Effects of Forestry Practices Network

Effects of Harvesting Methods on Soil Properties and Forest Productivity in Interior British Columbia

John Senyk and
Don Craigdallie

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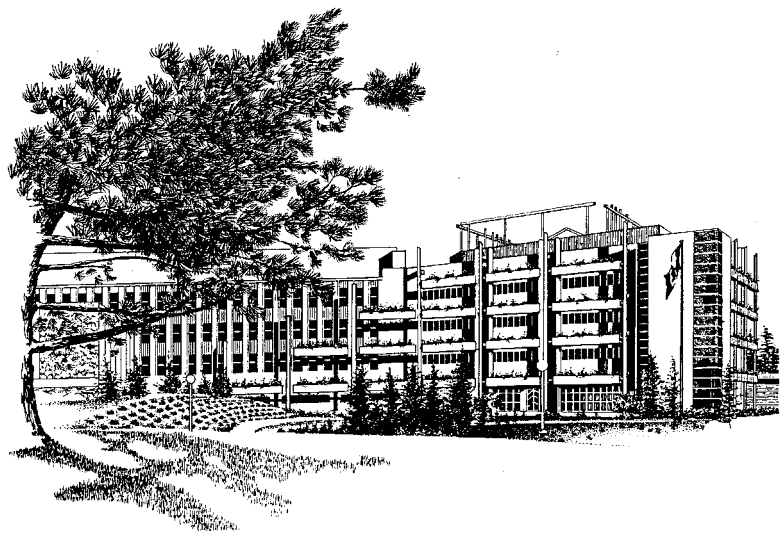

The Pacific Forestry Centre, Victoria, British Columbia

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The responsible stewardship and management of Canadas forest heritage, for present and future generations, is a key element in the future of our environment, our trade and our business relationships around the world. However, Canadas forests do not adhere to the artificial boundaries between provinces and landowners. Therefore, co-operation between governments and other forest managers is imperative. As Canadas major national forest research organization the Canadian Forest Service (CFS) has a major role to play. By developing scientifically sound forest management techniques and methods of sharing this information, Canada can assure its people and its customers that the best possible forest practices are being used. The Effects of Forestry Practices Network (EFPN) has been established to lead this effort.

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Abstract

Seven treatment units in three different clearcut blocks in the Golden Forest District were studied to assess overall soil disturbance levels resulting from ground-based harvesting using two methods of skidroad location. Three of the treatments were located within the Interior Cedar–Hemlock (ICH) and four within the Engelmann Spruce–Subalpine Fir (ESSF) biogeoclimatic zones.

The effects of skidroad construction on soil physical, chemical and micro-climatic properties was determined. In order to determine the impact of contour-built skidroads on survival and subsequent growth of planted seedlings, plantations were established on selected skidroad segments. Seedlings were planted in four disturbance types on the skidroad running surface and in the undisturbed (non-skidroad) soil adjacent to the skidroads. Tree growth and microclimate were monitored for three growing seasons after planting.

Total soil disturbance, which included haul roads, landings, fireguards, skidroads, skidtrails, deep gouges and deposits, ranged from 27 to 39%. Very little difference was found in overall soil disturbance levels between the pre-planned and operator choice methods of skidroad location. On the skidroad running surface, soils in the upper 20 cm of the inner track disturbance type were 40 to 60% more dense than undisturbed (non-skidroad) soils. Soils in the between track and outer track were also more dense than the undisturbed soils however the bulk density on the berm was not markedly different from the undisturbed soil. After three growing seasons, height growth and vigor of seedlings was poorest on the inner track disturbance type in all treatments. In the two blocks in the ESSF zone, average Engelmann spruce seedling height growth was less on all disturbance types, ranging from 27 to 31% less on the inner track to 3% less on the berm than in the undisturbed soil.

In the third block, in the ICH zone, height growth of Engelmann spruce followed a similar pattern; however, growth of western larch and lodgepole pine was greater on all disturbance types except for the inner track than it was in undisturbed soil (larch was 12–47% taller and pine 16–40% taller). Western larch showed the greatest height increase, followed by lodgepole pine and Engelmann spruce. Engelmann spruce had similar height growth on the neutral to slightly acid soils as on the calcareous soils.

Résumé

Nous avons étudié sept unités de traitement situées dans trois parcelles de coupe à blanc différentes, dans le district forestier de Golden, afin d'évaluer le taux de perturbation globale du sol résultant de l'exploitation par voie terrestre, pour deux méthodes de localisation des chemins de débardage. Trois des unités étaient situées dans la zone biogéoclimatique intérieure à thuya et pruche (ITP), tandis que les quatre autres se trouvaient dans la zone biogéoclimatique à épinette d'Engelmann et sapin subalpin (EESS).

Nous avons déterminé les effets de la construction des chemins de débardage sur les propriétés physiques, chimiques et micro-climatiques du sol. Afin d'évaluer l'impact des chemins disposés dans le sens des courbes de niveau sur la survie et la croissance subséquente des semis, nous avons établi des plantations sur certains segments de ces chemins. Dans chacun des cas, nous avons planté les semis dans quatre types de terrains perturbés de la surface de roulement ainsi que dans un terrain non perturbé voisin du chemin. Nous avons ensuite surveillé la croissance des arbres et le micro-climat, pendant les trois saisons de végétation suivant la plantation.

Le taux de perturbation totale, qui portait sur l'ensemble des chemins de service, des chantiers de façonnage, des pare-feu, des chemins de débardage, des pistes de débardage, des ornières profondes et des dépôts, variait de 27 à 39 %. Nous avons observé très peu de différence, quant à la perturbation globale, entre les chemins de débardage planifiés et les chemins de débardage laissés à la discrétion de l'opérateur. Dans les surfaces de

roulement, le sol du type de terrain perturbé correspondant aux 20 cm supérieurs de la piste intérieure était 40 à 60 % plus dense que celui du terrain non perturbé (situé en dehors du chemin); le sol des types de terrain situés entre les deux traces ou dans la trace extérieure était également plus dense, tandis que celui de la berme ne présentait pas de différence marquée, toujours par rapport au sol du terrain non perturbé. Après les trois saisons de végétation, les semis affichaient la croissance en hauteur et la vigueur les plus médiocres dans le type de terrain correspondant à la trace intérieure et ce, pour tous les traitements. Dans les deux parcelles situées dans la zone EESS, la croissance en hauteur moyenne des semis d'épinette d'Engelmann était moindre dans tous les types de terrain perturbé que dans le terrain non perturbé, l'écart allant de 27-31 % dans le cas de la trace intérieure à seulement 3 % dans celui de la berme.

