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Principles Used in Selecting Tree Species for Regeneration of Forest Sites in Southwestern British Columbia

by

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Abstract

Selecting the best tree species for reforesting a forest site is a critical decision in forest management. Ideally, this decision requires that the ecological characteristics of forest trees, sites and ecosystems are known, and that the intent, goal, strategy and objective of forest management are defined. This knowledge can then be used to develop criteria for selecting the most suitable tree species or combination of tree species for a given site. The criteria used in the tree species selection guidelines for southwestern British Columbia are: maximum sustainable productivity, crop reliability and silvicultural feasibility.

Résumé

Choisir les meilleures espèces d'arbres pour replanter une forêt est une décision très importante de l'aménagement forestière. D'une manière idéale, il faut connaître les caractéristiques écologiques des arbres, des endroits et des écosystèmes et les buts et les stratégies de l'aménagement forestière. Ces connaissances peuvent être utilisées pour établir des critères pour choisir les meilleures espèces d'arbres ou le meilleur regroupement d'espèces au sud de la Colombie-Britannique sont: la productivité maximale, la fiabilité et les possibilités quant à la sylviculture.

Introduction

Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] was almost the only species planted in the Vancouver Forest Region until well into the 1960's. As planting of this single species was extended to more diverse sites, a history of failure or poor growth became increasingly common. Early failures in the 1950's led to concerns about provenance and the establishment of the Douglas-fir genetics program pioneered by Dr. Orr-Ewing. Subsequently, based on the pioneering work of Krajina (1965, 1969, 1977), the need for a guide for allocation of tree species was realized. In 1977 guidelines for tree species selection were published (Klinka 1977a, b). These guidelines, however, did not provide any supporting evidence for the species selection recommendations; this paper provides that background. Part of this background has already been described by Nuszdorfer and Klinka (1982).

Tree species selection in forestry remains undeveloped in most parts of the world because of:

1. inadequate knowledge of the ecological characteristics of tree species and of the effect of these characteristics on the function and properties of natural and managed ecosystems (Jahn 1982);

2. inadequate knowledge of the growth and yield of various tree species in managed, pure and mixed stands on various sites, and the lack of long-term growth predictions (Assmann 1961; Fries 1978);
3. the difficulty in dealing with the complexity of selecting species combinations when considering both management and ecological factors (Mayer 1977; Mezera 1958); (Mayer, for example, listed 19 ecological, 13 management and 16 silvicultural factors, all of which must be taken into account in the choice of tree species); and
4. uncertainties in the future economics of forestry (for example, the economic costs and benefits associated with future forest products cannot be accurately predicted in advance).

Tree species selection in Europe has been more objective than elsewhere because some of the concerns mentioned above have been overcome. European forestry has benefited from a much longer accumulation of silvicultural experience, greater knowledge of the ecological requirements of tree species, and the early development of vegetation or site classification systems which have successfully related tree species selection, silvicultural treatments, and other forest management practices to site (e.g., Jahn 1982; Mayer 1977). For example, the guidelines proposed by Anderson (1950) for regenerating forest sites in Britain have become, in a modified form, part of the "Forestry Practice" manual (Blatchford 1978).

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In North America, tree species selection has been discussed in broad general terms in silvicultural texts (e.g., Daniel *et al.* 1979; Smith 1962). Little has been published discussing tree species selection, however, on an ecosystem-specific basis. In British Columbia there have been recent attempts to rectify this situation. In addition to Klinka's (1977a, b) guide, guidelines for site-specific selection of tree species have been prepared by Packee (1976), Utzig and MacDonald (1977), and are being compiled through the ecological program of the BC Ministry of Forests for all forest regions in British Columbia.

Principles of Tree Species Selection Used in Southwestern BC

The appropriate species for the managed forest are considered to be one or more which are ecologically viable on the site in question and which are best suited to the management objectives. Thus, the selection will depend on:

1. ecological factors — the ecological characteristics of forest trees, sites and managed forest ecosystems;
2. management factors — the intent, goal, strategy and objective of forest management; and
3. the criteria used to determine the suitability of tree species for different management conditions.

