rehabilitation in British Columbia are being used under a wide variety of soil and site conditions. Field visits during the summer of 1996 led to a preliminary conclusion that a careful and knowledgeable operator working with a good prescription is at least as important for a project's success as the choice of implement. On many sites, especially those with coarse-textured soils, several choices of implement appear to produce good results. Unfortunately, very few projects exist where the initial conditions and tillage procedure were documented well enough to reliably state that this first impression is correct. The effect of treatments on long-term plots can be evaluated only if initial conditions are recorded.

Long-term studies should address the following questions:

- Depth of tillage: What tillage strategies work best on a variety of sites and under varying conditions? Is restoration of a shallow surface layer an effective technique to restore productivity on sites with naturally shallow rooting depths?
- Resettling and soil structure stability: Under what soil/site conditions does resettling cause failure of the rehabilitation project? What techniques are suitable to prevent resettling?
- Minimum treatments: What low-cost rehabilitation treatments are effective for a variety of sites, including those with severe disturbance such as main roads and landings, and those such as rutted areas, minor trails, and roadside work areas with less severe disturbance?

5.2 Topsoil Conservation and Replacement

In forest soil rehabilitation, topsoil is operationally defined as the upper layer of the soil where most of the roots are located, with or without the forest floor. This definition recognizes that forest floor layers have distinct characteristics and functions compared to mineral soils, but that separating forest floors from mineral soil horizons is not usually practical using heavy equipment (Ballard 1980; Ziemkiewicz et al. [editors] 1980).

FIGURE 10 *Evaluating tillage depth (Morice Forest District, Telkwa River Forestry Road, km 15). The indicated depth of loosened soil is approximately 40 cm (total length of probe is 1 m), indicating effective tillage with a winged subsoiler.*

Replacing topsoil is an effective technique to restore productivity in degraded soils (e.g., Heilman 1983, 1990; Halvorson et al. 1986). The benefits of topsoil conservation and replacement are related mostly to the higher soil organic matter levels present in topsoil relative to subsoils, and the beneficial effect of the soil organic matter on physical, chemical, and biological conditions.

Compared to subsoil materials, topsoils usually have higher aggregate stability (Itami and Kyuma 1995), lower bulk density (Smith and Wass 1985; Carr 1988a), and more favourable pore size distributions, which leads to higher hydraulic conductivity, water-holding capacity, and aeration porosity (Potter et al. 1988; Sharma and Carter 1994). The loose, open structure of productive forest soils often depends on the presence of soil organic matter (Hudson 1994), but soil texture also plays a role in topsoils derived from medium- and fine-textured parent materials. In many parts of British Columbia, soil development has resulted in natural topsoils that contain less clay than subsurface layers (Lavkulich and Valentine [editors] 1978), and thus have inherently more stable macropores than their associated clay-rich subsoils. Variation in soil texture within the surface layers of undisturbed soils may result from translocation of clays in moist climates, or from additions of volcanic ash or wind-derived material to the soil surface.

Nutrient pools and cycling are also enhanced by the presence of topsoil on rehabilitated sites. For coal spoils in Washington, nutrient content of replaced topsoils was more than twice as high as for subsoils, even though the levels in topsoil were still well below those in undisturbed forests (Heilman 1990). Foliar nutrient levels in Douglas-fir reflected the soil nitrogen levels. In this study, 6- to 12-year-old Douglas-fir growing in reclaimed soils with topsoil had a similar site index to reference plantations on undisturbed soil. A plantation growing on subsoil material had a lower site index.

Topsoil also acts as a seedbank, which is often an important resource for revegetation with native species (Young 1990), but which also affects the need for subsequent treatments to control weeds and vegetation competing with crop trees (Heilman 1990). According to Young (1990), seeds are concentrated in the thin, organic-rich surface layer of soil. The seedbank layer may represent only a small portion of a thicker topsoil layer that would be conserved in many mine reclamation projects, but may closely reflect the types and amounts of materials commonly found near disturbed forest sites in British Columbia. Several factors affect the composition and viability of seed in soil seedbanks, including the composition of pre-disturbance vegetation and the ecological strategies (e.g., seed numbers, viability, dormancy periods, and germination requirements) of the plant species present. Removing and stockpiling the topsoil dramatically changes the environmental conditions that affect the seeds. Some seeds die as stockpiled topsoil ages, while others have their dormancy requirements satisfied. For a particular site and rehabilitation objective, changes in seedbank composition because of aging may be either favourable or unfavourable.

Farrish (1990) showed that seedling emergence was similar for loblolly pine grown in topsoil and subsoil, but that subsequent survival and early growth of roots and shoots was significantly higher for trees growing in the topsoil. Soil organic matter and nutrient levels were substantially lower for the subsoil treatments. The growth response was attributed to soil and plant nutrient status in this case, but the effects of low organic matter levels on soil physical properties affecting aeration and root penetration were not evaluated, and may have been significant.

When landings and roads are built without the intention to rehabilitate them, topsoil replacement simply involves retrieving and spreading any material piled at the edges of the landing or road (Figure 11). When rehabilitation is anticipated, and on steeper ground, topsoil is pushed to one side before levelling, or buried at a known location within the fill. If the topsoil is pushed to the side, full slope recontouring is not needed before the topsoil is respread.