Dans la troisième parcelle, située dans la zone ITP, la croissance en hauteur suivait la même tendance dans le cas de l'épinette d'Engelmann, mais elle était supérieure dans tous les types de terrain perturbé (sauf la trace intérieure) que dans le terrain non perturbé dans le cas du mélèze de l'Ouest (supérieure de 12 à 47 %) et dans celui du pin tordu latifolié (supérieure de 16 à 40 %). Le mélèze de l'Ouest affichait le meilleur accroissement en hauteur, suivi du pin tordu latifolié et de l'épinette d'Engelmann. Cette dernière affichait sensiblement la même croissance en hauteur dans les sols neutres ou légèrement acides que dans les sols calcaires.

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Introduction

Forestry operations in the Columbia Mountains and Southern Rockies of southeastern British Columbia have historically relied on tracked and wheeled equipment for all phases of harvesting and as carriers for various site preparation equipment. Clearcut harvesting of old-growth forests is commonly practiced on steep slopes, and techniques have evolved to use relatively large machines for extracting timber and constructing skidroads to maintain equipment stability.

Soil displacement and soil compaction are the most common forms of soil disturbance that result from these operations. Over much of this region, soils derived from sedimentary bedrock are mostly calcareous and even minimal soil displacement may expose subsoils that contain relatively high levels of calcium carbonate. On steep slopes, soils are often shallow and skidroads are often bladed to bedrock. The degree and severity of associated soil disturbance is influenced by the size of equipment, rolling gear, topography, forest stand characteristics, season of operation, soil characteristics, and skidroad and skidtrail layout.

The resultant physical, chemical and biological modifications to inherent soil properties often reduce long-term forest growth (Froehlich and McNabb 1984; Senyk 1990; Senyk and Craigdallie 1993; Smith and Wass 1994) and create potential sources of environmental degradation. Recognizing and quantifying these detrimental effects on site and future wood volumes, and on other resource values, both on- and off-site, have led to the adoption of soil conservation standards within the British Columbia Forest Practices Code (B.C. Ministry of Forests and B.C. Ministry of Environment, Lands and Parks 1994).

Forest managers are seeking economically and environmentally acceptable alternatives to clearcut harvesting and ground-based yarding on steep slopes, and mechanical site preparation methods that minimize potentially detrimental soil disturbance.

In response to concerns that ground-based harvesting operations on steep slopes were causing excessive levels of detrimental soil disturbance, Evans Forest Products, the B.C. Ministry of Forests Small Business Forest Enterprise Program (Golden Forest District), the Forest Engineering Research Institute of Canada, and the Canadian Forest Service undertook harvesting trials on a range of sites that are typical of those that forest managers face in the Golden Timber Supply Area.

This report discusses the effects of clearcut, ground-based harvesting operations on the physical and chemical properties of soils and on micro-climatic characteristics across a range of steep slope sites, and evaluates seedling performance after three growing seasons on various disturbance types.

Background

Forestry Practices

Wherever terrain characteristics are suitable, forest harvesting throughout most of interior British Columbia is generally ground-based and highly mechanized. However, this situation is changing with the increasing use of small aerial cable systems or “ecologgers” in response to public pressure and government regulations. This shift to alternative harvesting systems requires extensive training and costly changes in equipment profiles. Feller-bunchers, manual felling, grapple and line skidders, stroke delimbers and front-end and boom loaders, coupled with highway trucks, are the most common techniques and equipment combinations still employed. In most instances, blocks of timber are clearcut and whole trees are forwarded to a landing or roadside, where they are limbed, bucked and occasionally sorted before being loaded onto highway trucks. Terrain with slopes up to 50% and greater is harvested in this manner.

Generally, on slopes greater than about 30–35%, low ground pressure (LGP) track skidders or crawler tractors are used and skidding patterns are either random or dispersed. Rubber-tired skidders are also commonly employed on this type of terrain; however, they require the construction of contour skidroads for safety and stability. Stand density and tree size dictate to some extent the size of equipment required and the spacing of skidroads. Both ground skidding and cable systems have been considered feasible options on 30–50% slopes. Most of the potentially detrimental soil disturbance takes place on these slopes if ground-based systems are used. As topography steepens, the depth of cut and extent of sidecast associated with skidroad construction increase dramatically, resulting in potentially unacceptable environmental degradation.

Potentially detrimental soil disturbance resulting from ground-based harvesting on steep slopes is related to skidroad construction, random skidding and improper rehabilitation or drainage control measures which could result in mass wasting and erosion. Minimizing the frequency, width and length of skidroads will often reduce soil disturbance. Planning skidroad locations on cutblocks prior to harvesting may reduce soil disturbance compared to the conventional or operator choice method of skidroad location.

Soil Disturbance

Soil bulk density is strongly correlated with terrain and soil type, depth in the soil profile and degree of soil compaction. The latter depends largely on equipment type, number of passes and season of operation (Lewis et al. 1991; Senyk and Smith 1991).

For skidroads with cut-and-fill construction, particularly in morainal material, soil bulk density is invariably greater on the inside track (upslope side, most deeply cut) than on the between track and particularly the outside track which is generally an area of fill. This is a function of inherent soil properties intensified by equipment travel. On skidtrails (non-bladed structures), the level of compaction, displacement and rutting depth is largely related to the number of equipment passes and, to some extent, on the slope (Senyk and Smith 1991). Factors such as the depth of the humus layer, roots present in the humus layer and upper mineral soil, amount of surface woody debris or slash and branches can affect the severity to which the surface mineral soils are impacted. As well, site conditions during operations, such as soil moisture, depth of frost and snow pack, play a major role.

Total soil bulk density of about 1.4 Mg/m^3 is considered to be a threshold level at which tree roots show signs of being mechanically impeded (Carr 1987; Lousier 1990). Total soil porosity below about 30% is reported to seriously inhibit rooting in Douglas-fir seedlings (Heilman 1981).

Substantial data are required to establish acceptable levels of disturbance that would allow forestry operations to maintain suitable productivity and costs while protecting and sustaining the inherent productivity of on- and-off site soil and resource values. Some of these data could be obtained from retrospective studies, which offer an opportunity to obtain long-term growth data without waiting for the development of planted seedlings. However, the lack of information on initial environmental conditions during the early stages of seedling establishment and growth, and on mortality, and the lack of control over species, stocking levels and vegetation competition do not favour comparisons between areas. Therefore the use of information obtained from retrospective studies for long-term forecasting is restricted.

Study Sites

Description

The study areas were situated within the Golden Forest District in southeastern British Columbia (Figure 1). The cutblocks and treatments established within blocks were meant to stand alone as case studies, their main purpose being to determine the impact of specific forestry practices on ecosystem characteristics such as climate and soils, and on seedling performance in the long term. Although broad comparisons of various parameters are made between the three cutblocks (Small Business Block, Dainard Block, and Block 117), the main purpose is to develop the relationships that exist between forestry practices, disturbed soil and seedling growth within each ecosystem type.

