk to mortality in the short-term, or larger trees of poor quality which suggests they were a combination of low and selection thinning. The bulk of the work of this kind was done by Loren Kellogg and his associates at Oregon State University, in Corvallis. These researchers established a cooperative research program with industry and various government agencies in the late 1970's in an attempt to solve the "smallwood" problem anticipated by the forest industry as old-growth stands disappeared or became off limits and cutting was concentrated in second-growth timber. This project produced a wealth of material on the use of small and medium sized yarders in such thinnings (Burrows, Olsen and Kellogg, 1986; Kellogg and Olsen, 1988; Kellogg, Olsen and Hargrave, 1986; Kellogg and Olsen, 1984; Kellogg, 1983; Kellogg 1980a; Peters and Kellogg, 1980). The studies often focused on means for increasing the efficiency and decreasing the costs and damage to residual stems with these harvesting systems. They found that strip thinnings (clearcutting strips rather than individual tree selection) were less costly and reduced damage to the residual stand. Felling to lead is critical and a herring bone pattern with respect to the main yarding corridors is best. This helps minimize damage to residual trees and speeds production. They also found that congestion at the landing was a common problem with the smaller yarders, consequently, swinging material with a skidder or log loader was recommended. Hochrein and Kellogg (1988) compared three different thinning methods for two different intensities of cut and found that the light thinning resulted in 17-18% lower production compared to the heavier entries. Putnam, Kellogg and Olsen (1984) compared whole-tree, tree-length and log-length skyline thinning and found that production rates were about the same among the various options. One method employed by these researchers to increase productivity is called "pre-bunch and swing" (Kellogg, 1980b; Kellogg and Aulerich, 1977). Trees are manually felled and then laterally yarded and bunched at the main yarding corridors using either a small yarder or radio-controlled, sled-mounted winch. Such equipment is popular in Scandinavia. The idea is to complete the most time consuming portion of the yarding cycle, lateral yarding (Aulerich et al., 1974), with fewer workers and cheaper equipment, and increase the load size for the larger yarder by pre-bunching, both of which should decrease costs. Their findings suggest that while productivity increases substantially, total system costs do not change significantly. It might be possible to use grapple yarders (running skylines) to yard bunched wood in main yarding corridors. MacDonald (1988) and Peterson (1987a, 1987b) studied grapple yarding of bunched timber in clearcuts in coastal BC and found substantial increases in productivity over conventional single log turns. Two advantages to the use of grapple yarders are, *a*) ther are readily available in coastal BC, and *b*) they are capable of swinging material at the landing which eliminates the need for additional equipment during yarding. Disadvantages include short yarding distances and only partial suspension of loads.

There are several other studies of thinnings with skyline systems in the Pacific Northwest. Aulerich et al. (1974) compared cable yarding to tractor logging in thinnings and found that skylines were 1.5 to 1.7 times more expensive than ground-based systems and that the lateral yarding phase represented 46% of the productive cycle. This study motivated much of the work done by Kellogg. Mann and Mifflin (1979) conducted a test of a prototype small yarder in a 50-year old Douglas-fir stand in which 28% of the standing volume was removed. They found that productivity for the system was about 50% of that for typical clearcuts in similar conditions. Goetz (1987) tested two small yarders for thinning stands of western larch, ponderosa pine, lodgepole pine, and Douglas-fir. He observed that cooperation among the silviculturist, timber marking crew, and logger was essential for success.

Researchers in the northeastern United States have devoted considerable attention to the use of skyline yarding systems for harvesting in mountainous terrain (Biller and Peters, 1982; Gibson and Biller, 1975; Kochenderfer and Wendel, 1978; Wendel and Kochenderfer, 1978). Seymour and Gadzik (1985) compared various ground-based systems with skyline yarding in thinnings of small-diameter spruce-fir stands in Maine. They found that skyline yarding was the most expensive regardless of whether the wood was pre-bunched with a radio-controlled winch or not. Carvell (1984) summarized the findings of many of these studies as well as others from elsewhere in the US and Europe in a silvicultural evaluation of cable yarding for partial cuts. He commented that preventing damage to residual stems is critical for all entries in true selection management because all of the residual trees are expected to contribute to the future crop. In preparatory cuttings for shelterwood, damage to seedlings and saplings is often unimportant, only mature residuals need to be protected. Operational recommendations from these studies are similar to those from the Pacific Northwest. Trees should be felled to lead, preferably in a herring bone pattern. The carriage should be stopped uphill of turns to help minimize damage to residuals from partially suspended rolling logs. All main yarding corridors should be located parallel to the slope line which may require frequent setting changes. Fan shaped settings should be avoided. Log-length harvesting causes less damage to residual stems compared to tree-length or whole-tree logging, and finally, logger attitude and training are critical.

There have been only a few published trials of similar thinnings done with skyline systems in coastal British Columbia. Maxwell and Oswald (1975) reported on the use of a small, European skyline yarder called the Mini-Alp. The trials were done in a 50-year old Douglas-fir stand and a 60-year old Hemlock stand. Both cuttings removed approximately 35% of the standing volume and were preparatory type cuts. The machine proved successful and operated best rigged as a standing skyline. They commented that thinnings should be conducted when the bark on trees is tight, that is, not during spring or early summer when the sap is flowing. Johnson (1981) also reported on the use of the Mini-Alp yarder and concluded similarly that the machine's time had come. CANFOR in its operations near Was on Vancouver Island employs a thinning contractor who uses a Mini-Alp. Cottell and Sauder (1982) explored the possibilities of conducting thinnings in old-growth on the Coast, but concluded that, at least for that year, economic conditions were not favorable enough to justify trials.

There are numerous published accounts of skyline logging in shelterwood regeneration cuts. Benson and Gonsior (1981) investigated damage to residual crop trees and understory advance growth on a series of cuttings in Montana. They found that 23% of the marked leave trees were killed and another 10% received moderate damage during skyline logging. Heavier damage was observed on steeper slopes and for higher stand densities. Approximately 30% of the understory advance growth was also destroyed or seriously damaged. Presumably this latter result was unimportant given the goal of the regeneration cut is to promote establishment of seedlings rather than release existing vegetation. Kellogg et al. (1991) compared clearcutting to a system called "two story" cutting which resembles heavy shelterwood or seed tree regeneration cutting in 100+ year-old Douglas-fir. They employed slackline yarding, uphill with a mechanical slack-pulling carriage and major yarding corridors spaced at 75m. They found that planning partial cuts required substantially more time, and that yarding costs increased by more than 20% over clearcutting. Total logging cost including engineering was 23.4% higher for two story cutting. The largest contributor to increased cost was fixed costs associated with development and moving equipment. Hedin and De Long (1993) compared two intensities of shelterwood regeneration cutting with seedtree and clearcutting in the Coast-Interior transition zone of southwestern BC. They found handfalling production to be lower in all partial cutting methods compared to clearcutting, but no difference in yarding productivity. Mechanical felling and ground skidding were also slower in partial cuts. Dykstra (1976) compared skyline yarding in clearcuts and partial cuts in old-growth stands of Douglas-fir in Oregon. Logging was done with a "grapple yarder" equipped with a mechanical slack-pulling carriage. He found that costs increased by 67% over clearcutting. Gardner (1980) reported on the use of skyline systems in shelterwood regeneration cuts in Montana. In this study they employed a medium-sized yarder rigged as a running skyline with a mechanical slack pulling carriage. Piece size varied between .35 and .45 m3 on the tract. Shelterwood cutting produced the lowest yarding productivity compared to clearcutting and group selection. The final citation is simply a description of relatively heavy partial cutting in the redwood region of northern California (French, 1976). Partial cutting was required in buffer zones near streams as part of an integrated environmental protection plan for the area.

There have also been two published accounts of shelterwood overstory removal cutting with skylines. Tesch et al. (1986) studied mortality of regeneration during skyline yarding of a shelterwood overstory in Medford Oregon. The removal cut was completed three years after the regeneration cut. Natural regeneration was supplemented by planting of Douglas-fir and ponderosa pine in the year following the regeneration cut. Felling killed 22% of the 5-400 cm seedlings and yarding killed 28% of the same sized seedlings that survived felling. Seedlings between 61 and 100 cm in height faired the best. These researchers observed that harvest layouts which minimize the width of corridors and the number of corridors converging at a single landing result in the best distribution of seedlings after cutting. Youngblood (1990) compared various logging methods for shelterwood removal cuts in white spruce stands in Alaska. Crop trees were between 165 and 180 years old. A three-drum, yarder was rigged as a live skyline yarding uphill equipped with a manual slack-pulling carriage. Lateral yarding was up to

19 m. The findings of this study corroborated those of Tesch et al. (1986) showing that seedlings between 40 and 100 cm survived best.