In a study of skid site rehabilitation in New Zealand, Hall (1993) found that ripping and mounding effectively reduced soil shear strength, and the cost of ripping alone was modest. However, soil nitrogen on the ripped soils was well below the critical level for radiata pine, and some amelioration with chemical fertilizer or legume-derived nitrogen was considered essential. Respreading topsoil and logging debris was more expensive (accounting for 85% of the costs of a combined treatment that included ripping and mounding with respreading topsoil and logging debris) and nutrient limitations were only partially overcome. The equivalent cost of fertilizing to restore soil nutrients was not discussed, and comparative

FIGURE 11 *Topsoil piles commonly found adjacent to bladed areas on level ground (Kalum Forest District). Respreading these piles should enhance site nutrient conditions and improve productivity.*

tree performance on sites with and without topsoil was not available. Lawrie et al. (1996) showed that spreading topsoil on landings increased the cost of shallow tillage with an excavator by approximately 77%. Replacing topsoil during rehabilitation raises practical problems: the replaced topsoil should retain its beneficial physical properties and detrimental compaction should be avoided. Torbert and Burger (1990) observed that 70% of trees planted on restored mine soils in Virginia survived when planted on areas with minimal traffic, compared to 42% survival for trees planted on areas repeatedly travelled on during topsoil placement. Height growth after two years was also affected by the traffic. The areas of extensive traffic resulted from a grading operation that aimed to produce a uniform surface.

5.2.1 Information gaps: research needs

Three aspects of topsoil replacement in forest soil rehabilitation in British Columbia require further study. While the effects of topsoil replacement on productivity could be extrapolated from one disturbance type to another, the evaluation of costs and machine productivity must be investigated for individual disturbance types.

Quantify the benefits of topsoil replacement, in comparison to other methods of restoring soil structure and nutrient cycles Evidence from many sources indicates that topsoil conservation improves soil conditions, but the value of such benefits to growing trees is not known for forest soil rehabilitation situations in British Columbia. Long-term plots are needed to evaluate tree productivity on areas rehabilitated with and without topsoil replacement. One approach would include these plots as treatments in rehabilitation research projects that are evaluating various methods of restoring productivity.

Investigate biological processes in rehabilitated surface soils The biological processes that affect nutrient cycling and their relationship to site productivity are complex. In natural topsoils, populations of nutrient-cycling organisms are much larger than for associated subsoils. Studies of nutrient-cycling processes, such as microbial activity, populations of soil organisms, and characteristics of soil organic matter, would provide information about potential indicators of long-term site productivity on a range of site types.

Determine cost-effective construction methods for conserving and replacing topsoil Conserving and stockpiling topsoil for use in rehabilitation projects will likely become normal construction practice in forestry operations in the near future because of Forest Practices Code requirements. However, no obligation exists to respread topsoil piles that are adjacent to backlog sites requiring rehabilitation. Conserving, stockpiling, and replacing topsoil add significantly to the costs of access construction and rehabilitation. Many rehabilitation specialists in British Columbia are either not aware of the potential benefits, or do not feel that they justify the additional costs associated with the practice. Research, demonstration, and extension activities are needed to investigate cost-effective ways to manage topsoil. For example, studies of machine productivity (e.g., Lawrie et al. 1996) could be carried out to provide information for a variety of sites.

5.3 Slope Recontouring

Slope recontouring is a method where contour-built roads and trails are removed and the slope is restored to its initial shape. It is also called "road debuilding" on the coast, and in the southeast interior it is an important technique for skid road rehabilitation. Slope recontouring is carried out to control surface erosion, prevent mass wasting, restrict access, improve aesthetics, and restore soil productivity (Beese et al. 1994). The emphasis placed on restoring productivity depends partly on administrative issues such as the need for future access, and on site factors that affect the feasibility of restoring productivity.

Eubanks (1980) described a technique for restoring slopes that focused on hiding the road from view and preventing traffic from using the road. Although the goals were different from those of modern watershed restoration projects in British Columbia, some of the recommendations made by Eubanks were similar and included careful location of road takeoffs, topsoil stockpiling, and revegetation using seed. The estimated cost for full restoration was about equal to the initial cost of construction.

In the Nelson Forest Region, logging of steep slopes often involves construction of contour skid roads. The amount of land affected by skid roads became a concern in the early 1980s, after researchers drew attention to degraded soil conditions and reduced productivity. Soil conditions were especially poor on the gouged inner portions of skid road surfaces (Smith and Wass 1985). In response to the concern, and initially with the aim of improving visual quality of cutblocks on steep slopes, Crestbrook Forest Industries (Cranbrook) developed a system of skid road construction and rehabilitation that has evolved for over 10 years. Objectives of restoring drainage patterns, slope stability, and soil productivity were subsequently incorporated into the rehabilitation work.

Currently, skid road construction, use, and rehabilitation is planned through the entire harvesting operation by Crestbrook. Features of the operation's construction phase include consistently placing topsoil in a small windrow near the outside of the trail surface, minimizing the cut height, and avoiding calcareous materials, which are unsuitable as a growing medium for trees. Rehabilitation involves loosening and out-sloping the running surface, replacing the subsoil materials against the cutbank, replacing the topsoil, and scattering the slash across the surface. These techniques were among the most advanced viewed in British Columbia during site visits in the summer of 1996.

Dykstra and Curran (1996) described an investigation that was recently initiated to evaluate forest productivity on rehabilitated skid roads. The objective of the study was to quantify lodgepole pine and Engelmann spruce growth on rehabilitated skid road disturbance for various site types. A successfully rehabilitated site shows no differences in growth between trees in undisturbed conditions and at all positions within the profile of the rehabilitated skid road. On skid roads that have not been rehabilitated, trees growing on the inner gouged portion of the skid road are commonly smaller than trees growing on the outer portions (Smith and Wass 1979).