Summer and fall harvesting operations were studied in the Golden Moist Warm Interior Cedar–Hemlock Variant (ICHmw1), Dry Cool Engelmann Spruce–Subalpine Fir Subzone (ESSFdk), and Northern Monashee Wet Cold Engelmann Spruce–Subalpine Fir Variant (ESSFwc2) biogeoclimatic subzones and variants (Braumandl and Curran [compilers] 1992). Cutblocks with “pre-planned” and “operator choice” methods of skidroad and skidtrail location were included in the study. Two of the blocks were harvested by contractors under the supervision of Evans Forest Products, the other was harvested under the supervision of the Small Business Forest Enterprise Program of the B.C. Ministry of Forests District Office in Golden. Slopes ranged between 30 and 60% on all blocks. Surficial deposits were similar across all blocks, being mostly deep and shallow morainal and minor colluvial deposits with infrequent bedrock outcrops. Loess deposits were clearly identified only at Block 117; however, the cap appeared to be fairly shallow and discontinuous. Soil textures ranged from sandy to silt loam to loamy sand.

Environmental impacts and logging productivity and costs were evaluated and compared (Kockx and Krag 1993). The areas reported on in this study were harvested with conventional systems using manual felling and a combination of rubber-tired and tracked line skidders to yard whole trees to landings where they were limbed, bucked, sorted and loaded onto trucks.

To assess the effects of methods of skidroad location on levels of soil disturbance, three cutblocks were each divided into two parts or treatments; one part of each block had skidroad locations flagged prior to construction, while the other part was logged with the operator choosing the location of skidroads. The same operator harvested both parts or treatments. In Block 117, an additional treatment was logged at the same time as the other two treatments, but by a different operator with different equipment who chose his own skidroad layout (ELI).

Skidroads were constructed parallel to, and angled across, the contours on all blocks. As much as possible, natural features such as rock ridges and benches were followed to minimize excessive cut-and-fill construction, particularly on the “pre-planned” skidroad treatments. On the three blocks used for comparing soil disturbance related to methods of skidroad location, soils and slopes were similar (Table 1).

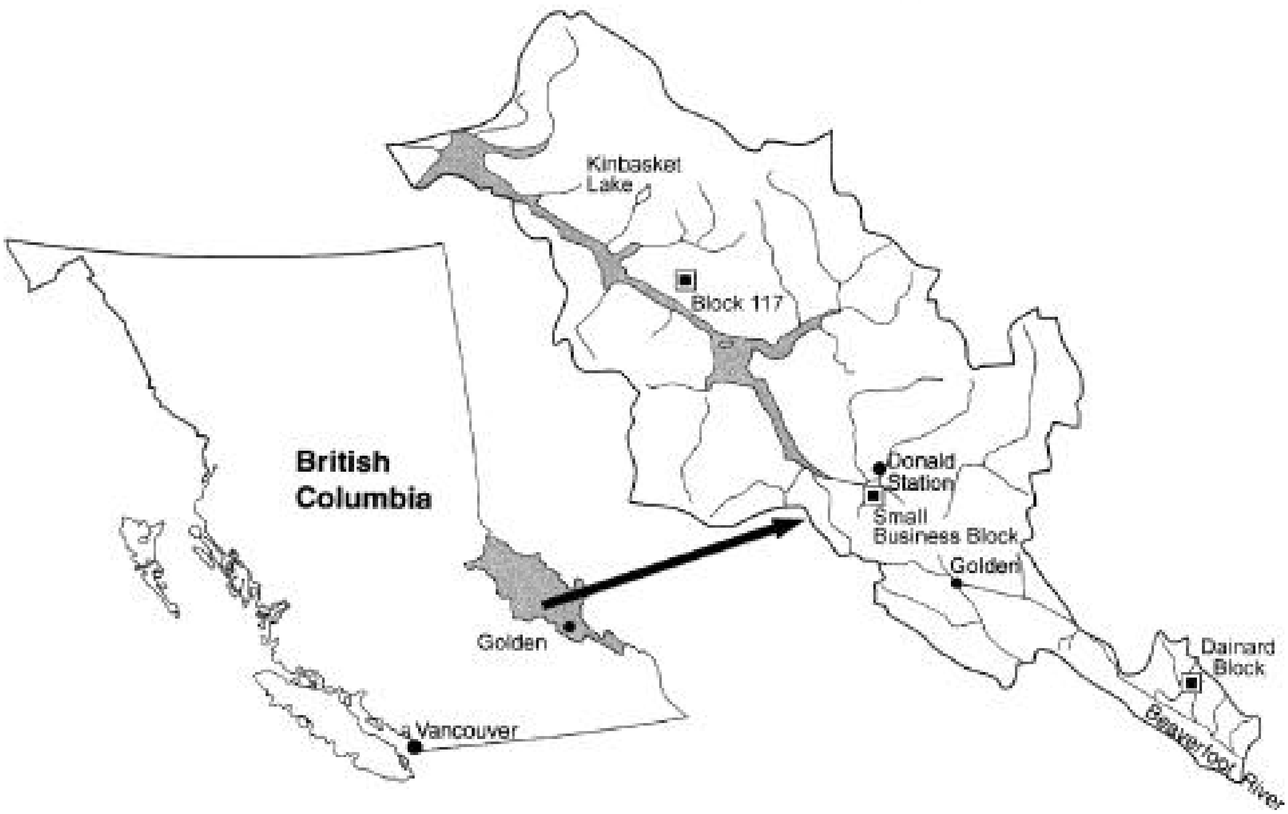

Figure 1.
Location of study sites.

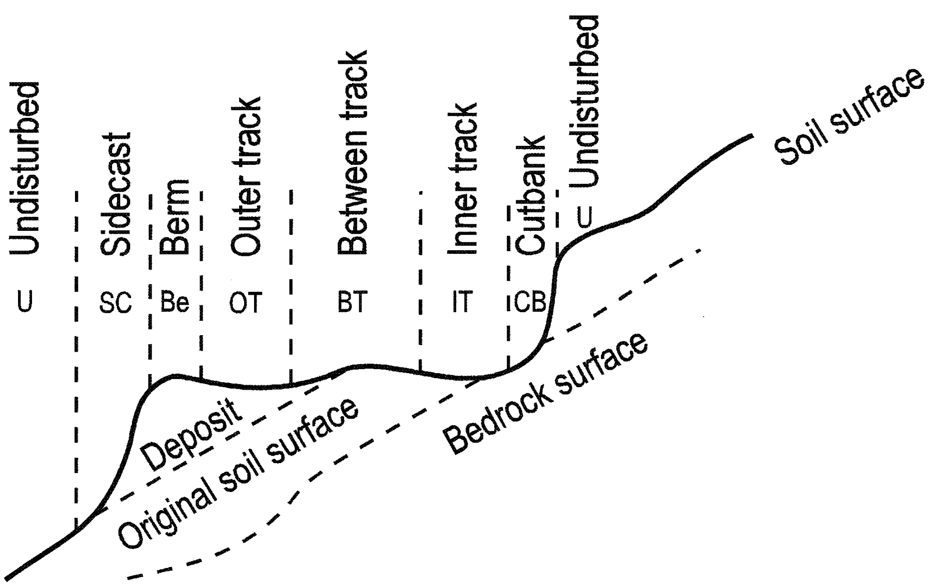

Figure 2.
Skidroad cross-section (showing disturbance types).