Group selection, and strip clearcutting which can be viewed as a modified group selection method, have also been tried using skyline yarding. Kellogg et al. (1991) found that, as with two story cutting, group selection in 100 to 125 year-old Douglas-fir was more costly than clearcutting. Patches were approximately 1/2 acre in size (0.2 ha) in 20 to 30 acre (8-12 ha) treatment units. The entire treatment area was planned for harvesting in three entries, so the spatial distribution and timing of cutting each patch had to be determined for all three entries to insure all of the timber could be reached physically and economically. Every clearcut patch had to be adjacent to a main yarding corridor to permit direct access. Needless to say, p9lanning costs were substantially higher for the group selection method. Interestingly, felling costs were actually lowest for group selection. Total logging costs were 24.7% higher for group selection compared to clearcutting. Kellogg et al. (1986), Kellogg and Olsen (1988) and Kellogg (1980) investigated strip clearcutting in thinning operations which is a type of group selection cutting. They observed that concentrating cutting and yarding activities in strips reduced both damage to residual trees and logging costs. Gardner (1980) found that group selection skyline yarding with a Skagit GT3 rigged as a running skyline, had higher productivity than both shelterwood regeneration cutting and clearcutting.

Finally, McIntosh (1963) studied a system called "pre-logging" in a coastal BC cedar-hemlock stand. He described three methods: one pass logging which is conventional clearcutting, two-pass "relogging" in which residual material is removed in a secondary operation after the majority of material is removed by traditional logging methods, and, two-pass "pre-logging" in which smaller diameter trees are removed first, followed by the remainder of the stand. He observed that pre-logging captures more of the smaller-sized timber intact compared to "relogging". The sole objective of both methods was to increase utilization, but "pre-logging" did require partial cutting.

Balloon Logging

Balloon logging is suitable for partial cutting and really represents a modified skyline method. The balloon provides the lift which the skyline gives in skyline yarding, and, lateral yarding is accomplished by either lengthy taglines or a carriage. Lines are worked with a yarder usually equipped with two drums. Balloons are actually easier to rig compared to skyline systems (Burke et al., 1973), but required considerably more capital and planning, and are limited by certain weather conditions which do not affect skyline logging. Balloons provide superior suspension of loads which leads to cleaner logging compared to skyline systems. Additional general information on balloon logging is available from Burke et al. (1973), McIntosh (1968), and Studier and Binkley (1974).

There is only one published trial of balloon logging in partial cuts. Hartsog (1978) investigated balloon logging in the Idaho batholith. Traditional logging methods involved "jammer" logging which is a rudimentary form of grapple yarding. This method requires very close road spacing, and, consequently, results in considerable site disturbance. Environmental concerns led to the trials of balloon logging. The cutting performed in the trial was referred to as "overstory removal", but in fact was a diameter limit cut. They observed very little damage to residual stems after logging, but calculated costs at double that of conventional jammer methods. Hartsog also commented that post logging management costs were likely to increase given access to the stands was limited by the lack of roads. The balloon was quite large holding 560,000 cubic feet of helium with a lift of 22,500 lb. (10,000 kg). They employed a two-drum yarder and rigged the system as both an inverted skyline and traditional "highlead", but found that the highlead method was superior. They used a tagline of varying lengths to permit lateral yarding.

Helicopter Logging

Helicopters have been used successfully in partial cutting and have tremendous advantages over other systems. Helicopters are extremely flexible, require no roads, are capable of yarding up to 2000 m or more, and provide full suspension of loads at all times. The major disadvantages is weather related restrictions, safety, and high costs . stemming from large crew sizes and very high fuel consumption. Additional general information on the use of helicopters for logging is available from Burke et al. (1973) and Moore (1991).

There are two published trials of helicopter logging in partial cuts. Dykstra (1976) compared skyline, balloon, and helicopter logging in a production study in Oregon. The cutting was an extremely heavy partial cut in an old-growth Douglas-fir stand, perhaps designed as a regeneration cut, although this was not stated. Dykstra found that there was essentially no difference in the productivity of helicopters between partial and clearcutting. The helicopter was a Sikorsky S64E skycrane. Moore (1991) conducted post logging surveys of residual stem damage in group selection cuts in old-growth hemlock-spruce stands in the Queen Charlotte Islands. Logging in this case was also done with a Sikorsky S64E skycrane. Damage from logging was limited, although some blowdown occurred. Burke et al. (1973) commented that large helicopters like the Sikorsky S64E are superior in partial cuts because they have the power required to fly straight up after hooking a turn of logs which helps prevent damage to residual trees. Moore (1991) observed that planning helicopter operations was more complicated than conventional logging methods.

Ground-based Systems

There are many ground-based systems which are suitable for partial cutting in coastal British Columbia. The limitations on such systems were discussed above and relate to slope, soil conditions, and, in some cases, timber size. The primary advantages to all ground-based systems over cable or aerial logging is lower cost and greater flexibility. The disadvantage is the relatively high potential for extensive site disturbance particularly where soils are poorly drained or on steep slopes; conditions which are common in coastal BC. Ground-based systems have been used to clearcut second growth stands in coastal BC (Rogers and MacDonald, 1989) including the use of highly mechanized systems (Peterson, 1988). Rogers and MacDonald (1989) concluded that ground-based logging is feasible in coastal BC provided that harvesting is limited to drier periods. Additional general information on ground-based systems is available in most textbooks on timber harvesting (for example see Conway, 1982), and Richardson (1993) discussed many important issues in the use of these systems in partial cutting. The following brief review is limited to ground-based systems used for partial cutting in the Pacific Northwest and BC, or where they have been compared directly to cable yarding.

Aulerich et al. (1974) conducted studies comparing tractor logging to skyline yarding and found that the ground-based system was significantly less costly. Tractor logging also left less slash, however, soil compaction was significantly higher. Damage to residual stems was about the same with the two methods. Goetz (1987) also compared various ground-based methods to skyline yarding. Youngblood (1990) did the same and recorded 3 times as much mortality to advance growth regeneration in a shelterwood overstory removal with rubber-tired skidders compared to skyline yarding. Kellogg et al. (1991) explored the use of ground skidding methods in two story (shelterwood regeneration like cuts) and group selection. Doyle (1993) described a highly mechanized ground-based system currently in use on Vancouver Island. A single-grip harvester is combined with a bunk forwarder for thinning second-growth coastal stands. The system is capable of handling material up to 50 cm in diameter at the butt, although optimum size is 36 cm. The operation is a log-length show. Aho et al. (1983) studied logging damage following skidder and tractor (bulldozer) tree-length logging in young-growth true fir stands in California. Damage was severe in many cases, but the study showed that damage can be reduced by improved logging methods. The report concludes with a list of recommendations for planning, execution, and supervision of ground-based thinning operations including: *a*) prohibit logging during spring and early summer when the sap is flowing to minimize scaring, *b*) mark residual crop trees to increase visibility, *c*) layout skid roads in advance, *d*) leave cull bumper trees along skid trails, *e*) regulate the length of material skidded according to the spacing of the residual stand, and *f*) communicate with the loggers. Seymour and Gadzik (1985) found that pre-bunching for grapple skidders increased productivity in thinnings of small-diameter spruce-fir stands in Maine. However, the total harvesting cost was about the same as conventional line skidding of non-bunched wood. They also observed no difference in damage to residual trees among any of the systems investigated including skyline yarding, grapple skidding, and conventional two-man handfalling and line skidding. Loggers in Maine are accustomed to partial cutting with line skidders which is perhaps why residual damage was controlled.

Another ground-based system which has been proposed but apparently remains untried is pre-bunching to corridors with radio-controlled, sled-mounted winches and grapple skidding to landings. Skidding corridors would be located on well-drained stable soils within cutting blocks to minimize soil disturbance. Use of the radio-controlled winches would reduce both soil disturbance and damage to residual stems throughout the remainder of the blocks compared to conventional line skidding. This system would be less costly than pre-bunching and cable yarding, and could reduce the amount of spur road construction by using the old railroad beds for major skid roads.

Combination Systems

There is at least one harvesting system which combines components of ground-based and cable systems. The system is currently in use on the Olympic Peninsula. The system involves felling and bunching trees with a single-grip harvester, followed by skyline yarding with either a carriage or grapple. This system appears to avoid the problems of residual tree damage associated with the bunk forwarder of the conventional ground-based combination employing the single-grip harvester. However, because these two machines are usually bought together, use of the single-grip independently means the bunk-forwarder is idle. Use of the bunk-forwarder to swing material at the landing could resolve this problem.

RECOMMENDATIONS OF HARVESTING SYSTEMS FOR INDIVIDUAL SILVICULTURAL TREATMENTS

In the following sections recommendations are presented for harvesting systems suitable for use in each of the cutting types by silvicultural system. The generalized observations contained in Tables 3-5 describing the impact of silvicultural objectives on the choice and employment of harvesting systems are used to motivate the discussion as well as the preceding review of equipment trials. Examples of the type of equipment recommended in each of the following sections are given in Appendix A and typical rigging methods for skyline systems are shown in Appendix B.

Shelterwood Management: Commercial Thinning and Preparatory Cut

Commercial thinnings and preparatory cuts in all variations of shelterwood management require the use of inexpensive harvesting systems given the quality of material, average tree size, and volume per hectare removed are all low. The systems must also be highly maneuverable because the residual basal area is high and there is concern for damage to uncut trees. Damage to advance growth is not of great concern because the future regeneration cut is designed specifically to promote the establishment of the needed regeneration. Similarly, soil scarification is not an issue with these cuts given the regeneration cut will produce the seedbed conditions required for successful seedling establishment.