In the Vancouver Forest Region, Hickling et al. (1996) established over 70 measurement sites to evaluate the establishment and early growth of trees growing on rehabilitated roads. Most of the sites were in the Coastal Western Hemlock (CWH) biogeoclimatic zone, and trees were planted on roads rehabilitated with an excavator as part of operational work carried out by forest companies. Average survival rates after one year were over 95%. Preliminary results indicated that, compared to soils with low organic matter content (0–6.5%), high levels of organic matter (> 12%) in the surface soils were associated with greater height growth of Douglas-fir and western redcedar (over 100% taller). The use of various forms of tea-bag fertilizer also improved growth, but not to the same extent that organic matter did. Grass-seeding reduced height and diameter of Douglas-fir on one site. Deer browsing affected 20% of the plots, and was considered a serious problem where deer used the debuilt road.

Based on their preliminary results, Hickling et al. (1996) provided a description of what a successful rehabilitation project might aim for, including:

- a road that takes its place in the natural landscape (recontoured to natural state);
- organic material that is mixed into the surface, along with the transplanting of young trees or brush; and
- stockpiled materials and other available resources that are used appropriately.

5.3.1 Information gaps: research needs

Evaluate conifer growth on recontoured roads and skid trails We lack reliable information on the productivity of rehabilitated roads and contour-built skid trails. The work initiated in the Nelson Forest Region (Dykstra and Curran 1996) and by Hickling et al. (1996) illustrates the types of studies that will gain such information.

5.4 Reforestation and Revegetation Techniques

Numerous strategies can re-establish productive forests on degraded sites; each approach includes a range of options for plant species, establishment methods, and subsequent vegetation management techniques. On sites with low potential for erosion, and where soil properties are suitable, a simple and low-cost strategy involves establishing suitable conifer or hardwood crop trees and allowing shrub, herb, and other understory species from nearby areas to subsequently invade the site. This strategy can succeed on flat sites (low erosion hazard) with medium- to coarse-textured soils (rapid infiltration, limited potential for resettling following tillage), and where topsoil is respread (seedbank of native species available). The trees can establish by either natural regeneration from seed, or by planting suitable container or bareroot stock types. Simple approaches such as these are likely suitable on many sites, but additional revegetation techniques are often required, including those that provide visual cover, control erosion, restore and maintain soil physical properties, or enhance site nutrient pools and nutrient cycling.

5.4.1 Coniferous and hardwood crop trees

The goal of establishing trees on rehabilitated soils is the same as that for general silvicultural planting on undisturbed sites—that is, to achieve high survival rates and rapid early growth. Early successional species such as Douglas-fir on the coast and lodgepole pine in the interior have been favoured for rehabilitation, partly because they are adapted to the harsh conditions on disturbed areas. As more experience is gained, however, other species may prove equally successful, depending on the site conditions. Recently on the coast, plots were established to evaluate the performance of western redcedar, western hemlock, amabilis fir, yellow-cedar, and red alder (Hickling et al. 1996). In the interior, white birch, white spruce, and western larch were also established on rehabilitated sites. The unique characteristics of each of these species, and others including subalpine fir, aspen poplar, and black cottonwood, will likely ensure that they are used in rehabilitation work on some sites.

Successful establishment and early growth of planted trees requires that a healthy individual of a suitable seedling stock type is planted in a suitable microsite. On undisturbed portions of recently harvested cutovers in British Columbia, this usually occurs, and plantation failures are rare. For rehabilitated sites, however, seedling mortality rates are often much higher, and early growth is usually slower than for undisturbed soils. Each element in this series of events (i.e., plant, stock type, site) needs evaluation when developing techniques to establish fast-growing plantations on rehabilitated sites. Armson (1980) described how poor root development, which may result from low-quality stock or poor soil conditions, can lead to seedling establishment problems. Armson also described how root systems, that fail to expand during periods of rapid growth, can lead to poor performance and mortality at the sapling, or pole, stage of stand development. Therefore, along with the need to restore soil properties to suitable conditions, the quality of biological material used in rehabilitation is also an important factor affecting success.

Arnott et al. (1988) showed that 2+0 bareroot lodgepole pine outperformed 1+0 container seedlings on landings near Fort St. James. The bareroot stock type was larger when planted, and maintained consistently larger annual height increments throughout the five-year study. Hickling et al. (1996) also showed that larger stock types (PSB 415) of Douglas-fir grew faster on rehabilitated roads in coastal British Columbia.

Williston and Ursic (1979) recognized the need for microsite planting, but found that nursery practices such as fertilization and top pruning had little effect on success of loblolly pine planted for erosion control in the United States. Shallow planting was the most common cause of failure, while auger planting in a six-inch posthole and carefully selecting the planting spot improved survival. Some ineffective techniques included very deep planting, kaolin root dip, wax coatings to reduce transpiration, fertilizing at 300 lbs/acre, and interplanting with legumes.

The range of cultural techniques available in a modern nursery is much wider than that available in 1979. In addition, the awareness that mycorrhizae and other biological partners play an important role in water and nutrient uptake has led to the development of various biological inoculants with the potential to improve seedling performance. Mycorrhizal inoculation was tested as a means of improving planted seedling performance, but the results for undisturbed sites with adequate moisture supplies were mixed.

Walker et al. (1989) compared the performance of one-year-old bareroot loblolly pine seedlings inoculated with the mycorrhizal fungi, *Pisolithus tinctorius*, to that of control seedlings colonized primarily by *Telephora terrestris*. The seedlings were outplanted with or without fertilizer on a recontoured coal mine site that was also revegetated with a herbaceous ground cover. The loam soils had 3.1% organic matter, a pH of 6.0, and 0.1% total nitrogen. Survival and growth of loblolly pine after seven years was improved by the presence of *P. tinctorius*. The effect of the *P. tinctorius* was attributed to improved water and nutrient uptake evaluated through measurements of xylem pressure potential and foliar nutrient analysis. Fertilization with 336 kg/ha each of nitrogen, phosphorus, and potassium reduced survival and had no effect on growth. The effect of the fertilizer was primarily to enhance the growth of herbaceous cover, which often overtopped the pine in the fertilized plots.