1. Ecological Factors

An ecological basis and ecosystem-specific approach to tree species selection have been adopted. This is necessary because each tree species is adapted to a certain range of environmental conditions; therefore, each species will grow and behave in ways that depend on the ecosystems or sites in which it grows (e.g., Anderson 1950; Daubenmire 1976; Fowells 1965; Krajina 1969; Mayer 1977). In unfavourable environments, the growth potential of the species will not be realized, it will be more susceptible to damaging agencies, or more effort will be required to establish and grow the species. The performance of one tree species compared with others on a given site largely determines the choice of species. Knowledge of the environment, the ecological characteristics of trees, and the influence of the environment on tree growth, will allow us to select the most suitable stand composition and appropriate treatments for different sites and management objectives.

Thus, to match tree species with site, we must have (a) an appropriate ecological classification system and (b) a knowledge of characteristics of forest trees, sites and managed forest ecosystems.

The usefulness of an ecosystem-specific approach to forest management has been well established in Europe (Jahn 1982) and, more recently, has been stressed in North America (e.g., Daubenmire 1976; Kimmins 1977; Krajina 1960; Pfister and Arno 1980; Rowe 1971). In 1975, the BC Ministry of Forests adopted the biogeoclimatic ecosystem classification system developed by Dr. V.J. Krajina and his students. From the development of this system has come not only ecosystem units suitable for tree species selection but also much information about the ecological characteristics of tree species, forest sites, and natural ecosystems set in the framework of this classification system (Krajina 1965, 1969, 1977; Krajina *et al.* 1982).

The first step in the process of selection is, therefore, to determine which species are ecologically suitable for a given site. This information was obtained from Krajina (1969) and BC Ministry of Forests regional ecosystem studies. Ecosystem studies conducted in southwestern BC have found that generally only environmentally extreme sites support pure

stands. Such sites are those having either large water and nutrient deficiencies or excesses [e.g., **Sphagno-Pinetum contortae** on very acid peat bogs or **Maianthemo-Piceetum sitchensis** on sites affected by brackish water (Krajina 1969)]. Most forest sites can support mixtures of species (Pojar 1983). The actual stand composition depends greatly on the successional status of the ecosystems and tree species diversity in the general area. In general, pure stands of shade-intolerant (pioneer) species are characteristic of the early stages of secondary succession, whereas mixed stands of shade-tolerant species are characteristic of the near-climax or climax successional stages. Not all possible tree species and site combinations could be examined in these ecosystem studies. Some combinations may be rare or non-existent under natural conditions. However, these rare or non-existent combinations may be more useful than the common ones, and on many forest sites a silviculturist may choose among a number of tree species.

2. Management Factors

A consideration of management factors constitutes the second step in the process of selection. At this stage the ecologically viable options are evaluated to determine which option best meets the management requirements.

The intent of forest management is often determined by government policy. In British Columbia, it may include management for one or more of the following: timber production, recreation, water, fisheries, and wildlife purposes (Forest Act 1979). Since the tree species selected will often be appropriate for purposes other than timber production, the tree species selection guidelines can satisfy more than one management intent. The following discussion refers to areas for which timber production is the primary management intent.

The management goal, as required by the BC Ministry of Forests Act (1979), is to utilize and maintain the productivity of ecosystems within constraints imposed by the natural environment and management objectives.

To avoid ambiguity in tree species selection, a general yield strategy must be defined. The yield strategy for managed forest stands in BC has been rather loosely defined. The question arises as to whether or not one should consider sustained yield (a sustainable yield based on the site's carrying capacity without constant inputs of material and energy) or amplified yield (a yield constantly exceeding the original carrying capacity of the site which depends on constant inputs). Silen (1982) discussed advantages and disadvantages of each and proposed a yield strategy for Douglas-fir. We adopted this strategy as generally applicable to long-rotation forest crops; it is based on the following requirements:

1. present soil fertility must be maintained or improved, not degraded;
2. soon after crop establishment the site must be occupied at all times by a full canopy of the growing crop;
3. the crop must be capable of using the site completely;
4. when practical and feasible, growth constraints should be relieved so as to enhance the inherent site potential for growing the timber crop; and
5. trouble-free ecosystems should be maintained at low costs; ability of the crop to survive through to time of harvest is the most important management requirement.

How is tree species selection related to these requirements? The first requirement depends largely on the impacts of forest management practices on the soil or the degree of nutrient management practised. However, tree species grown may have a long-term effect of soil properties. The second requirement relates to silvicultural policy. In BC, regardless of the management tenure or ownership, the aim is to achieve both full site occupancy and well-distributed seedlings for

plantations as well as naturally regenerated areas.