The small average tree size in these cuttings permits the use of smaller equipment because load sizes can be kept small. Smaller equipment is preferred because it has lower fixed costs and is, therefore, cheaper to operate. Smaller equipment is also more maneuverable which allows for increased protection for residual trees. Helicopter or balloon logging are probably too expensive for these cuttings. Small skyline systems are recommended in terrain or soil conditions where cable or aerial logging is required. These should be long-reach systems to allow for wider road spacing needed to control costs. The systems should employ a carriage which permits lateral yarding, and the longer the lateral distance the better as this helps reduce the number of roadway changes with the concomitant decrease in fixed costs. Alternatively, wood could be pre-bunched with a radio-controlled winch or other mobile, low impact machine. Bunched wood could then be yarded with conventional skyline equipment and production might be increased by pre-setting chokers while bunching. Grapple yarding with small- to medium-sized machines is another possibility. Grapple yarders have the advantage of swing capability for decking material which would eliminate the need for additional equipment in the landing. Grapple yarding needs good deflection due to the clearance requirements of the grapples, consequently, yarding distances and concomitant road spacing are often short. This limitation could be overcome by rigging backspar trees or it might be possible to engineer a multi-span grapple yarding system. This latter development would also help mitigate the problems associated with only partial suspension of loads characterisitc of grapple yarding.

There are numerous possibilities for ground-based systems where terrain and soil conditions are suitable for their use. Traditional hand-falling with line skidding is one option provided skid trails are planned and marked in advance, and relatively straight skidding is possible. Trees should be felled to lead, generally in a herring bone pattern. Conceivably, timber could be pre-bunched with a radio-controlled winch, small skidder or dozer, or even a farm tractor to strategically placed main skid trails and forwarded to landings with grapple skidders. If strip clearcutting were acceptable, feller-bunchers and grapple skidding whole-trees might be feasible, although the low volume per hectare cut may preclude this option. Finally, single-grip harvesters combined with bunk forwarders is also an option for these kinds of cuttings, particularly in younger stands with little or no material larger than 50 cm at the butt. These systems are preferred when cutting is extremely selective, that is distributed uniformly throughout the stand, given their high degree of maneuverability. Older stands with larger material would require log-length line skidding.

Shelterwood Management: Regeneration Cut

Regeneration cuts in shelterwood systems remove substantially more timber than preparatory treatments. As much as 60% of the original stand basal area may be taken, and, assuming preparatory cuts have preceded, the timber is larger and of higher quality.

This enables the use of larger more expensive equipment than in preparatory cuts, which in fact is required given load sizes are also larger. Harvesting systems must be maneuverable given the residual basal area is still relatively high, however, residual trees are larger on average compared to preparatory cuts, and therefore, the spacing between trees is greater. This provides more room for movement of equipment which helps control residual tree damage. Damage to existing advance growth is not an issue with these cuts. They are designed to promote the establishment of regeneration, therefore, any existing advance growth should be expendable. The survival and development of existing advance growth is, by no means , unwanted, and undoubtedly efforts made to protect residual trees will encourage this, however, this can be viewed as a bonus rather than a requirement. Finally, preparation of the seedbed is an important issue in the CDF zone if the preferred species is Douglas-fir. If advance growth exists and can be saved, soil scarification is unnecessary. In all other openings, efforts should be made to expose mineral soil and mix the humus layer with subsoil to provide a more favorable seedbed.

Both cable and aerial systems are possibilities for use where either terrain or soil conditions require such systems. The feasibility of using helicopters or balloon systems would depend entirely on the value of the timber removed given both these systems are expensive. Helicopters and balloons provide the greatest protection to residual trees of all the steep slope/sensitive soil harvesting systems which is a significant advantage in shelterwood regeneration cuts. Medium and perhaps even large skyline yarders could also be used. The appropriate size machine would depend on the size and quality of timber which impose physical and economic constraints on the choice of equipment. Long reached systems which have substantial lateral yarding capability are preferred given the volume per unit area harvested is still low compared to clearcutting. This will permit wider spacing of roads and the minimization of total logging costs. Cable systems may be superior to aerial systems in the CDF zone given soil scarification is desirable.

During lateral yarding, logs are usually only partially suspended resulting in light soil disturbance along lateral yarding corridors which is precisely what is needed. The use of helicopters and balloons may require post-logging site preparation in this zone given soil disturbance with these systems is minimal.

In areas where ground-based systems are suitable, either manual felling and line skidding, or mechanized log-length or shortwood systems could be used. Log-length or shortwood mechanized systems would have sufficient space to operate effectively permitting realization of the full benefits these machines afford regarding protection of residual trees. Maximum tree size for these systems is usually around 50 cm butt diameter, so if much of the timber were larger hand falling and line skidding would be required. The use of either rubber-tired or tracked skidding equipment would lead to the highest degree of soil disturbance, so these systems would be preferred in the CDF zone. Douglas-fir is the least susceptible to stem damage of all the preferred species in the two biogeoclimatic zones, therefore, the increase probability of residual tree injury associated with the use of tree-length systems should not be a problem. In the CWH zone, mechanized log-length or shortwood systems would be preferred given the greater concern for residual tree damage and the lack or requirement for soil scarification.

Shelterwood Management: Removal Cut

Removal cuts in shelterwood management, like regeneration cuts, remove substantially more timber per unit area than preparatory cuts. The timber is also larger and of higher quality still than in regeneration cuts. This permits, and often requires, the use of larger equipment due to the larger loads. Damage to residual trees is not an issue if all the remaining mature timber is harvested in a single entry which is generally the case. Prevention of damage to advance growth is extremely important as this cut follows successful establishment of regeneration resulting from the previous cut. In some cases, careful thinning of the regeneration may be desirable, especially in the CWH zone where hemlock seedlings can be expected to overwhelm the sites after the regeneration cut. Soil scarification is not required and, in fact, soil disturbance should be prevented given this would obviously lead to destruction of advance growth. If the advance growth needed thinning, light soil disturbance would be acceptable.

The large size and high quality of timber taken in shelterwood removal cuts permits the use of larger, more expensive equipment. In areas where cable or aerial systems are required, either type may be feasible depending on markets. Helicopter or balloon logging would provide the greatest protection for advance growth, so these systems would be preferred in areas where thinning was not required. Similarly, on sites where control of soil disturbance is critical, helicopter and balloon logging are preferable provided log values are sufficiently high to permit their use. When markets are less favorable and where thinning of the advance growth is desirable, medium- or large-sized yarders and skyline logging would the most appropriate system. Assuming the stands were engineered for long-reach systems with substantial lateral yarding capability for previous cuttings, such systems should be used again. Removal cuts in shelterwood management still yield substantially less timber per unit area compared to clearcutting, so wider road spacing would be required to minimize total harvesting costs. This dictates the use of long-reach systems.

In areas suitable for ground-based systems, logging would be limited to manual falling. On average, the timber would be simply too large for mechanized cutting. On sites where thinning of the regeneration was not an issue, line skidding with either rubber-tired or tracked machines equipped with long skidding lines could be used. These systems do not require driving machinery to each tree harvested, which helps control damage to regeneration. Herring bone felling patterns and straight line skidding would be required to help control damage to advance growth from the sweeping action of loads being swung into line. Where thinning of the advance growth was desirable, bunk or clam bunk forwarders could be used, however, it is doubtful that such equipment would prove more profitable than conventional line skidding.

Seedtree Management: Commercial Thinning

The recomendations for harvesting systems to use in these treatments are the same as those given for commercial thinnings and preparatory cuts in sheleterwood management.

Seedtree Management: Regeneration Cut

The observations and recommendations made for the regeneration cut in shelterwood management apply for the seedtree regeneration cut as well. Seedtree regeneration cuts remove more timber per unit area than similar cuttings in shelterwood management which permits the use of bigger machinery, and closer spacing of haul roads. Damage to residual trees is less of an issue as well because there is more space between uncut trees, again favoring the use of larger, less maneuverable equipment. Controlling soil disturbance is potentially more problematic in these treatments simply because of the increased equipment activity per unit area. Consequently, helicopter or balloon systems are preferred on highly sensitive sites provided markets permit their use.

Seedtree Management: Removal Cut

The observations and recommendations made for the shelterwood removal cut also apply to the seedtree management removal cut. The only difference is that the volume per unit area harvested is lower in the seedtree treatment which requires wider road spacing and lower cost harvesting equipment. This all but excludes helicopter and balloon systems except for under the very best market conditions. Similarly, where ground-bases systems are suitable, mechanized log-length or shortwood systems would be physically excluded due to the size of material cut.

Single Tree Selection

Cuttings in the application of single tree selection present the greatest challenge from a harvesting perspective. The intensity of these cuts as measured by volume harvested per unit area resembles preparatory cuts in shelterwood management, however, the size of timber harvested is much more varied. Trees in all commercially sized diameter classes are cut , consequently, tree and log sizes cover a wide range. Harvesting systems used for these cuttings must be capable of handling the biggest trees or logs to be cut, but large expensive equipment may not be economically feasible given so much of the timber is medium- or small-sized. Damage to residual trees is always a concern, so the equipment must be highly maneuverable, which also discourages the use of large machinery. Damage to advance growth is also a constant concern. Soil scarification is desirable in the CDF zone to favor regeneration of Douglas-fir, however, this is not critical given selection management is designed to promote more shade tolerant species.