Amaranthus and Perry (1987) showed that soil transfer increased survival and mycorrhizal colonization of Douglas-fir seedlings planted on old clearcuts by up to 50%. These authors found that the source of transferred soil was an important factor affecting success, and believed that the results demonstrated that ectomycorrhizal fungal inoculum had been transferred with the soil. Subsequent work by Colinas et al. (1994), however, showed that the situation was more complex—soil that was treated with fungicide also enhanced the formation of mycorrhizae on planted seedlings. They suggested that some aspect of the rhizosphere biology was altered by the transferred soil, which led to enhanced ectomycorrhizal colonization of the roots by inoculum already present in the clearcut.

These results might have relevance for rehabilitated sites, where soils would probably have low amounts of inocula for mycorrhizae and other soil organisms, and where soil aeration and moisture conditions are altered compared to undisturbed soils.

5.4.2 Grasses, legumes, and native shrubs for soil amelioration

Various revegetation strategies are available to enhance productivity on degraded soils. Revegetation is necessary to control surface erosion. Vegetation also helps to restore the soil by increasing soil organic matter levels. Techniques for controlling erosion with grass and legume plantings were the subject of several research projects carried out by the B.C. Ministry of Forests in the early 1980s. Results were presented in several reports and the techniques are well developed to address erosion concerns in forestry (Carr 1980, 1985; Homoky 1984, 1987; Beese et al. 1994). Although much was learned, some revegetation issues remain unresolved and others were raised more recently, including:

- the ecological benefits and hazards associated with establishing grasses and legumes on rehabilitated forest soils;
- the potential for improving soil structure through biological tillage; and
- the enhancement of site nutrient pools through nitrogen fixation.

Grasses and legumes Agronomic seed mixes are widely used in soil rehabilitation, and sometimes the purpose of this work was unclear. For example, several forest districts developed rehabilitation policies in the 1980s that required landings on all cutovers to be loosened and seeded to grass and legume mixes. In many cases, seeding grasses and legumes took precedence over planting trees, even on sites where no erosion hazard existed. While many of these landings provide valuable forage for cattle, and soil conditions may have been improved, they are not yet developing into productive forests.

In 1975, several landings near Williams Lake were loosened and seeded with combinations of lodgepole pine and grass seed as part of a trial on the effectiveness of landing rehabilitation techniques (Vyse and Mitchell 1977). Although the experiment was abandoned shortly after it was installed, recent observations indicate that lodgepole pine was successfully established from seed on landings not seeded to grass (Figures 12 and 13). Grass may hamper germination and subsequent establishment of pine on sites in this area. Poor germination of pine seed on the study sites was documented in the first year of the trial, but in subsequent years more of the seed germinated. Competition between trees and grass, and cattle damage to seedlings, may also cause reforestation problems (Figure 14). More recent evidence from throughout British Columbia illustrates that, where delayed seeding or other factors have resulted in poor development of grass and legume cover crops, growth of pine trees is satisfactory (Figure 15), suggesting that grasses and legumes are not an essential part of soil rehabilitation on all sites.

Amaranthus et al. (1993) observed that seeding annual ryegrass (*Lolium multiflorum*) in an area characterized by extended summer drought caused low soil moisture levels and increased mortality of sugar pine seedlings planted the following spring. In the following year, the grass died and the thatch cover acted as a mulch, which resulted in increased soil moisture content and improved survival for trees planted into the thatch. On unseeded plots, bare mineral soil covered 85–95% of the area, but native species re-established to cover 30% of the area after two growing seasons. Grass covered 85% of the seeded areas after one year. Differences in mycorrhizae between seeded and unseeded plots were not consistent. The authors did not encourage grass seeding because other studies indicate that grasses restrict mycorrhizal formation. This can occur

FIGURE 12 *Landing rehabilitated as part of EP 777 in the Williams Lake Forest District. The entire landing was tilled and lodgepole pine established from seed. The left-hand portion was not seeded to grasses, and reasonable stocking and growth of lodgepole pine was observed 20 years after rehabilitation.*

FIGURE 13 *The right-hand portion of the landing from Figure 12 (Williams Lake Forest District), which was seeded to grasses and legumes. Very few pine survived.*

FIGURE 14 *Seedling damaged by cattle trampling in a rehabilitated roadside work area (Moffat Road, Williams Lake Forest District).*

FIGURE 15 *Rehabilitated landing with good pine growth, but poor germination of birdsfoot trefoil because of delayed seeding (Kispiox Forest District). Favourable seedbed conditions persist for only a short time after tillage.*

directly by inhibiting ectomycorrhizae, or indirectly by slowing the invasion of native shrubs that have ectomycorrhizae.

In another study of the effects of grass seeding on tree establishment, Carpenter and Albers (1981) showed that moisture stress and mortality were highest in June for alder seedlings planted into a dense stand of fescue (*Festuca arundinacea* Schreb.) on surface mine soil in Kentucky. Leaf water potential and soil moisture content were generally lower for trees planted in plots with fescue and where fescue was mowed, compared to plots where grass cover was scalped away or where it was temporarily set back by herbicide.