The third requirement means that we must identify tree species capable of using a site completely and we must select local natural populations of these species for regeneration. Silen (1982) considered such populations to be genetically adapted to a site and resistant to any insect or disease hazards present. The third requirement is related to the fourth one; it can be expected that a crop capable of using a site fully should provide a yield approaching the production potential of the site providing that stocking is adequate. The decision of whether or not to enhance the inherent site productivity by relieving growth constraints depends on our ability to identify effective and socially acceptable enhancement options. Finally, the fifth requirement, as with the third and fourth, is met by using for regeneration provenances of tree species that are genetically adapted to the site. For this reason, tree species selection should be carried out at both species and population levels. In western North America, foresters have recognized that selection of genetically adapted tree species populations is essential for best reforestation results (e.g., Ching and Beaver 1960; Haddock 1967; DeBell 1981; Silen 1982).

The management objectives define the nature, quality and quantity of the produce desired. These objectives depend on industrial demands and management and ecological constraints. In southwestern BC, maximizing piece size or quantity of fibre for lumber and pulp products, respectively, are two major management objectives. In view of recent and probable future developments in technology, maximization of both merchantable biomass and piece size appears to be a suitable option for the yield strategy discussed above. Different management objectives may sometimes require amendments to the tree species selection guidelines, but, more likely, use of different silvicultural regimes. It will often be possible, however, to mix two or more species or vary tree species composition of stands on similar sites in order to meet diverse produce and production requirements (e.g., Anderson 1950; Daniel *et al.* 1979).

3. Selection Criteria

To determine the most suitable tree species for areas where timber production is the management intent, we have used the following three criteria:

1. maximum sustainable productivity;
2. crop reliability; and
3. silvicultural feasibility.

Criterion 1. Maximum Sustainable Productivity. This means that the most productive tree species or combination of tree species should be selected for a given forest site and that the species or combination of species will fully utilize and not lower the potential of the site for growing timber crops. The selection should consider the long-term effects of tree species on soil fertility.

Forest productivity represents the capability of a site to produce timber assuming the presence of a certain species or a combination of species and a certain level of growing stock. Because forest productivity will vary according to the tree species present on a site, the maximum value of forest productivity is used to indicate the production potential of a site (Assmann 1961; Daniel *et al.* 1979; Daubenmire 1976).

The productivity ranking of stands of different tree species composition on the same site may change depending on whether volume, weight, or value units are used to measure forest productivity (Assmann 1961). The most commonly used estimate of forest productivity is the site index based on height of a stand at a reference age. Advantages and weaknesses of using site index to estimate site quality have been discussed by many workers (e.g., Assmann 1961; Daniel *et al.*

1979; Daubenmire 1976; Hägglund 1981). Because of the lack of ecosystematic yield tables for managed stands in BC, the availability of much site index data, and the relative ease with which further data could be obtained, it was decided to use site index (m/100 yrs) based on the top height to estimate productivity of all tree species-site combinations under comparison. Generalized site units were produced by the biogeoclimatic ecosystem classification. Site index data of Krajina (1969) and those collected in the regional ecosystem studies from unmanaged, single-species stands were used for productivity ranking.

Timber production of forest stands, however, does not always correlate well with site index because it is influenced by other factors such as tolerance to shade, spatial requirements of crowns, and form factor of the tree species. A comparison of cumulative volume production given by Hamilton and Christie (1971) for several western North American species grown in Britain of the same site index based on top height illustrates this point. Thus, at 80 years of age, 35 m of top height, and under the same thinning regime, the cumulative production for Douglas-fir, grand fir [*Abies grandis* Dougl. ex D. Don] Lindl., Sitka spruce [*Picea sitchensis* (Bong.) Carr.], western hemlock [*Tsuga heterophylla* (Raf.) Sarg.], and western redcedar [*Thuja plicata* Donn ex D. Don in Lamb.] is predicted to be 1197, 1282, 1292, 1416, and 1838 m³/ha, respectively. These other factors influencing timber production become more important in mixed-stands or when site indices of several tree species are not markedly different, and were considered in the productivity ranking.