On steep slopes or in areas with highly sensitive soils, cable or aerial systems are most appropriate. Helicopter and balloon systems provide the greatest protection to both residual trees and advance growth, so these systems are preferred when markets permit their use. Under most conditions, medium-sized yarders and skyline yarding with substantial lateral yarding capability is the most appropriate system. Larger trees may have to be bucked into short logs to permit yarding if the system does not have sufficient pulling power. The use of larger yarders may be feasible if economic conditions were favorable. Regardless of the size of equipment, the systems must be long-reach owing to the low volume per hectare removed.

In areas where ground-based systems are suitable, hand falling with line skidding is preferred because of its high degree of maneuverability. Mechanized log-length or shortwood systems may be feasible if markets are good, however, damage to advance growth could be problematic with these systems. In fully developed stands, there might be too much oversized material to permit the use of systems that employ mechanized felling and processing.

Group Selection

Cuttings in group selection management resemble those of single tree selection except that the cutting is concentrated in patches. This allows the concentration of logging activities spatially which has advantages with respect to productivity and damage control. Economically group selection should enjoy some advantages which may permit the use of larger, more expensive equipment. Stand-level planning for group selection cuttings is more complex and time consuming than in other partial cutting methods. Careful attention must be paid to the scheduling of treatment units within individual stands or cutblocks. For cable systems in particular, the location of clearcut patches with respect to yarding corridors is of critical concern. The size of the various patches is also important as the economic viability of future entries must be assured.

On steep slopes or highly sensitive soils where cable or aerial logging are required, terrain and timber size would dictate the choice of system. Long-reach medium-sized or large yarders and skyline systems are preferred where ever possible due to their lower cost. Balloon and helicopter logging would be justified only where engineering considerations precluded the use of long-line skylines, or where the absolute minimum amount of soil disturbance was required for seedbed or other reasons like in the CWH zones.

Where ground-based systems were appropriate, feller-bunchers and grapple skidding of whole-trees would be preferred provided that most of the timber were smaller than 60 cm at the butt and the volume per hectare cut were sufficiently high. In all other areas hand falling and conventional line skidding would be the only option. It is unlikely that single-grip harvesters and bunk forwarders could compete economically with less mechanized systems, and the physical restrictions with respect to maximum timber size would likely preclude the use of this equipment in many areas.

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APPENDIX A
Examples of Harvesting Systems Suitable for Second-growth Logging in Coastal British Columbia

The following are examples of harvesting systems suitable for logging in second-growth forests of coastal British Columbia. No attempt was made to document all possible machine makes and models, and the University of British Columbia does not explicitly endorse the use of any of the machines mentioned.

WHOLE TREE LOGGING WITH FELLER BUNCHERS AND GRAPPLE SKIDDERS

Treatments
Seed tree - regeneration cut
Group selection / strip clearcut

Capital costs
400,000 + $CDN for feller bunchers
200,000 + $CDN for grapple skidders

Crew Size
1 operator for feller buncher
A spotter on the ground may be necessary to aid in selecting trees during felling.
1 operator for grapple skidder

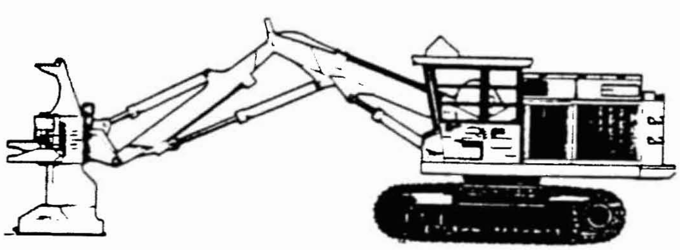
Comments:
Low ground pressure equipment like, track-type carriers or wide tires on wheeled machinery are recommended. Downhill (favourable skidding) is preferred. A delimber and/or processor is required at roadside to prepare logs for secondary transportation.

Table A-1. Representative examples of feller bunchers and grapple skidders.

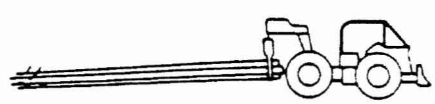
Make/Model	Carrier	HP	Weight (kg)	Ground Pressure (kPa)[1]	Max. Stump Diameter (cm)	Speed (kph)	Reach (m)
FELLER BUNCHERS							
FMG Timberjack 608	Track	137	19000	43	46	0 - 4.5	7.1
Caterpillar E110B	Track	79	16500	31	50	0 - 5.0	7.3
GRAPPLE SKIDDERS							
John Deere 648E	Wheeled	140	10800	NA	-	0 - 25.0	2.0 - 5.0
Caterpillar D4H TSK III	Track	105	15000	37	-	0 - 9.0	2.0 - 4.0

[1] 1 kPa = 1000 N/m^2

Diagrams



Feller Buncher



Grapple Skidder

LOG LENGTH LOGGING WITH SINGLE GRIP HARVESTER AND FORWARDER

Treatments
Preparatory and regeneration harvests for shelterwood
Regeneration cuts for seed tree in small diameter stands
Individual and group selection in small diameter stands

Capital Costs
450,000 + $CDN for harvester
400,000 + $CDN for forwarder

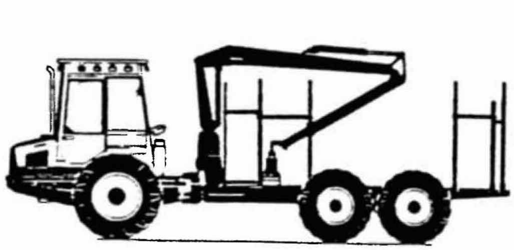
Crew
1 operator for harvester
A spotter on the ground may be necessary to aid in selecting trees during felling
1 operator for forwarder

Comments
Harvesters are limited by large diameter stems. Manual fallers working in conjunction with the harvester, can fall large diameter trees. Forwarders carry logs either uphill or downhill. Productivity is higher in downhill forwarding. Operations for single grip harvesters is up to 40%, but forwarding is cumbersome and dangerous above 30%. Harvesters and forwarders can be equipped with wide tires, or bogie tracks which reduce soil compaction.

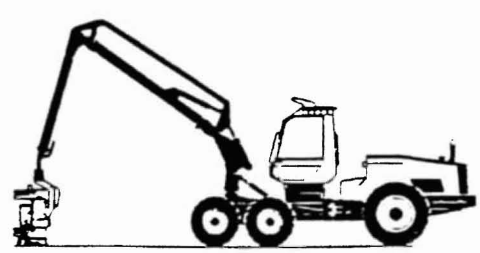
Table A-2. Representative examples of single grip harvesters and forwarders.

Make / Model	HP	Weight (kg)	Ground Pressure (kPa)[1]	Reach (m)	Payload (kg)	Max Diameter at stump (cm)	Speed (kph)
SINGLE GRIP HARVESTERS							
FMG Timberjack 1270	152	16,400	51 [2] 44 [3]	8.3	-	50	0 - 31.5
Valmet 862	103	13,000	49 [2] 26 [3]	9.6	-	45	0 - 30.0
FORWARDERS							
FMG Timberjack 1010	110	11,000	75 [4] 68 [5]	6.8	11,000	-	0 - 34.0
Valmet 832	98	9,800	78 [4] 39 [5]	6.6	10,000	-	0 - 30.0

All models are mounted on wheeled carriers
[1] kPa =1000 N/m^2
[2] Front tires
[3] Front tires, with bogie tracks
[4] Rear tires, loaded
[5] Rear tires, loaded, with bogie tracks



Single Grip Harvester



Forwarder

WHOLE TREE, TREE LENGTH, AND LOG LENGTH LOGGING WITH HAND FALLING AND LINE SKIDDERS

Treatments
All silvicultural treatments, under 35% slope

Capital costs
180,000 + $CDN for skidder

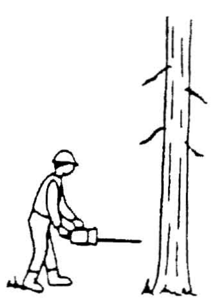
Crew
1 or more fallers
1 operator for skidder
1 - 2 persons may assist the operator in setting chokers

Comments
Wheeled carriers are faster and capable of longer skidding distances, but haul smaller loads than track-type machines. Uphill and downhill skidding is feasible, but downhill skidding is preferred. For downhill skidding over 20% slope "rub" trees should be used, especially on corners, to restrict potential damage to the site and residual trees.

Table A-3. Representative examples of line skidders.