Although grass seeding can result in moisture stress to trees in dry climates, the negative effects of grass are not well documented in moist climates in

British Columbia. Several examples from various areas of the province show healthy forests growing on rehabilitated sites that also support vigorous stands of grass and legume (Figure 16). Grasses and legumes may provide a cost-effective means of enhancing soil organic matter and nutrient levels on these sites (Figure 17). In the Interior Cedar–Hemlock (ICH) and Engelmann Spruce–Subalpine Fir (ESSF) biogeoclimatic zones of interior British Columbia, seeding with grasses and legumes is employed to reduce competition between crop trees and native vegetation (Steen and Smith 1991). Early results suggested that the shorter agronomic grasses and legumes displaced taller native species, which was the objective, but had little effect on conifer crop trees. Hickling et al. (1996) suggested that the growth of tree seedlings planted in grass-seeded areas was slightly reduced in coastal British Columbia.

Biological tillage Information in Table 2 indicates that the roots of some tree species can penetrate compacted soils better than others; the same is true for agricultural crops. This observation has led some researchers to suggest that such plants could be used as "biological plows" to penetrate compacted soil layers, and create channels for the roots of crop species. Henderson (1989) estimated that this effect was true of lupine, which improved wheat yields by 100 kg/ha, on a sandy soil in Australia that was compacted by agricultural machinery.

Materachera et al. (1991) evaluated 22 plant species for their ability to penetrate a soil medium compacted to a strength of 4200 kPa (penetrometer resistance), and found that all species had their root elongation reduced by over 90%. The roots of dicotyledonous plants generally had larger diameters and penetrated the medium better than graminaceous

FIGURE 16 *Landing rehabilitated in 1987 in the Quesnel Forest District. Excellent pine growth on sandy soil with organic-rich surface horizon. Excellent growth of grass and legume. Steel probe penetrated to 20 cm.*

FIGURE 17 *Surface soil conditions on the landing illustrated in Figure 16 (Quesnel Forest District). Grasses and legumes contribute soil organic matter and nutrients to develop a productive soil.*

monoctyledons with smaller-diameter roots. The best species included lupine, medic, and fava bean. In subsequent field tests (Materachera et al. 1993), lupine and safflower produced the greatest effect on water sorptivity of the compacted layers, but sorptivities were still well below levels for a tilled subsoil. The soil strength values used in the study by Materachera et al. (1993) are near the upper limits of values presented in Table 2.

The use of biological plows to rehabilitate compacted forest soils has not been investigated. However, studies that would be of obvious interest include evaluating root thickness of forest trees and shrub species in British Columbia compared to root thicknesses for species already tested, and using biological plows to restore severely disturbed sites, and as additional treatments to stabilize and maintain soil structure after conventional tillage.

Native shrubs A native shrub program was initiated in 1980 by the B.C. Ministry of Forests under Project E.P. 863. Over 40 native British Columbia tree and shrub species were propagated, a propagation manual was written, and field trials were established between 1981 and 1984 before funding for the program was discontinued. The results of this work appear in several publications including Marchant and Sherlock (1984), Homoky (1984, 1987), and Carr (1985).

Native woody species are useful in rehabilitation because they provide deep rooting and long-term erosion control, although it takes longer for the surface cover to develop than with grasses and legumes. However, on sites where immediate erosion control is not a major concern, or where other measures have been taken to control surface erosion in the short term, they may provide a method for re-establishing ecosystem characteristics similar to those of undisturbed areas. Marchant and Sherlock (1984) recommended that the selection criteria for species be based on the biogeoclimatic subzones. They presented 13 criteria that affected rehabilitation success, which were subsequently grouped into three major criteria:

1. known biological and ecological characteristics of each candidate species;
2. performance in field trials; and
3. performance in propagation trials.

Nitrogen-fixing species The potential benefits of establishing nitrogen-fixing species to restore nutrients on rehabilitated sites has been known for some time, but few studies have quantified the nitrogen inputs to rehabilitated soils from seeded legumes or nitrogen-fixing shrubs. For coastal sites, considerable information is available about the effects of red alder on soil properties and the potential rates of nitrogen fixation (e.g., Tarrant et al. 1992). For interior sites, use of legumes was investigated in the Prince Rupert Forest Region on rehabilitated landings (Marsland 1994), on blade scarified areas (Coates et al. 1993), and on cutovers subject to various forms of site preparation (Trowbridge and Holl 1989). This work has successfully established species such as birdsfoot trefoil on landings, and alsike clover on blade-scarified areas. Establishing legumes to enhance site nitrogen levels resulted in increased foliar nitrogen levels for lodgepole pine, but height growth after four years was not affected.

The establishment, growth, and development of grey alder (*Alnus incana*) and lupine (*Lupinus* spp.) on low-productivity sites in northern Sweden were studied by Huss-Dannell and Lindmark (1988). The sandy soils had been subjected to repeated severe fires, harvesting, or windthrow, and had thin mor humus layers, low soil organic matter, pH values near 4.0, and low soil nitrogen. Survival of alder after six years ranged from very good (84–92%) to poor (5–30%), with better performance indicated for warmer sites. Survival and growth of alder was similar for nursery-raised and locally transplanted seedlings, and for fenced and unfenced plots. *Lupinus nootkatensis* was the most successful lupine, either established from seed or by planting nursery-grown stock. Liming and scarifying the site improved the success of sown lupines. A companion experiment, in which 1000 kg/ha per year of alder leaves were added to the soil (which represents approximately the amount expected from established stands of alder or lupine) showed that the forest floor achieved the properties of more productive sites after only six years.

For restoration purposes, the authors concluded that lupin seemed hardier than alder. Lupines are easier and cheaper to establish because they are sown from seed, and their high reproductive potential is useful when complete site occupancy after about four years is desired. The authors noted, however, that lupines are toxic to cattle, and that they required inoculation with *Rhizobium*. Huss-Dannell and Lindmark (1988) considered alder as an effective species for soil restoration.