Equipment

Various conventional ground-skidding operations were included in the study. Part of Block 117, Evans Forest Products holdings, was divided into two parts or treatment units (logged by the same contractor) to compare disturbance levels between operator choice (OC) and pre-planned (PP) methods of skidroad location. An additional portion of the block, harvested by another operator, was included in the study. This latter treatment was harvested using:

1 Caterpillar D8H road building
1 Caterpillar D7G tracked line skidder
2 Caterpillar 518 rubber-tired line skidders
1 Caterpillar 966C front-end loader

In the above treatment (named ELI), skidroads were located by the operator choice method. It was included in the study to allow additional replication of soil sampling and seedling plantation trials.

The other two treatments in Block 117, operator choice and pre-planned, were harvested using:

1 Caterpillar D7G road building, line skidding
1 Caterpillar D6C tracked line skidder
2 Caterpillar 518 rubber-tired line skidders
1 Caterpillar 966C front-end loader

The Small Business Block (administered by the Small Business Forest Enterprise Program, B.C. Ministry of Forests, Golden) was similarly divided into operator choice and pre-planned treatment units and harvested using:

1 International TD15 road building, line skidding
2 Timberjack 380A rubber-tired line skidder
1 Caterpillar 966C front-end loader

The other area (Dainard Block), part of Evans Forest Products operations, was harvested using:

1 John Deere 550 road building, line skidding
1 self-loading log truck

The Dainard Block, situated on highly calcareous soils, was also divided into operator choice and pre-planned treatments. Both parts were hand-felled and the JD 550 used for both trail building and line skidding. Trees were limbed and bucked and piled at a landing. A self-loading truck loaded from the piles with little sorting required.

Study Methods

Soil Sampling

Soil bulk density sampling (excavation-sand-funnel method) (Klute [editor] 1986) and profile sampling for classification (Agriculture Canada Expert Committee on Soil Survey 1987) were undertaken on the study blocks prior to harvest. On Block 117 and Dainard Block, transect lines running across the blocks on the contour (approximately at the mid-slope position of the cutblock) were established and soil sampling sites were located at random distances along these lines. Soil pits were excavated, and a profile sample and two bulk density samples, each to a minimum depth of 50 cm in 10 cm increments, were taken at each site. Pre-harvest soil sampling was completed on the Dainard Block and Blocks 117 in 1988. On the Small Business Block, access and timing did not allow pre-harvest sampling; road cuts and undisturbed areas within the cutblock were sampled in 1989 after the block was opened up but before harvesting was completed.

Upon completion of harvesting on each block, two skidroads were selected at random within each treatment for further study. Skidroad lengths were initially divided into three broad “impact” classes (heavy, medium and light) roughly related to number of machine passes on the basis of distance from landing. A soil pit was excavated across the skidroad running surface in each of the impact classes. The skidroad running surface was divided into inner track (portion of road on the upslope side, most deeply cut), between track, and outer track (downslope side, generally an area of deposit or fill); each of these disturbance types (Figure 2) was sampled separately. Associated disturbance types (undisturbed and berm) were also sampled. On all blocks the sidecast was not sampled as the deposited soil was generally discontinuous and mixed with and covered by large woody debris (slash) so that effective bulk density sampling was impossible. Post-harvest soil sampling was completed in 1989 at Block 117, and in 1991 at the Dainard and Small Business Blocks.

Positions on the skidroad running surface and berm were sampled to a depth of 50 cm, if possible, in 10 cm increments. For each 10 cm depth increment, total and fine soil bulk density, field moisture content and porosity were calculated. Subsamples were selected to cover the range of ecosystems and disturbance types, and delivered to Griffin Laboratories Corporation in Kelowna, B.C., for standard soil chemical and physical analyses (McKeague [editor] 1976).

Skidtrails (non-bladed structures) were sampled in two treatment units in two different blocks (Dainard and Small Business Blocks) in a manner similar to the previous except that they lacked a berm and cutbank. In the cutblocks sampled, all travel was across the contour so that no inner or outer track designations were possible. On these skidtrails, disturbance types were identified as track, between track and undisturbed soil, and were analyzed separately from the skidroad disturbance types.

Plantation Trials

Replicated plantation trials were established on the skidroads and skidtrails immediately adjacent to the excavated soil pits. Seedlings were planted on each disturbance type sampled (track, inner track, between track, outer track and berm) and on the undisturbed soil on either side of the skidroad or skidtrail. Because of the woody debris covering and mixed with sidecast soils, no seedlings were planted on this disturbance type. In Block 117 and the Small Business Block the seedlings planted were the same as those used in the operational planting. Block 117 was planted in 1990, and the Small Business Block in 1991. The Dainard Block was not operationally planted until the year following logging so seedlings obtained for the trials, which were planted the same year harvesting was completed in the fall of 1990 (Table 1), were allocated from an adjacent area.

All western larch and Engelmann spruce seedlings were plug 1+0 stock type. Lodgepole pine seedlings at Dainard Block were plug 2+0 stock type. The lodgepole pine trials at Dainard Block used seedlings grown at the Pacific Forestry Centre from seed collected on site and from seed supplied by the Ministry of Forests in Golden.

Planting seedlings on the various disturbance types, particularly on the skidroad running surface and on the skidtrail tracks, required loosening the compacted soils to a depth of 15 cm or more, in a 8–10 cm wide slit, to enable insertion of the seedling root plug. The seedlings were tamped in solidly; however, the soil within the immediate vicinity of the seedling roots was modified by this procedure.

Plantations established in the spring of 1990 in Block 117 contain 216 seedlings each of western larch, lodgepole pine and Engelmann spruce. The Small Business Block plantation trials established in 1991 contain Engelmann spruce only (372 seedlings in total). The Dainard Block plantations established in 1990 contain 276 Engelmann spruce and 75 lodgepole pine seedlings. The larch seedlings at Block 117 are planted beyond the present natural range of the species and perhaps are the most northerly western larch plantings thus far in the Nelson Forest Region. Seedlings have been remeasured each year since establishment and will be remeasured annually for the first five years then in the seventh and tenth years.