Establishment of mixed-species stands is common in Europe (e.g., Assmann 1967; Mayer 1977), but has been given relatively little attention in North America (Smith 1962). For example, investigating actual timber production (m³/ha) of 21 managed, mature stands which included all major combinations of white fir (*Abies alba* Mill.), European beech (*Fagus silvatica* L.), and Norway spruce [*Picea abies* (L.) Karst.] in the Abieto-Fagetum Association, Prudic (1971) reported 69 percent difference between the most productive (fir 6, spruce 4) and least productive (beech 8, spruce 2) species combination. Summarizing the European studies, Assmann (1967) concluded that depending on tree species and site, merchantable timber production (m³/ha) in vertically stratified mixtures of compatible species may be as much as 30 percent higher than that of pure stands of any one of the included species. This increased production was attributed to increased photosynthetic efficiency and to asynchronous variations in growth rhythm, rooting habit, and litter quality of the participating tree species all of which contribute to full site utilization. Because of the potential productivity gain, establishment of mixed-species stands was always considered when determining the selection guidelines for southwestern BC.

The choice between a single species and a mixture of species depends on the characteristics of the site and the compatibility of the species in question. When ecological and stand history data indicated the potential for a merchantable crop of a mixed stand with a stratified canopy, then productivity of the available mixtures of species was examined. In southwestern BC, fresh to moist and nutrient-rich sites were evaluated as most suitable, while the combinations of very dry or very wet and nutrient-very poor or nutrient-very rich sites as least suitable for this purpose. Available information on shade tolerance and spatial requirements of tree species in pure or mixed stands (e.g., Fowells 1965; Krajina 1969; Krajina *et al.* 1982; Minore 1979) and available information on growth and yield (e.g., Cochran 1979; Farr 1981; Eis 1962; Handley 1976; Hoyer 1981; Klinka *et al.* 1981, 1982; MacArdle *et al.* 1949; Oliver and Kenady 1982; Osborn 1968; Ruth and Harris 1979; Stanek 1966; Osborne 1968; Wiley and Chambers 1981) were

interpreted to indicate the composition and structure of the most productive mixed-species stand.

An example of a single-species choice is on very dry and nutrient-very poor sites in drier mesothermal climates. Pacific madrone (*Arbutus menziesii* Pursh), lodgepole pine (*Pinus contorta* Dougl. ex Loud.) and Douglas-fir grow on these low productivity sites in pure or mixed stands. Pacific madrone is excluded from consideration since it is a non-commercial species. Of the other two species, lodgepole pine has a more rapid initial growth rate than Douglas-fir and would become merchantable at an earlier age. Consequently, a mixture of the two species would be less productive than a pure lodgepole pine stand on such sites.

Stratified double-canopy mixtures of compatible species (compatible primarily with respect to light requirements) are likely to be more productive than pure stands of any one of these species. Non-stratified single-canopy mixtures are likely to be less productive than pure stands of the most productive of the species because the production potential of the fastest growing species is simply diluted by intermingling with the less productive (Smith 1962). Creation of an essentially even-aged stand of usually no more than two or three species either by artificial or natural regeneration will then maximize production. Such a stand would consist of a less shade-tolerant species in the upper tree layer with one or two more shade-tolerant species in the lower tree layer. This results in maximum utilization of the above- and below-ground growing space (Mayer 1977).

Examples of such potentially highly productive mixtures are: (1) Douglas-fir with grand fir, western redcedar, or both on fresh to moist and nutrient-rich sites, or grand fir with western redcedar on moist to wet and nutrient-rich sites and active floodplains, both in temperate and mesothermal climates; (2) western hemlock (in a wetter maritime mesothermal climate), mountain hemlock [*Tsuga mertensiana* (Bong.) Carr.] (in a wetter maritime subalpine-boreal climate), or Engelmann spruce [*Picea engelmannii* Parry ex Engelm.] (in a subcontinental subalpine-boreal climate) with Pacific silver fir [*Abies amabilis* (Dougl. ex Loud.) Forbes]; and (3) Sitka spruce with western hemlock in hyper-maritime mesothermal climates on fresh to moist and nutrient-medium sites.

Still unresolved is the question of the relative productivity of different Douglas-fir — western hemlock mixtures. These species are commonly found in mixtures in natural stands in the area, but each species grows most productively under markedly different soil nutrient regimes (Eis 1962; Krajina 1969; Lowe and Kliska 1981). Preliminary studies in mature unmanaged stands have indicated the productivity of mixtures of these species will probably be less than that of pure stands of Douglas-fir or western hemlock. Thus, to date, either western hemlock with a minor component of Douglas-fir or Douglas-fir with a minor component of western hemlock has been recommended for a variety of sites.