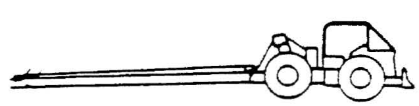
Make / Model	HP	Carrier	Weight (kg)	Ground Pressure (kPa)	Payload (kg)	Lateral Skidding (m)	Speed (kph)
Caterpillar D4H	90	Track	12000	50	8000	115	0 - 7.6
John Deere 450	70	Track	6600	30	6400	48	0 - 10.4
Tree Farmer C6D	117	Wheel	9600	NA	7000	88	0 - 20.8
FMG Timberjack	87	Wheel	7100	NA	4000	121	0 - 22.0

NA - information not available



Hand falling

Track-type



Rubber Tire

Line Skidders

WHOLE TREE, TREE LENGTH, AND LOG LENGTH LOGGING WITH STATIONARY SPAR YARDERS

Treatments
All silvicultural treatments

Capital costs (fully rigged)
180, 000 + $CDN for small yarders
500,000 + $CDN for medium yarders
1,000,000 + $CDN for large yarders

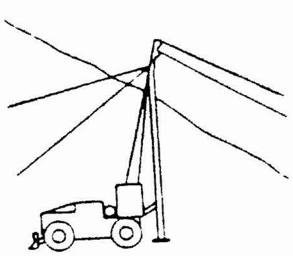
Crew
1 operator for yarder
5 + persons for rigging and setting chokers

Comments
Haulback drum capacity and deflection dictate maximum yarding distances. For carriages whose dropline is attached to the mainline, the lateral yarding capacity is a function of ground clearance, weight of cable, and terrain characteristics. Heavy mainline cable will restrict rigging crew capability of pulling the dropline laterally. Machines with taller spars and larger engines can lift and yard larger stems than smaller yarders, however expertise of the yarder operator and machine size are important in control of the load and damage to residuals. Larger machinery may take longer to tower down and change corridors than smaller equipment.

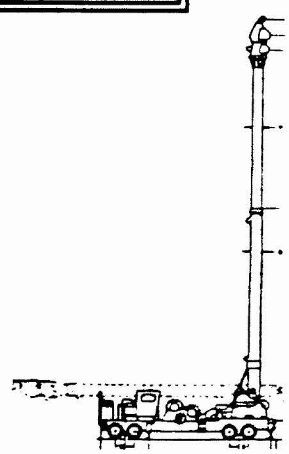
Table A-4. Representative examples of small, medium, and large stationary spar yarders.

Make / Model	HP	Tower Height (m)	# of Drums	Skyline Capacity (m)	Haulback Capacity (m)	Mainline Capacity (m)	Interlock Drums
SMALL							
Skylead C35	116	10.7	4	520 [2]	600 [1]	300 [1]	no
Koller K800	152	11	4	850 [2]	1500 [1]	750 [2]	no
MEDIUM							
Madill 171	248	14.3	5	589 [4]	929 [2]	665 [2]	no
Thunderbird TMY 50	325	15.2	5	762 [4]	1340 [2]	820 [2]	no
LARGE							
Madill 046	525	27.4	5	701 [5]	1615 [3]	792 [4]	no
Thunderbird TY90	425	27.4	4	762 [5]	1860 [2]	945 [3]	no

[1] 12 mm wire rope
[2] 19 mm wire rope
[3] 22.225 mm wire rope
[4] 25.4 mm wire rope
[5] 31.75 mm wire rope


Small Yarder


Medium Yarder


Larger Yarder

WHOLE TREE, TREE LENGTH, AND LOG LENGTH LOGGING WITH SWING YARDER

Treatments
All silvicultural treatments

Crew
1 operator for swing yarder
2 -3 persons in rigging crew

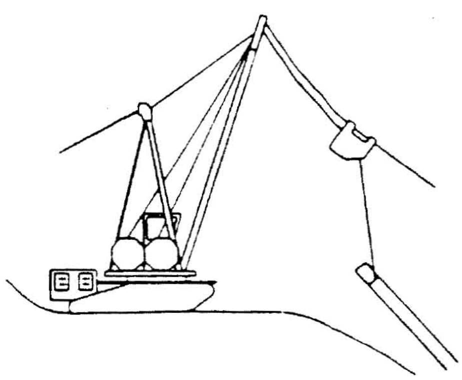
Capital Costs
800,000 + $CDN

Comments
Technical advantages of the swing yarder are: interlocked main and haulback winches which increases speed and control during yarding; ability to swing loads at the landing, reducing required landing size; and rapid setup between skyline corridors. Swing yarders operate most efficiently using a running skyline rigging system. Maximum yarding distances is restricted by the haulback capacity (usually capacity divided by 2). Lateral yarding distances of carriages whose dropline is attached to the mainline or slackpulling line is determined by the weight of the line, and deflection of the haulback.

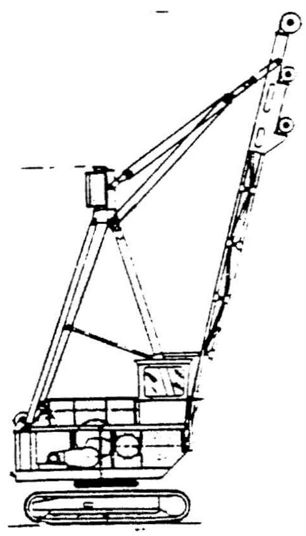
Table A5. Representative examples of medium, and large swing yarders.

Make / Model	HP	Tower Height (m)	# of Drums	Slackpuller Capacity (m)	Haulback Capacity (m)	Mainline Capacity (m)	Interlock Drums
Cypress 7280	450	18.3	4	820 [1]	1645 [1]	820 [1]	yes
Madill 1400	325	12.8	4	450 [1]	960 [1]	450 [1]	yes
Madill 122	450	16.5	4	610 [1]	1550 [1]	610 [1]	yes
Thunderbird TSY 155	350	16.8	4	450 [1]	915 [1]	450 [1]	yes

1 19 mm wire rope



Medium Swing Yarder



Large Swing Yarder

WHOLE TREE, TREE LENGTH, AND LOG LENGTH LOGGING WITH HELICOPTERS

Treatments
All silvicultural treatments, except in thinning of dense, young stands.

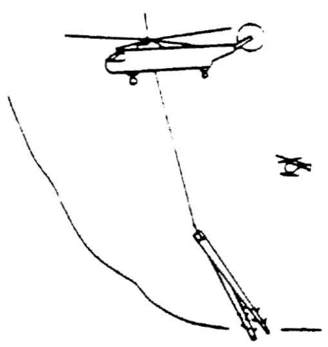
Capital costs
10,000,000 + $CDN

Crew size
4 pilots
2 aircraft engineers
5 persons in rigging crew
2 persons in the landing retrieving chokers

Comments
Helicopters used for logging must have the following characteristics: ability to lift and lower logs vertically; ability to place logs accurately, fast acceleration, and fast turning ability. To operate successfully helicopters should have work speeds of 100 - 150 kph. Optimal yarding distances are below 1 km, and yarding distances should not exceed 2 km.

Table A6. Representative example of helicopters used in logging.

Make / Model	Lift (kg)	Cruise Speed (kph)	Fuel Consumption (L/hr)
Boeing Vertol 107	4500	247	650
Boeing Chinook 234UT	12700	269	1930
Sikorski S61	4000	222	650
Sikorski S64E	8250	269	1363



Helicopter Logging

WHOLE TREE, TREE LENGTH, AND LOG LENGTH LOGGING WITH A BALLOON

Treatments

Final harvest in shelterwood and seed tree systems
Group selection / strip clearcuts

Capital Costs
1,000,000 + $CDN for Balloon
500,000 + $CDN for balloon yarder (2 - required)

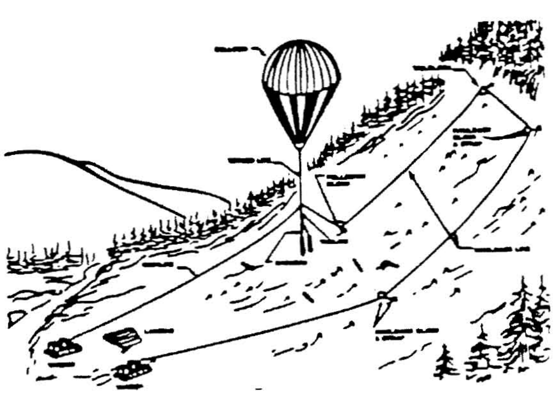
Crew
2 balloon yarder operators
5 rigging persons

Comments
The two main technical advantages of balloon logging are: Large payload size; and good deflection and ground clearance. Unfortunately, yarding times are quite slow, and large yarders are required to move the balloon. Uphill and downhill yarding is feasible. Two yarding configurations are used: the haulback configuration, with maximum yarding distance of 1000 m; and the Yo-Yo configuration, with a maximum yarding distance of 1500 m.

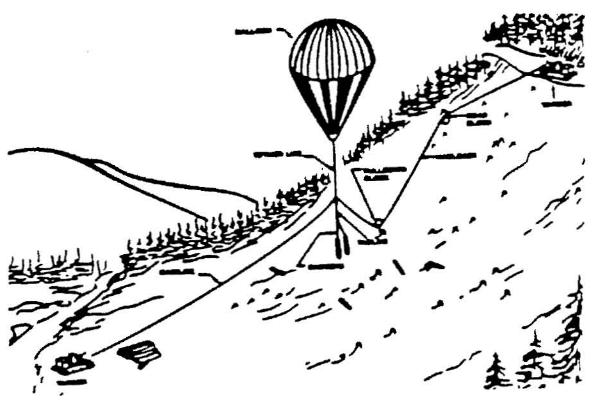
Table A7. Representative examples of balloons and balloon yarders.