Competing vegetation was removed on the undisturbed areas on all treatments during the early summer of the third year following plantation establishment.

Climate Monitoring

In one of the treatment units in each block, a climate station (Campbell Scientific CR 10 data logger) was established to monitor year-round above- and below-ground climates for both disturbed and undisturbed soils within a plantation (Figure 3). Sensors monitoring disturbed soils were installed in the inner track position on the skidroad running surface; those monitoring undisturbed soil conditions were placed between skidroads, generally on the up slope side of a skidroad well away from any soil disturbance. The climate stations were serviced in spring and fall, at which time the data obtained in the intervening period were downloaded to a cassette tape.

Site climate data collection, using CR 10 data loggers and a wide array of sensors, is often difficult. Above-ground sensing equipment, such as 1.3 m temperature and relative humidity (RH), solar radiation, rain gauge and +5 cm temperature probes (housed in PVC pipe), can function reliably for long periods without difficulty. However, below-ground sensors, temperature probes in particular (installed at -5 cm and -15 cm), occasionally become immobilized shortly after installation, giving erroneous readings. Often the problem is difficult to spot when the sites are serviced and six months or more of erroneous data can accumulate before they are processed and an error picked up. Soil moisture potential sensors (gypsum blocks) function reasonably well for extended periods of time within the range of soil conditions in this study. Also above-ground equipment can be damaged by vandals or animals.

Results

Inter-block Comparisons

General Climate

Temperatures at Block 117 were considerably warmer for every month of the year than at either Dainard Block or the Small Business Block, while the growing season temperatures at the Small Business Block were slightly warmer than Dainard. Mean monthly air temperatures at 1.3 m, total solar radiation (monthly averages) and mean monthly total rainfall for the growing season are shown in Table 2. The Small Business Block received the least sunshine and most precipitation during the growing season followed by Dainard Block and Block 117, respectively.

Soil Physical and Chemical Properties

On Block 117, soils were well-drained Orthic Eutric and Orthic Dystric Brunisols with lithic inclusions (Agriculture Canada Expert Committee on Soil Survey 1987). On the Dainard Block, soils were well-drained Orthic Eutric Brunisols with lithic soils common. On the Small Business Block, soils were Orthic and Gleyed Humo-Ferric Podzols. The humus layer was thin at both the Dainard Block and Block 117, ranging from Xeromor to Hemimor. At the Small Business Block the humus layer was considerably thicker and was in the Hemihumimor group (Klinka et al. 1981).

Soil parent material was acid to slightly alkaline across the treatments. Only at the Dainard Block were carbonates occasionally found close to the soil surface in high concentrations. Individual pH ($CaCl_2$) values were as high as 6.9 in the undisturbed surface mineral soil, increasing to 7.2 and higher at depths of 10 cm and greater. This compares with pH ($CaCl_2$) of 3.5 and 5.5–6.2 at the Small Business Block and Block 117, respectively. The high lime soils at the Dainard Block occur sporadically throughout the block. Some 40–50% percent of the samples were moderately to strongly calcareous (pH as high as 7.5 and $CaCO_3$ equivalent percentage up to 29 at 40–50 cm) from the surface to 50+ cm; the remaining samples were neutral to slightly acid. Tables 3, 4 and 5, show results of chemical analyses by disturbance type and depth for typical skidroad cross-sections in each of the blocks.

Soil textures ranged from silt loam (sand 6–29%, silt 55–82%, clay 10–18%) at Dainard, to silt loam–sandy loam (sand 39–76%, silt 30–57%, clay 4–10%) at Block 117, to loam - sandy loam (sand 44–53%, silt 30–46%, clay 7–18%) at the Small Business Block. Coarse fragment content varied from 30–40% at Dainard Block and Block 117 to 50% at the Small Business Block (Table 1). Depth to bedrock, which varied within and between blocks, was shallowest on the Dainard Block and deepest on the Small Business Block. The bedrock consisted mostly of weathered schists and was often exposed and ripped during skidroad construction.

Soils were similar between treatments within blocks. Because no difference was found in soil physical or chemical characteristics between the skidroad "use-impact" classes (light, medium, heavy) identified before sampling was initiated, this stratification was abandoned and soil samples within treatments were combined by disturbance types and depth. Only slight differences in slope, aspect and elevation (< 100 m) existed between treatments within blocks.

Soil Disturbance

Since the main objective of this study was to determine the long-term effects of soil disturbance resulting from skidroads and skidtrails on tree growth, the original soil disturbance survey data (Senyk 1989; Kockx and Krag

1993) was supplemented with skidroad width and disturbance type measurement data (Table 6). Identified by treatment unit, the skidroad-related disturbance types were cutbank, inner track, between track, outer track, berm and sidecast. As well, a skidtrail category was identified at the Small Business and Dainard Blocks.

The data for the disturbed areas were collected the same year as or the year immediately following harvest; therefore, little natural soil amelioration would have taken place. Data for undisturbed areas were gathered prior to harvest where possible or as soon as roads were built to the site. Within blocks, differences in soil characteristics between treatments were minimal, and for overall comparisons between areas, data were averaged within blocks.

Block-By-Block Results

Block 117

Disturbed Area

Block 117 covered approximately 120 ha and was comprised of treatments: OC - 25.4 ha, PP - 48.2 ha and ELI - 46.1 ha (Table 12 - Kockx and Krag 1993). Given the results from Table 6, the area occupied by the various disturbance types is shown in Table 7.

Soil Bulk Density and Porosity

Table 8 shows total and fine soil bulk density by disturbance type and depth for all three treatments (OC, PP and ELI) combined in Block 117. The inner and between track total soil bulk densities are significantly higher than those in the undisturbed soil and berm at a depth of 0–10 cm; those in the undisturbed soil, berm and outer track at 10–20 cm; those in the berm and undisturbed at 20–30 cm; and those in the undisturbed and outer track at 30–40 cm. The inner and between track fine soil bulk densities were significantly higher than those in the undisturbed soil and berm at a depth of 0–10 cm; those in the undisturbed soil, berm and outer track at 10–20 cm; and those in the undisturbed soil and berm at 20–30 cm.

Total soil porosity was significantly lower on the inner track and between track for depths 0–10, 10–20 and 20–30 cm than on the undisturbed soil, the berm and, except for the 10–20 cm depth, on the outer track (Table 9).

Seedling Performance

Seedling performance assessment was based on three years of measurement data (three full growing seasons on site). Since differences in disturbed soil characteristics related to operating method were minimal between treatments within blocks, seedling measurement data were combined by disturbance type for all treatments within blocks.