Productivity declines resulting from successive, short rotations of even-aged, single-species stands have been a major concern to foresters in some areas. Work on Norway spruce and Scots pine (*Pinus silvestris* L.) monocultures in Europe (Pelisek 1975), radiata pine (*Pinus radiata* D. Don) monocultures in Australia (Farrell et al. 1981; Squire and Flinn 1981), and monocultures of native species in North America (Baker 1977; Ballard 1980) has suggested that such productivity declines have been due to changes in soil fertility caused by the species or management practices. Successive rotations of western hemlock monocultures in southwestern BC might ultimately cause similar productivity declines or reduce growth potential for other species on certain nutrient-poor sites. Western redcedar can increase the supply of available nutrients in the soil due to its ability to decrease soil acidity and

increase forest floor decomposition rates (Alban 1969; Tarrant et al. 1951; Krajina 1963). Consequently it has sometimes been recommended to accompany western hemlock as a compatible crop species.

Carter et al. (1984) reported dieback and distorted growth of Douglas-fir plantations established on climatically less suitable sites for that species in coastal BC. The cause(s) of this problem has (have) not yet been conclusively determined, but it appears that (a) nutrient deficiencies or nutritional imbalances are responsible, and (b) Douglas-fir is more susceptible than the ecologically more suitable mixtures of Pacific silver fir, western hemlock, and western redcedar, which grew on these sites prior to harvesting. Although the possibility that these species could be also affected at a later stage of stand development must be taken into consideration, selection of Douglas-fir as the only crop species for these sites is an ecologically less desirable option which fulfills poorly the criterion of maximum sustainable productivity. Stratified double-canopy mixtures of western hemlock and Pacific silver fir or western redcedar, or Pacific silver fir and western redcedar have been recommended for such situations.

Successive harvesting of timber crops will always cause removal of nutrients from the soil. This may be aggravated further by management practices. There are, however, some opportunities to conserve or add to the nutrient reserve of a site through selection of species, genotypes, and the use of plants living in symbiosis with nitrogen-fixing organisms (DeBell 1981). This, together with other aspects of nutrient management, will help overcome the adverse effects of harvesting and sustain or even increase forest productivity levels.

Consequently, when selecting compatible tree species for a mixed-species stand, in addition to considering shade tolerance, one should also evaluate nutritional characteristics of tree species and the effects of species on soil fertility. Thus, western redcedar, due to its beneficial effects on available soil nutrients, has been recommended as a crop or non-crop species on some nutrient-poor sites.

Criterion 2. Crop Reliability. This means that the established stand should be both resistant and resilient to all potential hazards so that the stand will survive to time of harvest.

A timber crop must survive and grow successfully for many years before it is harvested. During this period, it is likely to encounter many biological and environmental hazards which it must overcome. These hazards may include animals, insects, fungi, other pathogens, wind, snow, frost, drought, fire and floods. Exposure of a stand to some hazards cannot be entirely avoided but can be minimized by ecologically and genetically sound tree species selection and application of appropriate stand treatments. Periodic catastrophic disruptions occur, however, even in natural ecosystems (Ford 1981; Svoboda 1952). Since one disastrous year can destroy the accumulated production of many years, crop reliability is regarded as the most important criterion by many workers (e.g., Anderson 1950; Haddock 1967; Mayer 1977; Silen 1982; Smith 1962; Svoboda 1952).

High vulnerability to destruction by wind, insects and fungi has been common in pure stands of Norway spruce or Scots pine in central Europe, particularly on sites marginally suitable for the species or outside their natural range. Widespread blowdown, disease and insect attacks upon these major species have stressed the need for reevaluation of tree species selection. Severe blowdown problems of Norway spruce stands in northern Germany were countered by the planting of hardwoods indigenous to the area to increase the wind-firmness of the stands (Otto 1976).

Crop reliability problems, due to maladapted tree-species populations, which have arisen within a few decades after

stand establishment have been also noticed in western North America. In the US Pacific Northwest, Silen (1982) noted the attack of Bynum's blight (*Lophodermella morbida* Staley & Bynum) on ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Lawson) plantations originating from seed from eastern Oregon planted in southern Oregon. He also noted that rhabdocline disease (*Rhabdocline pseudotsugae* Syd.) and Swiss needle cast (*Phaeocryptus gaumanni* Rohde) attack introduced Douglas-fir plantations in temperate climates.