Make / Model	Volume of Air (m^3)	Usable lift (kg)	HP	Machine Weight (kg)	# of Drums	Mainline Capacity (m)
BALLOONS						
530k	15,000	11,300	-	-	-	-
630k	17,500	13,150	-	-	-	-
BALLOON YARDERS						
Berger Balloon Yarder	-	-	700	54,400	2	2,130 [2]
Washington 608A Areo Yarder	-	-	550	66,200	2	1,980 [1]

1 25.4 mm wire rope
2 27 mm wire rope



Haulback Configuration



Yo-Yo Configuration

TREE LENGTH AND LOG LENGTH LOGGING WITH HORSES AND OXEN

Treatments
All silvicultural treatments

Capital Costs
5000 + $CDN for horse or oxen

Crew
1 - 2 operators for the horse or oxen
1 - 2 persons setting chokers or moving rigging

Comments
Horse and oxen logging has not proven to inflict less site damage than other logging methods, but is relatively low cost. Downhill (favourable) skidding is preferred, because of increased payload size, and increased longevity of the livestock. Slopes should not exceed 25%. Yarding distances are short, less than 100 m, to reduce strain on the livestock. Hot summer weather is very detrimental to productivity. Availability of quality feed and water is very important.

WHOLE TREE, FULL TREE, AND LOG LENGTH LOGGING WITH SKYLINE CRANE (SLEDS)

Treatments
All silvicultural treatments

Capital Costs
? + $CDN for Wyssen Skyline Crane

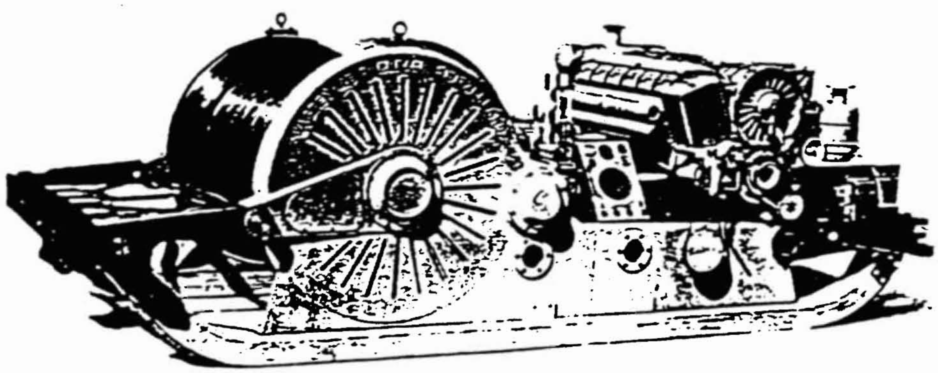
Crew
1 operator
3 - 5 in rigging crew

Comments
Wyssen Skyline Cranes (sled) have 1 drum. Logs are yarded in a single operation to the skyline and yarded uphill or downhill. Slopes of at least 20% are necessary. Standing or live skylines are used. Wyssen has patented it's own carriage, which clamps mechanically to the skyline, and releases the dropline from the crane. Lateral yarding up to 110 m is possible.

Table A-9. Information for two Wyssen Sky Cranes

Make / Model	HP	Weight (kg)	Drum Capacity (m)	Load Capacity (kg)
Wyssen W-90	80	1800	2900 [1]	2500
Wyssen W-200	200	6800	2900 [2]	7000

[1] 12.7 mm wire rope
[2] 19 mm wire rope



Wyssen Sky Crane

SMALL WINCHES FOR PRE-BUNCHING OF LOGS

Silvicultural Treatment
All treatments

Capital costs
2000 + $CDN

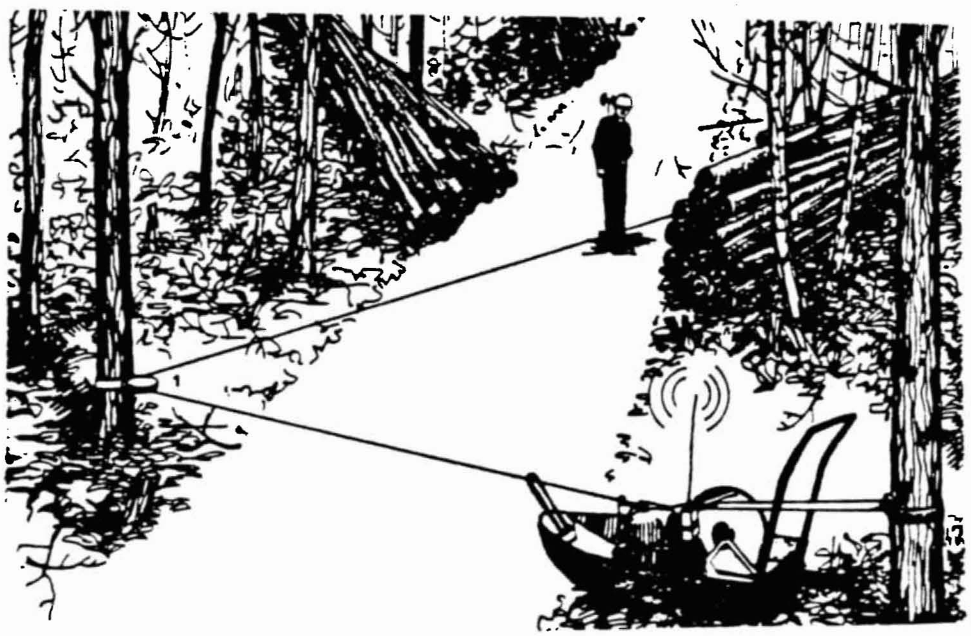
Crew
1 - 2 persons

Comments
Winches for pre-bunching must be strong enough to move logs, but excess power and weight decreases maneuverability, increases potential damage to residuals, and raises accident rates. Sled winches need to be anchored to a stump or tree. Winches can also be mounted to small tractors or skidders.

Table A-10. Example of two small sled winches.

Make / Model	HP	Weight (kg)	Drum Capacity (m)	Pulling Power (kg)	Radio Control
RADIO-TIR	6	150	150 [1]	800	yes
Wyssen W-20	20	860	1180 [2]	2500	no

1 9.5 mm wire rope
2 12.7 mm wire rope



Small radio controlled winch

CARRIAGES FOR PRIMARY TRANSPORTATION IN CABLE LOGGING

Treatments
Lateral yarding capabilities necessary for all treatments involved with partial cuts
Grapple and highlead rigging optional for pre-bunched logs in skyline corridors, strip clearcuts and group selection

Capital costs
5000 + $CDN for simple mechanical carriages
25000 + $CDN for more complex carriages

Comments
Lateral skidding capability is dependent upon type of carriage, capacity, and deflection. Carriages which store the dropline in the carriage, or have a motorized dropline have greater lateral yarding capabilities, because the rigging crew must only drag the dropline from the carriage, and the carriage has it's own line independent of the yarder. Carriages can be clamped manually or mechanically to the skyline. The clamp ensures that the carriage stays in one position during lateral yarding. Unclamped carriages use the haulback line to hold the carriage in place during lateral yarding.

Table A-8. Representative examples of carriages used in primary transportation in cable logging.

Make / Model	Weight (kg)	Skyline Size (mm)	Clamping Device	Haulback Required	System	Lateral Yarding (m)	Motorized HP
MECHANICAL, DROPLINE ATTACHED TO MAINLINE							
Christy Heavy Duty	204	28.6	Mechanical	yes	live or standing	30 - 50	-
Danebo B2	1590	28.6	Mechanical Radio controlled	yes	live or standing	30 - 50	-
MECHANICAL, DROPLINE STORED IN CARRIAGE							
Maki DLC 36S	725	-	Not clamped	yes	Live	76	-
Ballenger	2100	44.5	Hydraulic Radio Controlled	yes	live or standing	92	-
MOTORIZED DROPLINE CARRIAGE							
Thunderbird SC - 15	1900	28.6	Not clamped	yes	Live or standing	175	100
Danebo Skycar SC-40	3175	38.1	Not clamped	yes	Live or Standing	150	160

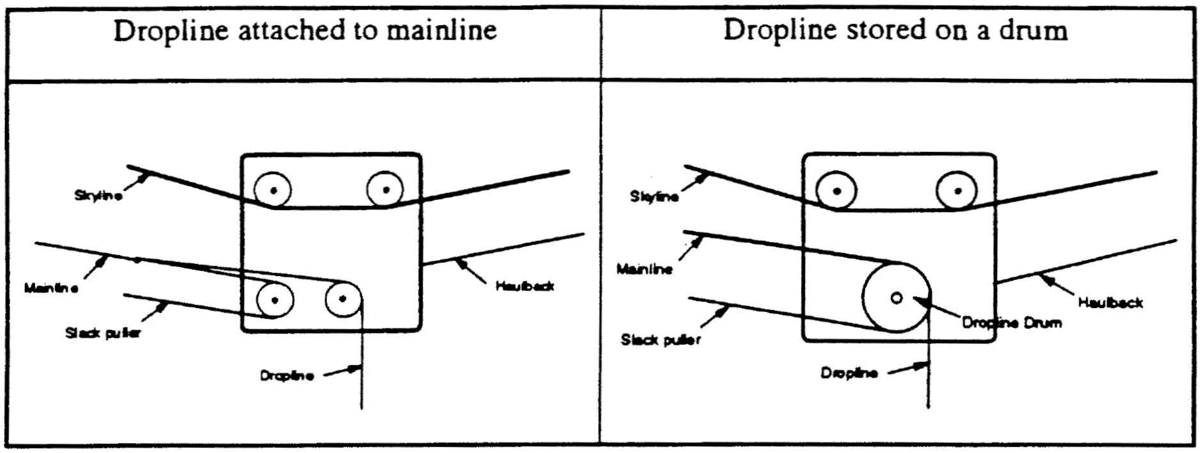


Figure A-1 Mechanical slack pulling carriage with mainline, slack pulling line and haulback