After three growing seasons, average height of Engelmann spruce seedlings growing on the inner track was significantly lower and height on the berm significantly greater than height on all the other disturbance types (Figure 4). Compared to the berm, height was 36% less on the inner track, 23% less on the outer track, 20% less on the between track and 13% less on the undisturbed soil. One-year change in height of Engelmann spruce was significantly greater on the berm than on all the other classes except the between track (Figure 5). Seedling vigor and mortality are shown in Figure 6. Seedlings had the best vigor on the berm and were least vigorous on the inner track.

Average height of western larch on all the disturbance classes was significantly less than on the berm (i.e., 54% less on the inner track and 31%, 23% and 19% less on the undisturbed soil, outer and between tracks, respectively) (Figure 7). One-year change in height of western larch was greater on the outer track, between track and berm than on either the inner track or undisturbed (Figure 8). Seedling vigor was greatest on the berm and outer track and poorest on the inner track, undisturbed and between track disturbance types (Figure 9).

Average height of lodgepole pine was greatest on the berm, followed by the outer track and between track, followed by the undisturbed soil and finally the inner track (Figure 10). Significant differences existed between the berm and all other disturbance types, the outer and between track and all other types, the undisturbed soil and all other types, and the inner track and all other types. Height on the inner track was 43% less than on the berm, 29% less than on the undisturbed soil, and 18% and 17% less than on the between and outer tracks, respectively. One-year change in height of lodgepole pine on the berm, between track and outer track was significantly different than that on the inner track and undisturbed soil (Figure 11). Lodgepole pine seedling vigor and mortality are shown in Figure 12. Seedlings were most vigorous on the berm and outer track followed by the between track, undisturbed soil and inner track.

Soil Chemistry

Soil chemical characteristics are shown in Table 3. The pH ($CaCl_2$) of undisturbed soils increased with depth from 5.2 in the surface mineral soil to 5.6 at 40 cm, while on the inner track pH ranged from 5.6 at the surface to 5.3 at 40 cm. Available K, Ca and Mg (mg/kg) were highest on the outer track followed by the berm, inner track, between track and undisturbed soil, while P was highest in the undisturbed soil, followed by the berm, inner track, outer track and between track.

C and N at the 0–10 cm depth were highest on the outer track followed by the berm, inner track for C, undisturbed soil for N and finally the between track. The C/N ratio was highest on the inner track followed by the outer track, berm, undisturbed soil and between track disturbance types.

Site Climate

The area had just over 1500 Growing Degree Days greater than 5˚C and a mean annual temperature of about 5.4˚C measured at 1.3 m. The data for years 1989 to 1994 indicated that the potential for a late spring frost at 5 cm above the ground exists until mid to late May, and the first fall frost can occur in the first or second week of September. Maximum temperatures can reach as high as 40˚C during late June, July and the first part of August.

Most years appeared to receive ample rainfall spread uniformly over the growing season (Table 2). Soil moisture block readings indicated that seedlings growing in undisturbed soils suffered severe moisture stress towards the latter part of August and into early September. Moisture conditions on the skidroad remained close to field capacity over the entire year. The moisture block was located in a flat to slightly depressional area on the skidroad that received moisture from downslope subsurface seepage as well as run-off from adjacent portions of the skidroad surface itself.

Small Business Block (SBB)

Disturbed Area

The Small Business Block covered 26.3 ha (Kockx and Krag 1993) of which 13.4 ha was in the operator choice treatment and 12.9 ha in the pre-planned treatment. Given the relationships in Table 6, 2.8 ha and 2.6 ha were occupied by skidroad and skidtrail-related disturbance in the operator choice and pre-planned treatments, respectively. Of this 5.4 ha total skidroad and skidtrail disturbance, the area occupied by the various disturbance classes was 0.26 ha by cutbank, 1.31 ha by inner track, 0.81 ha by between track, 1.31 ha by outer track, 0.81 ha by berm, 0.81 ha by sidecast and 0.13 ha by skidtrail track.

Soil Bulk Density and Porosity

At the Small Business Block, no significant difference in total soil bulk density existed between any of the disturbance types except at the 30–40 cm depth, where the inner track was significantly higher than the berm (Table 10). Despite the large differences in mean bulk density figures between disturbance types the variation or range within disturbance and depth classes is large and sample numbers apparently too few to provide statistical significance. Fine soil bulk density was lower at the 0–10 cm and 10–20 cm depth on the skidtrail track than on any other disturbance type; however, it was significantly lower than the inner track only. Total soil porosity was lower on the inner and outer tracks than on all other disturbance types except all the 20–30 cm depths; however, it was significantly lower on the inner track only at the 30–40 cm depth (Table 11).

Seedling Performance

Average height of Engelmann spruce seedlings on the undisturbed soil was significantly greater than on all the other disturbance types and growth on the centre track and skidtrail track significantly greater than on the inner track (Figure 13). Compared with seedlings planted on undisturbed soil, the height of Engelmann spruce seedlings planted on the inner track averaged 28% less; on the outside track 23% less; on the berm 18% less; on the between track 15% less; and on the tracks of skidtrails approximately 13% less. The height change on the inner track was negative due to top die-back. One-year change in seedling height on both the inner and the outer tracks was significantly less than the change on the undisturbed soil (Figure 14). The largest proportion of healthy seedlings occurred on the undisturbed soil, followed by seedlings growing on skidtrails, on the berm, between track, inner track and outer track (Figure 15).

Soil Chemistry

The pH ($CaCl_2$) at the Small Business Block ranged from 3.5 to 4.4 and increased with depth (Table 4). Percentages of C and N at 0–10 cm depth are highest on skidtrail tracks, followed by the undisturbed soil, between track, berm and outer and inner track. The C/N ratio was highest on the skidtrail track, second highest on the between track followed by the berm, outer track, inner track and undisturbed soil. This compares reasonably well with the findings of Smith and Wass (1994). No significant differences in pH or levels of available P, K, Mg, and Ca were found between disturbance classes or depths except for available Ca which was significantly higher in the outer track at the 10–20 cm depth.

Site Climate

The Small Business Block had slightly over 900 growing degree days greater than 5˚C and a mean annual temperature of slightly over 2˚C measured at 1.3 m.

Above-ground seedling environment temperatures (+5 cm) in the undisturbed soil reached higher maximums and slightly lower minimums than on the track. However, these above-ground maximums did not reach temperatures that could cause physical damage or mortality to seedlings (Spittlehouse and Stathers 1990). Indications are that a late frost could occur into the first or second week in June and an early fall frost in late August. Undisturbed soil temperatures at -5 cm and -15 cm increased more slowly in spring, decreased more slowly in fall, and showed far less fluctuation than corresponding temperatures in the track.