Widespread attack of weevil [*Pissodes strobi* (Peck)] on Sitka spruce plantations has been common in coastal southwestern BC. This has happened even on the outer coastal sites, eminently suitable for Sitka spruce, where it grew with excellent vigor in pure stands (Cordes 1972) and where little risk of serious damage from the spruce weevil was predicted (McMullen 1976). Thus, Sitka spruce cannot be considered a reliable crop species until the spruce weevil hazard is overcome.

Studies of crop reliability problems have led to the conclusion that (a) stands with composition and structure similar to that found naturally in any given area are more resistant and more resilient to the various hazards likely to be encountered, (b) many of these hazards can be minimized by establishing mixed-species stands (e.g., Assmann 1967; Malcolm 1979), and (c) genetic adaption of the trees to the prevailing environment is a prerequisite for maintaining stand health, with climatic adaptation being just as important as adaptation to biotic agents (Silen 1982).

As a consequence of the criterion of crop reliability, a tree species that is very productive on a given site but also very susceptible to environmental hazards, was not recommended for establishment in a pure stand or as a major species in a mixed-species stand. In such cases, a mixed-species stand or a less productive but more resistant species was selected. An example of this would be western white pine (*Pinus monticola* Dougl. ex D. Don in Lamb.) which can outproduce its associates on fresh to moist and nutrient-medium to rich sites in temperate and mesothermal climates, but which is also susceptible to blister rust (*Cronartium ribicola* J.C. Fischer ex Rab.). Until genetically improved stock of western white pine resistant to blister rust is available, other tree species should be selected as the major crop species. Similarly, increasing problems with root diseases [e.g., *Phellinus weirii* (Murr.) Silb.] in young natural or planted stands of Douglas-fir in coastal BC have led to recommending a mixed-species stand which includes a resistant species, such as western redcedar, as the more reliable option.

Another example of the use of the crop reliability criterion concerns susceptibility of a stand to blowdown. Inclusion of western redcedar or yellow-cedar [*Chamaecyparis nootkensis* (D. Don) Spach] as minor or major crop species in a stand is considered to help increase stand wind-firmness and/or soil stability since both species develop a very dense root system.

Criterion 3. Silvicultural Feasibility. This means that the species or combinations of species that will provide for the most biologically- and cost-effective silvicultural system appropriate to the management objective should be selected.

The most suitable forest stand is not necessarily the most productive one or the one that can be harvested at lowest cost — one must also consider the cost of all treatments required to produce the desired crop (Smith 1962). Each tree species-site option will require a more or less different series of silvicultural treatments during the life of a stand. Some tree species options may require complicated and expensive treatments, whereas other options will require only a few inexpensive treatments. Thus, costs of producing the timber crop may be decisive in

selecting the most suitable tree species composition.

The purpose of applying this selection criterion is not to determine the optimum series of treatments, but rather to identify those tree species options which on a given site will likely require more expensive treatments than other options, irrespective of the intensity of silviculture currently practised. On the basis of silvicultural experience and ecosystem studies, each tree species option was examined with respect to likely costs of establishment, maintenance and tending. The silvicultural treatments considered were: site preparation, regeneration, control of competing vegetation, and fertilization, i.e. those considered either essential for continuity of timber production or effective in increasing nutrient supply. The tree species options requiring the fewest and most effective treatments were ranked as silviculturally most feasible.

Using the example of a very dry and nutrient-very poor site in drier mesothermal climates, we concluded earlier that it is unsuitable for a mixture of species and that on the basis of maximum sustainable productivity lodgepole pine should be used as the major species on these sites. Lodgepole pine is shade-intolerant, while Douglas-fir requires shade for establishment and is shade-tolerant thereafter. Consequently after cutting, Douglas-fir has been very difficult to regenerate either naturally or by planting on this site and its initial growth has been very slow. In contrast, lodgepole pine is less susceptible to drought and easier to regenerate. Thus, on the basis of silvicultural feasibility, lodgepole pine was also considered preferable to Douglas-fir.

For a high brush hazard site, a tree species option that would allow vigorous growth of competing vegetation and would require excessive brush control costs was considered less feasible than one which either retarded growth of, or outgrew, competing shrubs. For example, on some low elevation, moist and nutrient-very rich sites in a mesothermal climate, a dense layer of several shrub species develops shortly after cutting the original stand. Attempts to establish Douglas-fir have often failed or have required considerable effort because the species is shade-intolerant on these sites and cannot survive without frequent brush control operations. On the other hand, the establishment of black cottonwood (*Populus trichocarpa* Torr. & Gray ex Hook.), also a shade-intolerant species, is not difficult because of its extremely high growth rate. Shade-tolerant tree species which, with some delay, will outgrow the shrub species present on these sites, are also preferable to Douglas-fir.