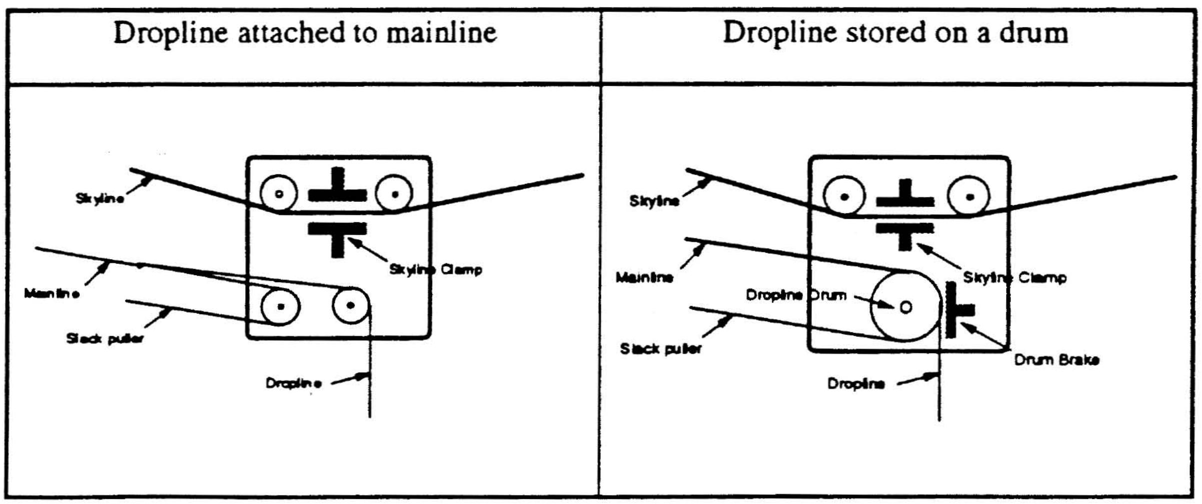


Figure A-2. Mechanical slack pulling carriage with mainline, slack pulling line and radio controlled skyline clamp

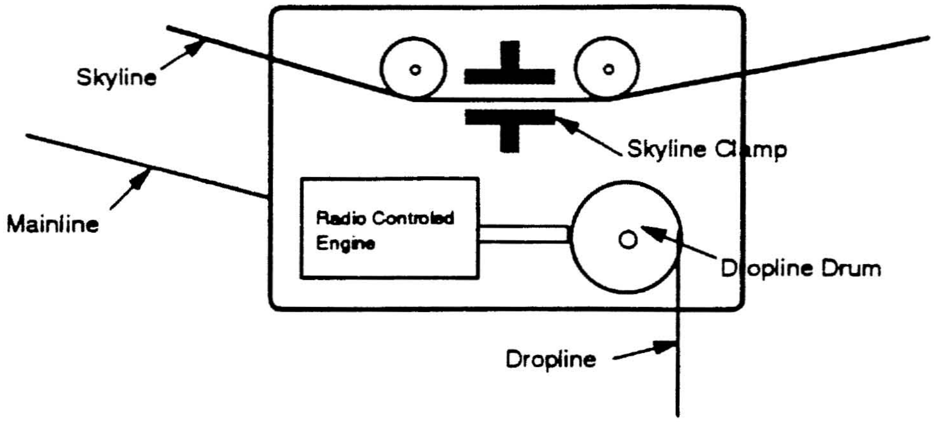


Figure A-3. Motorized drop line carriage with mainline

APPENDIX B
Examples of Skyline Rigging Methods

Cable systems used in partial cutting operations require specific operating characteristics. They must be capable of operating in skyline corridors of minimum width. This capability normally excludes systems with independent haulback lines, such as highlead and slackline, since these must return along the skidding corridor, creating rigging, operational and safety problems. The yarder must have effective skyline and operating line control to minimize residual damage created by the lines and logs striking the residual trees. Interlocked winch sets improve line control considerably, and are thus recommended when available. The system used must be sized correctly for the timber being removed. This is important to obtain the required turn suspension for the existing allowable deflection on the yarding road. Full turn suspension is particularly important when damage to advance growth must be avoided. It is also important in situations involving down hill (particularly cross slope) yarding in partial cuts as full suspension is required to avoid having the turn tumble out of lead into the residual stand on the downhill side of the corridor. Running skyline and multi-span standing skyline systems are particularly useful in these situations. In all cases, the skyline system must be capable of significant lift to avoid ground leading and the resulting trench formation that disrupts the natural hydrology of the area. Finally, cable systems used in partial cuts must be mobile and easily rigged to minimize the inter-corridor move time.

Live Skyline Systems:

Live skylines can be raised and lower during the yarding cycle. In clearcut operations, this can alleviate the need for a dropline carriage, since the carriage can be lowered to the ground to hook the turn. In partial cutting operations, however, a dropline carriage will always be required to provide lateral yarding capability. As well, the live feature may not be fully utilized since slacking the skyline will increase the potential for line damage to the residual trees on the edge of the corridor. Rub trees which are later removed can be used to reduce this problem. Since the use of an independent haulback is to be avoided the live skyline system would normally be rigged as a gravity system which limits the system to uphill yarding configurations.

Figure B-1 shows the live skyline gravity system. Normally, a radio controlled, motorized carriage is required to provide lateral yarding capability with this system. A mechanical slackpulling carriage can be used if an operating line is employed. This of course requires the added complexity of another winch drum. In very small systems it is possible operate with a manually clamped carriage or carriage stop. The mainline is manually pulled through the carriage for lateral yarding.

Single-Span Standing Skyline Systems

In standing skyline systems the skyline is not normally raised or lowered during the yarding cycle. The most common standing skyline system used in partial cutting would be identical to the live system described above. See Figure B-1. Similarly, this system would be used for uphill yarding only. The manual slack pulling option is not possible with the standing skyline.

Running Skyline Systems:

Running skyline systems employ the haulback as a skyline. These systems have significant potential for use in some partial cutting situations. They have reasonable lift capacity, are relatively simple to rig, operate well in a narrow corridor and can handle a variety of carriage types, including the simpler mechanical slack pulling carriages. They are, however, restricted to single span applications which limits the maximum yarding distance in some terrain. Figure B-2 shows a running skyline configuration with a mechanical slackpulling carriage.

Multi-Span Standing Skyline Systems

New, small multi-span systems are available for partial cutting operations. These systems can yard over substantial distances, providing full suspension when properly engineered. They can utilize a variety of carriage types. Figure B-3 diagrams a typical multi-span system.