Rainfall was spread uniformly over the growing season (Table 2). Moisture blocks emplaced at -10 cm in mineral soil (i.e., between the -5 cm and -15 cm temperature probes at both undisturbed and track positions) indicated none to only a very low level of growing season moisture stress in the undisturbed (between 0.1 and 1.0 bar). However, a severe moisture stress (15.0–25.0 bars) with peaks in June, July, August, September and October occurred on the track. (At 0.1–0.3 bars the soil is at field capacity and between 15 and 25 bars the soil is at the permanent wilting point [Spittlehouse and Stathers 1990]).

Dainard Block

Disturbed Area

The Dainard Block was 8.1 ha in size (Kockx and Krag 1993) consisting of 5.5 ha in the operator choice and 2.6 ha in the pre-planned treatments. Of the total area 0.08 ha was occupied by cutbank, 0.32 ha by inner track, 0.20 ha by between track, 0.32 ha by outer track, 0.24 ha by berm, 0.16 ha by sidecast, and 0.16 ha by skidtrail track.

Soil Bulk Density and Porosity

Total soil bulk density was highest on the inner track, significantly higher than on the undisturbed and berm at 0–10 cm, the berm at 10–20 cm, and the skidtrail track and berm at 20–30 cm depth (Table 12). No significant differences in fine soil bulk density existed between any of the disturbance types at any depth. A significant difference in total soil porosity was found between the inner track and the undisturbed soil and berm at the 0–10 cm level, between the inner track and berm at 10–20 cm depth, and between the inner and outer tracks and the skidtrail track at the 20–30 cm depth (Table 13).

Seedling Performance

After three growing seasons, the average height of Engelmann spruce seedlings growing in the undisturbed soil was significantly greater than seedlings growing on all the other disturbance types (Figure 16). The height of Engelmann spruce seedlings planted on the inner track averaged 31% less than those planted in the undisturbed soil. These results are almost identical to those obtained on the Small Business Block. Compared with results on the undisturbed soil, height was 29% less on the outer track, 26% less on the between track, and 20% and 17% less on the berm and skidtrail track, respectively. Engelmann spruce seedlings growing on the inner and outer track had significantly less height growth than those on undisturbed soil (Figure 17). As at the Small Business Block, the seedlings growing on the inner track show a negative height change resulting from top die-back. At least 60% of the Engelmann spruce seedlings planted in the undisturbed soil had good vigor while all seedlings growing on the inner track had poor vigor (Figure 18). There was no significant difference in height of lodgepole pine seedlings on any of the disturbance types at the Dainard Block (Figure 19). Compared with results on the undisturbed soil, height of lodgepole pine averaged 27% less on the inner track, 11% less on the between track, 3% less on the outer track, 2% less on the berm, and 6% less on the skidtrail tracks.

No significant difference was found in the average annual height change in lodgepole pine seedlings in different disturbance types; however, the change in height of seedlings growing in the undisturbed soil was about 10 cm as compared with 1 cm for seedlings on the inner track (Figure 20). All lodgepole pine seedlings on the inner track were rated as having poor vigor (Figure 21).

Soil Chemistry

Exchangeable Ca (meq/100 gm) in undisturbed soils at the Dainard Block increased from 3.0 to 4.0 at the surface to 30.0 at 50 cm and available Ca from 422 to 2159 mg/kg for the same depths (Table 5). As a result of the redistribution of organic matter and solum, the exchangeable or available Mg, K, P, Ca and C, N and C/N ratio are often highest on deposited soils, such as the berm and outer track, and lowest in the undisturbed soil.

Despite the high $CaCo_3$ levels in the seedling rooting zone on various disturbance types in the Dainard Block [pH ($CaCl_2$) values of up to 7.65 on the inner track, 7.74 on the berm, 7.12 on the between track and 7.48 on the outside track] seedling height and diameter growth, and health and vigor assessments of both pine and spruce did not indicate any detrimental effects attributable to potential nutrient deficiencies caused by the high carbonate concentrations. Thompson and Troeh (1973), in trials with a variety of agricultural crops, found that at pH (H_2O) above approximately 6.5, the availability of iron (Fe) and manganese (Mn) became restricted, while at pH 7.0–7.5 the availability of boron (B), copper (Cu) and zinc (Zn) was limiting and above pH 7.5 the availability of potassium (K) and phosphorous (P) was affected.

Site Climate

Climate data for the Dainard Block is based on information gathered during the period 1991 through 1994. Mean annual temperature was approximately 1.5˚C and there were just under 800 growing degree days above 5˚C.

Variation between maximum and minimum temperatures (skidroad and undisturbed soil) ranged from about 3 to 25˚C during May, June, July, August, September and October. None of the recorded temperatures were potentially damaging or lethal to seedlings, except a late spring or early summer frost after seedlings had flushed (Spittlehouse and Stathers 1990). Indications are that a ground frost is possible every month of the year. Over the period from 1990 to 1994 the maximum daily temperatures 5 cm above ground in the undisturbed soil steadily increased over those reached on the track. The relationship between minimum temperatures on the track and undisturbed soil was nearly identical (only slightly colder on the undisturbed) and has remained relatively constant over this period. The mineral soil exposed on the track tends to conduct more heat into the underlying profile than does the humus layer in the undisturbed soil. Therefore, temperatures 5 cm above the undisturbed soil were somewhat higher during the day and lower at night.

The mean daily temperatures at a depth of 5 cm on the track fluctuated more, reached higher, and often dipped lower than those in the undisturbed soil. The only difference in temperatures found between the two disturbance types at depths of 5 cm and 15 cm was a slower spring warming and slower fall cooling in the undisturbed soil.

The amount and timing of rainfall fluctuated considerably from year to year. Mean total monthly rainfall was highest in June (85 mm) and July (97 mm) (Table 2).

Soil moisture (gypsum block) readings indicated that the track alone undergoes slight to moderate moisture stress (water potential up to 3 bars). This occurred at any time during the growing season; however, it was most common during June, July, August and September.

Discussion and Conclusions

Block 117 had a moderate potential for detrimental soil disturbance to occur from summer, ground-based harvesting while the Dainard and the Small Business Blocks had a high potential for detrimental disturbance. Soils in all three areas had a moderate compaction and soil erosion hazard. The Dainard Block, which is on calcareous parent materials, had a high soil displacement hazard. The Small Business Block had a high mass wasting hazard due to the presence of abundant subsurface seepage.

Total skidroad and skidtrail related soil disturbance was about the same in all three areas, being only slightly lower in the Dainard Block. Methods of skidroad location, whether pre-planned or operator choice, did not affect levels of soil disturbance to any extent; more important factors were the slope of the cutblock and the equipment used in skidroad construction.