In situations where (a) Douglas-fir will require site preparation and planting, (b) western hemlock has regenerated or will regenerate naturally without unacceptable delay and distribution and, hence does not require site preparation, and (c) excessive natural regeneration of western hemlock in any established Douglas-fir plantations is predicted, the lower cost of establishing western hemlock, together with its probable shorter rotation if advance regeneration can be used, has led to western hemlock being recommended in preference to Douglas-fir.

In general, silvicultural management of even-aged pure stands is considered to be simpler, less expensive and more profitable than that of mixed-species stands. Securing regeneration and the desired proportions of the individual species in mixed-species stands may be relatively expensive unless compensated for by a higher crop yield or reliability. However, in many situations in coastal BC, natural regeneration has produced or will probably produce one or more tree species of the desired mixture. As a result, mixed-species stands can be established either naturally or by a combination of natural regeneration and planting. Planting of one species will be often sufficient to achieve both full site occupancy and the desired tree species composition. This is the case for western

hemlock or mountain hemlock — Pacific silver fir mixtures in montane maritime mesothermal or subalpine-boreal climates. Because advance regeneration usually produces an adequate component of Pacific silver fir, planting of hemlock, if deemed necessary, may satisfy the regeneration objective. Similarly, western hemlock and/or western redcedar, often desired or acceptable as minor crop species with Douglas-fir, will regenerate naturally with little delay in established Douglas-fir plantations.

The choice between a single species and mixture of species was said to depend on the characteristics of the site and the compatibility of the species in question. Mixtures of tree species, incompatible in light or nutrient requirements, have often been found to require additional treatments or to prevent the effective application of silvicultural treatments.

An example of a mixture needing additional treatment is the combination of red alder (*Alnus rubra* Bong.) and Douglas-fir on most coastal sites. Red alder may enhance soil fertility through its nitrogen-fixing ability, but its faster growth will soon allow it to dominate the stand canopy, adversely affecting the growth or even the survival of shade-intolerant Douglas-fir. Operations will then be required to release the Douglas-fir.

An example of a species mixture preventing the effective application of a silvicultural treatment is the combination of western hemlock — Douglas-fir. Different nutritional requirements of the two species suggest that fertilization effective for one species may be ineffective or even detrimental to the other (e.g., Webster *et al.* 1976). This may prevent effective fertilization of these mixtures, thus limiting the opportunity to improve nutrition for either species.

Integration of the Criteria

Clearly, selection of the most suitable tree species composition for a managed stand on a given site requires optimization using the criteria discussed above. Dynamic programming suggested by Hann and Brodie (1980) or simulation modelling, such as that described by Payandeh (1977), were proposed as suitable techniques for determining the optimum selection of the tree species. Elsewhere, linear programming methods have been used for selecting tree species options, taking into account a number of quantitative selection criteria (Mayer 1977).

In practice, such an optimization is fraught with difficulties associated mainly with uncertainties in future prices of silvicultural treatments and of the final crop. Furthermore, the intensity of silviculture practised will be ultimately determined by the amount of funds available for long-term silvicultural investments, which, in turn will be influenced by the crop revenues obtained. In addition, determination of the optimum series of treatments for a particular tree species option requires an economic assessment of alternative silvicultural regimes (e.g., Blatchford 1978). The results of such an assessment may dictate different silvicultural regimes for the same tree species-site combinations in different geographic locations. This could then lead to a change in the original tree species selection.

Because of these difficulties, the lack of growth and yield data and lack of economic assessments of silvicultural regimes associated with each ecologically viable tree species-site option, the above mathematical techniques for determining the optimum selection could not be employed. Instead, subjective assessments and choices were made. Thus, the tree species options recommended must be regarded as approximations, which are open to future amendments.

The examples given above in the discussion on selection criteria demonstrate the reasoning used to rank the available

options. This ranking usually restricted the choice to one or two options only. A few site types have such extreme characteristics that the number of viable options was severely limited and the ranking dispensed with all but one of them. When the ranking indicated that none of the options had met all the criteria, the first consideration in making the final choice was given to crop reliability. If this resulted in two or more first ranked options being equal with one or more having a higher maximum sustainable productivity but the other(s) having a higher silvicultural feasibility, then all the first ranked options were presented as alternative recommendations. It was not considered possible to determine whether maximum sustainable productivity or silvicultural feasibility was the more important criterion. This decision should be made by the field forester on a site- and situation-specific basis. In other situations where two or more tree species options were ranked equal, alternative options were also recommended. This commonly occurred due to the large number of uncertainties dealt with in the ranking procedure.