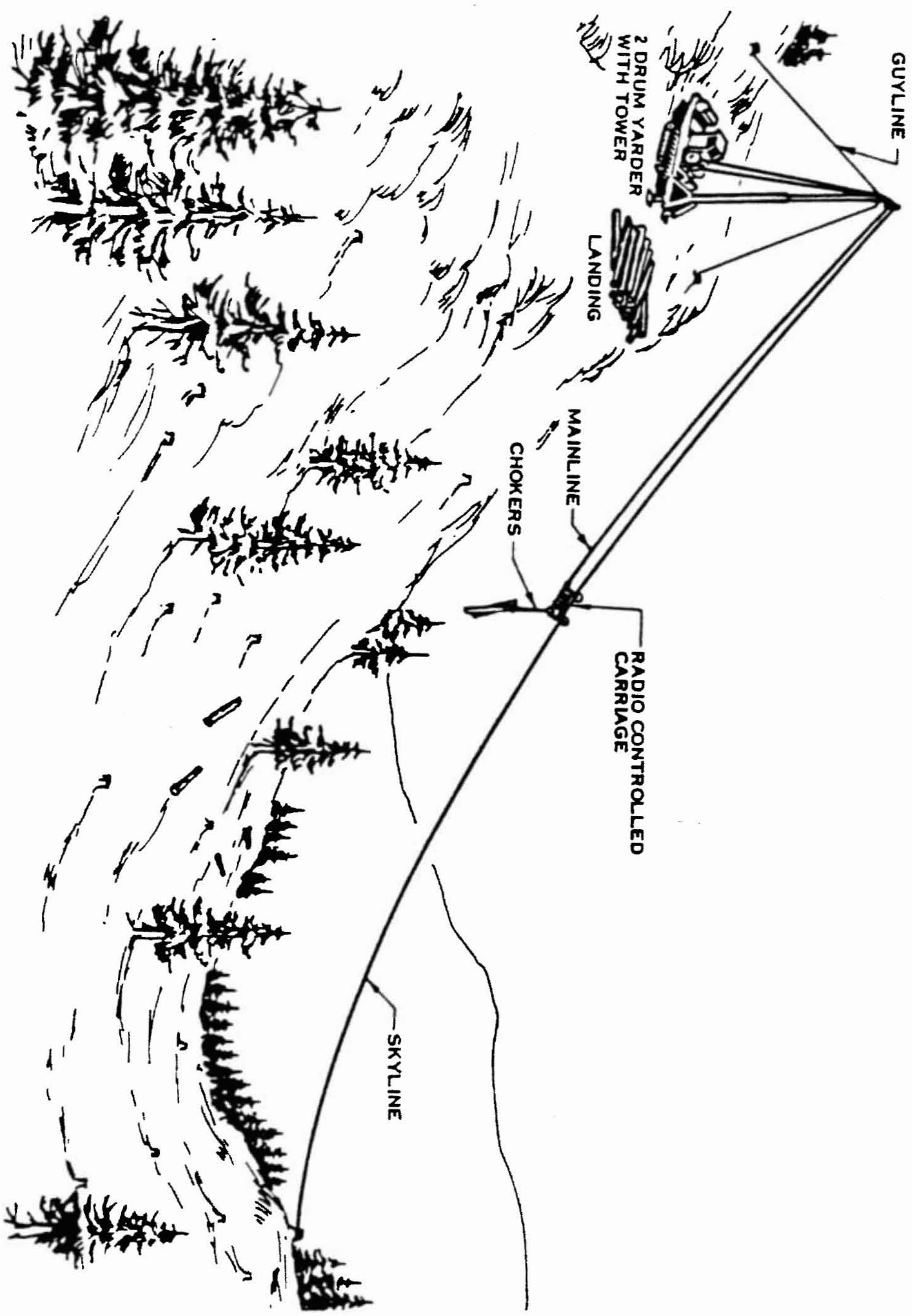


Figure B-1. Live skyline with radio-controlled carriage (from Studier and Binkley, 1974).

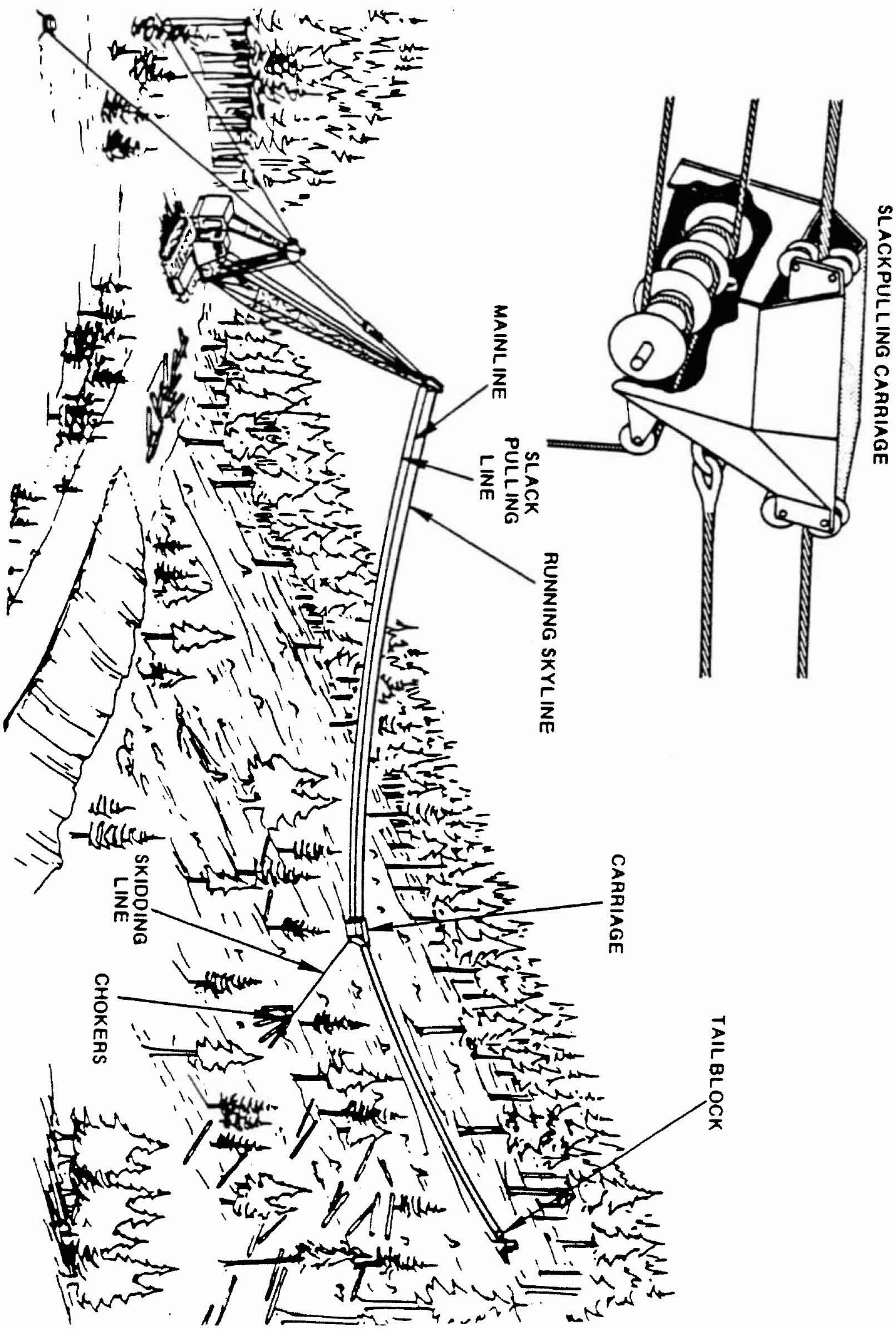


Figure B-2. Partial cutting with running skyline (from Studier and Binkley, 1974).

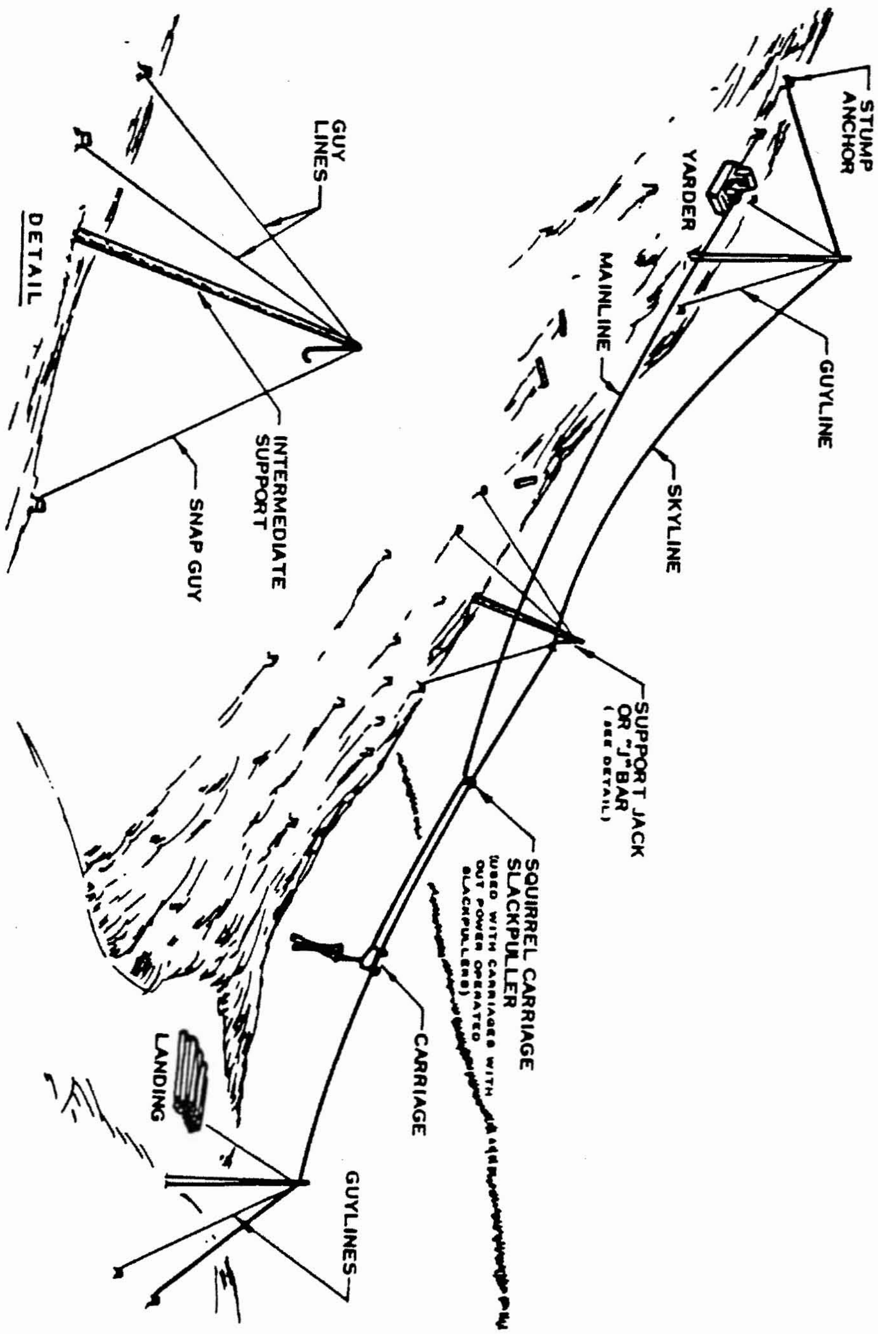


Figure B-3. Multispan skyline (from Studier and Binkley, 1974).