One strategy for using nitrogen-fixing species involves planting conifers before lupines are sown.

This is so that the trees do not face severe competition in the first three years after planting; after that they are likely well established, and begin to shade the lupine out. When alder is chosen to restore soils, conifers may be planted at the same time because the alder does not shade the ground as much as lupine.

Other potential sites of nitrogen fixation in forest ecosystems is the subject of recent studies. Nitrogen fixation associated with coarse woody debris (Graham et al. 1994) and in the rhizosphere of pine trees (Bormann et al. 1993) are of interest as potential nitrogen sources on degraded soils.

5.4.3 Information gaps: research needs

Establishing a productive second-growth forest is the ultimate test of success for rehabilitation projects. The renewed focus on rehabilitating soils for conifer productivity suggests that investment is necessary in revegetation research. As described previously (Figure 1), the amount of ongoing operational rehabilitation work in British Columbia is increasing rapidly and the need for information is acute. The following knowledge gaps were identified.

Testing conifer and hardwood species and stock types for rehabilitated sites and evaluating beneficial micro-organisms The range of species and stock types suitable for use on rehabilitated sites needs expanding. Large conifer stock types have been recommended for coastal areas (Hickling et al. 1996) and in the interior different stock types have shown varying rates of early growth on degraded sites (Arnott et al. 1988). In addition, the potential benefits of using biological inoculants to enhance rhizosphere populations of beneficial organisms should be investigated. Initially, a program of operational monitoring for survival and early growth of a range of stock types and species seems a practical approach. The efforts should expand if an unacceptable rate of plantation success on rehabilitated sites is observed.

Native plants Native plants can provide many benefits, but their potential is only starting to be realized. For example, native species that are unpalatable to cattle could be used in areas where cattle damage to crop trees is a problem. The loss of the B.C. Ministry of Forests native shrub program in the 1980s has resulted in a significant information gap at a time when the demand is great. Native species could be used as biological plows, or otherwise developed as low-cost alternatives for rehabilitating degraded sites. One research approach would involve screening of appropriate species and varieties for desirable characteristics.

Effect of agronomic species on forest ecosystems Some concern exists that agronomic grasses and legumes used for rehabilitation could displace native species. Trials show that grass and legume seed mixes can control competing vegetation on cutovers (Steen and Smith 1991). However, others feel that native plants quickly invade seeded areas and restore the natural ecosystem. Once crown closure occurs, agronomic species can lose their competitive advantage because of shading. Also, the chances of agronomic plants displacing native species increase in dry environments, especially in the southern interior, and dry sites in other areas where the native vegetation is dominated by grasses and shrubs. A retrospective approach could provide useful information on these topics for select ecosystems in diverse regions of British Columbia. These studies could, for example, evaluate vegetation succession on historic sites where hydroseeding was used to control erosion along road rights-of-way.

Role of grasses in forest soil rehabilitation Traditionally, grasses have played a dominant role in road and landing rehabilitation. That role may need re-examining in light of the information now available about moisture competition, potential allelopathic effects on tree seedlings (Amaranthus et al. 1993), and cattle trampling damage to seedlings. Other studies (Walker et al. 1989) show that seedlings and herbaceous cover can co-exist on surface-mined land. The range of site types where competition between trees and seeded ground cover hinders rehabilitation success should be determined. Research could initially focus on evaluating methods for establishing trees on sites previously tilled and seeded to grass. In addition, techniques to prevent cattle trampling damage to seedlings on rehabilitated sites should be developed further.

5.5 Soil Amelioration: Fertilizers, Amendments, and Mulches

On many degraded sites, soils are deficient in organic matter and nutrients, and even after tillage may have unstable pore structure, low available water retention, and poor nutrient-retention characteristics. Various strategies can address limitations on individual sites, including fertilizer application, application of organic residues, and mulching.

5.5.1 Fertilizers

Fertilizer is used in rehabilitation work to enhance plant establishment, accelerate plant growth, and maintain productivity (U.S. Department of Agriculture 1979). Fertilizer use is recommended for erosion control work and the fertilizer is frequently blended with the seed mixture in hydroseeding operations (Beese et al. 1994). The purpose of initial applications is to enhance plant establishment and promote early growth. Subsequent applications are recommended to maintain the cover of seeded grasses and legumes (Carr 1980).

Fertilizing to meet the nutritional demands of tree seedlings on rehabilitated sites may involve application at time of planting to enhance early growth of seedlings located on rehabilitated roads (Hickling et al. 1996). Broadcast, or single-tree, fertilization after establishment is an approach used if vegetation competition is not a problem. For subsequent fertilizer applications, foliar testing can reliably indicate tree nutrient status, and should occur before fertilizing to improve the growth of established trees (Ballard and Carter 1984).

While some fertilizer is often required to establish a productive forest on rehabilitated sites, the possibility of applying too much fertilizer should be considered. Fertilizer should not be used alone as a means to re-establish site nutrient pools. Unless vegetation or a nutrient-demanding organic amendment such as wood waste is present to utilize the nutrients, much of the added fertilizer (especially in the form of NO_3^- and K^+) will be lost either to the atmosphere or in drainage water. Over-fertilization does not affect local areas alone; the global consequences of profligate fertilizer use were described by Vitousek (1992).