The Data Base

In applying the criteria discussed above it is necessary to have data relating to (a) productivity, (b) damaging agencies, and (c) the response to various silvicultural treatments, of trees in a wide range of species-site combinations. Ideally, such data would be obtained from experimental trials in which stands with different composition and structure had been established on the existing range of sites, and had been studied for a rotation. Unfortunately, such data do not exist in BC.

Such trials are necessary, but an interim alternative which is cheaper and more rapid, is the study of natural ecosystems with differing stand composition. This approach cannot replace the long-term study of permanent sample plots, but it can complement permanent plots because observation of seral stages can be made on many more locations within a site type. Natural ecological processes have produced stands of different tree species composition on the same site type. Frequently the stands may also have a similar age. In these instances, ecological and growth studies of such stands in southwestern BC have provided useful ecological and growth data (e.g., Lowe and Klinka 1981; Klinka *et al.* 1981, 1982). The approach using natural ecosystems, has also been advocated by Franklin in the US Pacific Northwest where it has yielded information relevant to managed forests (Franklin 1981; Waring and Franklin 1979).

There are however, some drawbacks to these studies. Not all possible tree species-site combinations have been found in southwestern BC. The naturally occurring combinations provide no data relating to the establishment of a species outside its natural range or in areas within its range where it occurs only rarely. In this respect, Engelmann spruce has recently been planted and is growing successfully on some montane mesothermal, temperate, and subalpine-boreal sites in southwestern BC where it had not previously been found naturally. Also, when comparing the productivity of different species on a given site, considerable care must be taken to ensure that the stands studied are in fact on equivalent sites and that they have had a similar history. The development of natural stands in response to treatments cannot be accurately determined.

Summary

In this paper we have attempted to clarify principles used in selecting tree species for regenerating forest sites in southwestern British Columbia. The choice of tree species is one of the most important and difficult problems that the forester has to solve. It has far-reaching influences on the utility of a new

forest and success of management; the particular concern of this paper is the effect of species choice on the level and continuity of timber production. The perfect solution to this problem is not yet available due to a lack of basic ecological data and uncertainties about the future. Choices must be made, however, even if based on incomplete knowledge.

The choice of species for the managed forest is accomplished by selecting that ecologically viable option which is best suited to the various management requirements. Thus, the selection process is based on ecological factors, management factors, and the criteria used to determine the suitability of tree species for different management conditions (Figure 1).

Figure 1. A flow chart illustrating the approach used to develop recommendations on tree species for regenerating forest sites in southwestern BC, as described in the text.

The first step in the process of selection is to determine which tree species, individually or in mixtures, are ecologically viable on a given site. This requires knowledge of ecological characteristics of forest trees, sites and managed forest ecosystems. Thus, before a new forest stand is established, an ecosystem-specific model of its composition and structure comprising all developmental stages from regeneration to maturity should be constructed. In this respect, British Columbia is particularly fortunate that, through the work of Dr. V.J. Krajina and his students, some of the information required has become available from the development of the biogeoclimatic ecosystem classification.

The next step is to select that species or those species, which will best fulfill the management requirements. We specified these requirements at four levels: intent, goal, strategy and objective. For the intent of timber production and the goal required by BC government policy, we adopted the yield strategy proposed by Silen (1982) and concluded that for maximization of both merchantable biomass and piece size as the

management objective, those tree species that are genetically adapted to a site and capable of utilizing the site completely should be selected. Three selection criteria used to determine such tree species are: maximum sustainable productivity, crop reliability, and silvicultural feasibility. The first criterion implies that the most productive tree species option should be selected; the second criterion implies that the most resistant and resilient tree species option should be selected; the third criterion implies that we should select the tree species option that will allow for the most biologically and cost-effective silvicultural system appropriate to the management objectives.

The choice of species poses a complex optimization problem. Even though objective mathematical techniques to solve such a problem exist, the lack of basic ecological and economic data necessitated a subjective assessment of the tree species options. In view of the lack of data and consequent subjective nature of the optimization procedure used, the existing tree species selection recommendations should be considered only as approximations which are open to future amendments.

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