5.5.2 Nutrient-poor residues

Organic amendments with low nutrient content are available in all areas of British Columbia, and are perhaps the only practical material to amend soil organic matter on rehabilitation projects in remote areas. Depending on the source of the material, C:N ratios can range from 500:1 or higher for wood chips or fresh sawdust (Arends and Donkersloot-Shouq 1985), to 111:1 for primary paper mill sludge (Zhang et al. 1993). Some residues have relatively low values such as 46:1 and 30:1 for brown and green needles, respectively (Pluth et al. 1995). Various organic materials have been used as soil conditioners (Saini and Hughes 1973; Graves and Carpenter 1980; Schuman and Sedbrook 1984; Olayinka and Adebayo 1985). Various methods are used to process, spread, and incorporate materials into soil. Woody materials with high C:N ratios can immobilize soil nitrogen as the added residue decomposes. Nitrogen fertilizer, sewage sludge, manure, or other nutrient-rich materials are usually added with woody residues to prevent nitrogen deficiency in plants.

Saini and Hughes (1973) added 30 t/ha of shredded tree bark (C:N = 256:1) to clay loam potato soils in New Brunswick, along with 300 kg/ha N. The shredded material was spread with a manure spreader and disced into the surface. The bulk density declined to 1150 kg/m^3 from 1240, and increases were observed for aggregate stability (60.2% compared to 55.1), oxygen diffusion rate (53.0 g /cm^2 compared to 43.9), water percolation rate (10–15 times faster), and potato yields (27.3 t/ha compared to 24.1). Assuming a bulk density of approximately 150 kg/m^3 for the shredded bark, the application rate represented a 2-cm layer.

Ground or chipped woody residues can potentially improve soil structure and prevent resettling in fine-textured soils. Schuman and Sedbrook (1984) investigated the application of sawmill residues, which consisted of fresh wood chips, sawdust, and bark, to abandoned bentonite spoils at rates of 0, 112, and 224 t/ha (dry weight basis). Fertilizer was also added at a rate of 112, 560, and 1120 kg N/ha for the three treatments. This reduced the C:N to 100:1. Wheatgrasses and other forage species were established from seed. Over four years, forage production averaged 12, 712, and 897 kg/ha for the three treatments. Average soil moisture content was twice as high in the plots receiving wood waste as in the controls. Wood waste improved productivity of these clay soils, and the medium application rate of 112 t/ha (a 7.5-cm layer, assuming a bulk density of 150 kg/m^3) achieved a large part of the gain.

Sawdust (initial C:N of 590:1), supplemented with either inorganic nitrogen (final C:N of 12:1), or dairy manure (final C:N of 25:1) was evaluated as an amendment to improve the organic matter content of a sandy loam soil (Olayinka and Adebayo 1985). Two application methods were used: incorporation and mulching. For maize grown in a greenhouse, incorporating unamended sawdust reduced dry matter yield (0.3 g per pot) compared to the control (1.3 g per pot), but amended sawdust improved growth (2.0–4.6 g per pot). In the field experiment, the amount of amendment added was substantially lower (5 t/ha versus equivalent of 42 t/ha estimated for the greenhouse experiment). Untreated sawdust, whether incorporated to surface soil or applied as a mulch, reduced dry matter yield (3.3 t/ha) relative to the control (4.4 t/ha). Amended sawdust improved growth in the field (4.7–6.0 t/ha).

These results illustrate the potential for improving plant growth when woody amendments are used in rehabilitation work. The use of harvesting residues and sawmill wastes will likely be encouraged in the near future, particularly as sawmills adjust to the loss of burning permits, and seek alternative means for disposal.

Although a considerable body of knowledge from other areas is available, applying woody residues to degraded forest soils is still experimental. The principles in British Columbia are similar to those elsewhere, but more experience is needed with specific materials in local situations so that potential benefits can be realized (e.g., increased soil productivity, appropriate use of a waste material), while minimizing environmental consequences (e.g., reduced site productivity because of over-application or inappropriate fertilizer regime, toxic leachate production because of over-application, or fertilizer leaching because of inappropriate fertilizer regime). Operational experimentation with these residues in various situations should be encouraged.

5.5.3 Nutrient-rich amendments

Using nutrient-rich byproducts, such as sewage sludge (McNab and Berry 1985; Simpson 1985), urban refuse (Roldan and Albaladejo 1994), paper mill biological waste (Zhang et al. 1993), and manure (Aoyama and Nozawa 1993; Robertson and Morgan 1995), to improve soil physical properties and nutrient status is well documented. For many of these materials, composting before applying helps to control detrimental side effects, such as the introduction of plant pathogens, weeds, phytotoxic substances, or odors. A wealth of recent literature exists on the processes involved in composting and the potential uses of composts and other nitrogen-rich wastes (e.g., Kayhanian and Tchobanoglous 1992), but local experience still needs developing in British Columbia.

McNab and Berry (1985) described experimental results in which three species of pine were planted on a site denuded by air pollution, and subsequently ameliorated with 34 t/ha of dried sewage sludge. All three species of pine grew faster in the presence of sewage sludge than when inorganic nitrogen was applied at 90 kg/ha, a rate intended to match the one-year release from the sludge. Additional release of nitrogen (i.e., higher than 90 kg/ha) from the sludge might be responsible for the improved response.

A trial in the Prince George Forest Region (Kranabetter and Bulmer 1995) showed that the particle size of wood waste had a significant effect on the composting process. Sawdust helped to maintain an open structure in a well-aerated compost pile that maintain high temperatures over an eight-week period. Rapid decomposition occurred initially in a compost pile with pulp fibre waste and sewage sludge, but decomposition slowed after three weeks because of poor aeration. In the sawdust compost after six weeks, nitrate was the dominant form of mineral nitrogen, while ammonium was the dominant form in the pulp fibre compost. Some unexpected results can occur when using composts and other materials. Applying high rates of (120 t/ha) of urban refuse (C:N = 20) to degraded soils in Spain resulted in reduced formation of mycorrhizae on pine (Roldan and Albaladejo 1994). The major species of fungi colonizing seedling roots was also affected by changing application rates. A moderate rate (60 t/ha) provided the best results for inoculated seedlings.

The Greater Vancouver Regional District and other communities in British Columbia have gained experience in recent years in using sewage sludge, fish wastes, and other materials to improve forest sites and to reclaim surface mine sites. Although nutrient-rich residues will probably improve soil conditions and tree growth, many of the field sites that need rehabilitating are far removed from the urban centres where these materials are usually produced. Transport costs are often so high that their use is justified only on sites in close proximity to the source of the material.

5.5.4 Mulches

Mulches applied to the soil surface control erosion, preserve water, and moderate soil temperatures. In hydroseeding for erosion control, thin mulches are used to stabilize soil surfaces and enhance the establishment of grasses and legumes. Thicker mulches (approximating the thickness of forest floors on similar sites in the area) derived from logging residues or other materials may have a unique application to certain forest soil rehabilitation projects.

Graves and Carpenter (1980) showed that as mulch thickness varied through 1-, 2.5-, 5-, and 10-cm increments, soil moisture content changed significantly with each increment, while soil temperature changes were not significant for mulch thickness greater than 2.5 cm. Applying a 2.5-cm layer of bark mulch improved the stocking levels obtained for three deciduous tree species established from seed, compared to control treatments with no bark mulch. Survival of planted bareroot seedlings was also higher for plots with either a 2.5 or 5 cm bark mulch layer. Average leaf water potential for European alder during the growing season was reduced by applying the bark mulch, compared to plots with no mulch or with grasses and herbs.

Although some results show that mulch alone is ineffective for rapidly improving mineral soil physical properties (Donnelly and Shane 1986), mulches are effective in combination with tillage treatments to protect soil structure (Luce 1997). Mulches derived from woody materials (branches, needles, bark), which resist decomposition, will probably provide longer-term effects than material such as straw, which decomposes rapidly.

5.5.5 Information gaps: research needs

Use of woody residues in soil rehabilitation Despite the potential benefits of using woody residues to rehabilitate soils, their use is not widespread in British Columbia. This partly reflects the logistical problems associated with preparing and delivering amendments to field sites, but also reflects:

- a poor understanding of their potential benefits; and
- concern about the risk of degrading site productivity through inappropriate use.

However, some rehabilitation practitioners are gaining local experience with their use, and a research effort is justified to determine the effects of these materials on productivity. Also, more information is needed on the specific aspects of using these amendments, such as identifying potential sources, developing methods for transport, and monitoring to document their effects in various ecosystems. Because these materials alter the soil physical properties as well as nutrient cycling, their effects should be evaluated in field trials.

Use of nutrient-rich residues in soil rehabilitation A large body of knowledge is available concerning processes of composting and the detailed transformation of organic matter within compost piles. Sufficient information probably exists (e.g., Kayhanian and Tchobanoglous 1992) for the successful composting of most materials likely used to rehabilitate forest soils.

The results of Olayinka and Adebayo (1985) illustrate the hazards of relying on greenhouse experiments to predict field performance. Field performance of nutrient-poor amendments was better than would have been predicted from the pot trial, likely reflecting the effect of residues on soil organic matter and soil water retention capacity.

Research on the use of nutrient-rich amendments for soil rehabilitation should focus on high-value lands close to the source of the waste. Many potential amendments derived from wastes represent a problem for the owner of the waste, so research can also address waste management concerns as well as environmental restoration.

Use of mulches Evaluating the benefits associated with the use of mulches should be considered when developing treatments for field studies of rehabilitation.

6 CONCLUSION

The primary goal of soil rehabilitation efforts is to improve soil conditions and establish productive forests on degraded lands. Research is needed to enhance those efforts by improving our knowledge of how soil properties and processes affect productivity on rehabilitated soils, and how rehabilitation techniques can improve soil conditions and tree growth.

Soil rehabilitation research should be focused at the incremental and strategic research levels (Binkley and Watts 1992). Incremental research is required to provide land managers and rehabilitation practitioners with information about problems that affect the success of rehabilitation projects. Strategic research is required to provide higher levels of management with information about the benefits associated with soil rehabilitation investments made in response to the Forest Practices Code, and the role of soil rehabilitation in maintaining the productivity of our forests. The following information gaps should be addressed to meet the information needs of operational rehabilitation projects that are currently being implemented by Forest Renewal BC, which are therefore considered incremental research (Binkley and Watts 1992).

- Developing and calibrating short-term tillage evaluation techniques.
- Determining cost-effective construction methods to conserve and replace topsoil.
- Testing conifer and hardwood species and stock types for rehabilitated sites, and evaluating beneficial micro-organisms.
- Using woody residues in soil rehabilitation.
- Using nutrient-rich residues in soil rehabilitation.
- Using mulches in soil rehabilitation.

The following information gaps should be addressed to meet the information needs of forest management. Results of these projects, which fall under the category of strategic research (Binkley and Watts 1992), could be expected within three to five years.

- Evaluating the long-term success of various tillage strategies for various site types.
- Quantifying the benefits of topsoil replacement, compared to other methods of restoring soil structure and nutrient cycles.
- Investigating biological processes in rehabilitated surface soils, and evaluating soil quality.
- Evaluating conifer growth on recontoured roads and skid trails.
- Using native plants in rehabilitation.
- Using agronomic species in forest ecosystems.
- Using grasses in forest site rehabilitation.

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