In all cases, skidroad construction exposed relatively dense subsoils in the cut portion of the skidroad. On occasion, weathered bedrock was intersected. Soil compaction from skidder traffic further increased the inherent soil bulk density and decreased the total porosity on the running surface. Cross-contour skidtrails at both the Dainard and Small Business Blocks were generally short and single pass, causing only minor rutting and minimal soil displacement and compaction.

Total soil bulk density was always greatest and total porosity always the least on the inner track. In many cases similar conditions (high bulk density, low porosity) were observed for the between track and outer track disturbance types as well. Soil bulk density threshold levels, considered limiting to root development of about 1.4 Mg/m^3 in the upper 30 cm, were always exceeded on the inner track, and occasionally on the outer track and between track disturbance types. Total soil porosity in the upper 30 cm fell below the threshold level (about 30%), considered limiting to root development only on the inner track, at the Small Business Block and approached this level at Block 117.

Only at the Dainard Block did the parent material contain high levels of calcium carbonate (pH in the C horizon over 8.0) (Table 5). Even here, however, where pH of the sampled skidroad surfaces averaged about 7.3, nutrient availability was not considered to be seriously affected. Of 10 separate undisturbed sites, sampled randomly across the block, five were alkaline within the upper 40 cm (pH 7.4–7.8) while five were acid to near neutral (pH 5.5–6.5) at similar depths. Given these conditions the displacement hazard on these soils varied not only with depth of cut but also with location in the cutblock.

The percent organic carbon, nitrogen and the C/N ratio in the upper 30 cm of soil on the skidroad running surface was generally somewhat higher on the outer track, inner track and berm disturbance types in Block 117. At the Small Business Block the ranking from highest to lowest was skidtrail track, the between track and the undisturbed soil, while at the Dainard Block the berm, inner track and outer track disturbance types had the highest percentages of C, N and C/N ratio. The cut-and-fill construction mixed the humus and woody debris with mineral soil and deposited the material on the outside half of the skidroad. The organic matter on the skidroad surface was further augmented by woody debris left behind from the whole tree yarding operation.

The constructed skidroad surfaces had above- and below-ground temperature and soil moisture conditions that differed from the undisturbed. At the Dainard and Small Business Blocks, moderate to severe moisture stress (water potential approaching and above permanent wilting point) occurred only on the skidroad running surface. At Block 117, the section of skidroad running surface being monitored did not suffer from moisture stress, however severe moisture stress occurred in the undisturbed soils. Seedling environment temperatures 5 cm above ground were more extreme in the undisturbed than on the skidroad surface in all areas; however, none approached levels that could be considered lethal to seedling survival.

Natural soil movement on skidroads was not measured, however soil ravelling on cutbanks was common in all areas. Only at the Dainard Block were seedlings actually killed by smothering due to cutbank sloughing. Water erosion on the skidroad running surface was active at Block 117 and the Small Business Block. Erosion and deposition resulted in both exposed roots and buried seedling stems particularly on the inner and outer track disturbance types. Although seedlings were stressed, mortality due directly to these processes was minimal. Cross-contour skidtrails were much more prone to water erosion than the skidroads, however sections of trail at the Dainard and Small Business Blocks were short and the erosive forces were dissipated before causing extensive soil movement.

Plantation trials in all three areas had the poorest seedling growth on the inner track of the skidroad running surface where soils were most dense and least porous. Although health and vigor of seedlings growing on the inner track were most often the poorest among all disturbance types, seedling mortality was not always the greatest.

At Block 117, seedlings of all three species attained their best height growth on the berm followed by the between track (except Engelmann spruce which did better on the undisturbed than between track), outer track, undisturbed soil and inner track disturbance types. The superior performance on the berm and outer track is likely related in part to the favourable soil moisture conditions, low soil bulk density, high total porosity and the higher organic C and N concentrations and C/N ratio often found in the upper 30 cm of soil at these locations. The high bulk density and low porosity on the between track disturbance type, however, did not have the expected effect as seedling height growth (larch and pine) was comparable to growth on the outer track. Mortality after three growing seasons was highest in the larch followed by spruce then pine. The growth trends at Block 117 were atypical of results obtained from many other disturbed soil plantation studies (Senyk and Smith 1991). The total area of Block 117 was 120 ha. Of this area nearly 25 ha was disturbed by skidroads. After three growing seasons height of western larch was 9.4% greater and height of lodgepole pine 9.6% greater than on undisturbed soil, while Engelmann spruce height was 8.9% less on skidroads than on undisturbed soil.

At the Small Business Block Engelmann spruce height was greatest on the undisturbed soil, followed by the skidtrail tracks, between track, berm, outer and inner track disturbance types. These trends relate decreasing height growth to increases in total soil bulk density and decreases in total soil porosity percentage, as well as slightly lower organic C and N percentages. Soil moisture was more favourable in the undisturbed soil as well; soil temperatures, however, were somewhat cooler. The total area of the Small Business Block was 26.3 ha of which 5.4 ha was disturbed by skidroads and skidtrails. Height of Engelmann spruce after three growing seasons was 25.9% less on the disturbed soils than on the undisturbed soil.

At the Dainard Block, height of both Engelmann spruce and lodgepole pine was greatest on the undisturbed. As on the Small Business Block, spruce height decreased with increases in total soil bulk density and decreases in total soil porosity. Of the total area of 8.1 ha at the Dainard Block, 1.4 ha was occupied by skidroads and skidtrails. On these 1.4 ha, the height of Engelmann spruce was 28.3% less and the height of lodgepole pine 14.2% less than on undisturbed soil.

The study confirms that seedling survival vigor and growth is strongly related to the disturbance type on the skidroad in which the seedlings are located.

The poor growth of Engelmann spruce on skidroad surfaces likely indicates that it is less tolerant of disturbed soils and modified microclimate than either lodgepole pine or western larch. On all areas the overall height increase of spruce is generally inferior to that of the other species planted.

This study has shown that many soil and climatic factors acting together affect seedling performance following clearcutting and ground skidding on steep terrain. All soil disturbance affects site productivity and ultimately can determine the natural sequence of seral development. If appropriate seral species such as lodgepole pine and western larch are used in reforesting these disturbed soils, an opportunity exists to maintain or even increase productivity, at least in the short term, when compared to the performance of the operationally planted, most often mid- to late-seral species.

Although considerable information is available on the effects of high lime or carbonate rich soils on tree productivity (Smith and Wass 1994), results from this study do not indicate specific detrimental effects on the growth of either pine or spruce after three growing seasons that could be directly attributable to this condition. This may in part be due to a residual or buffering effect of the slow release fertilizer in the plug of the container grown stock and to the inherent variability of carbonate concentration in the soil itself.

Previous studies (Senyk and Smith 1991; Smith and Wass 1994) have found that seedling growth on severely disturbed soils is reduced in the long term when compared to growth on undisturbed soils. These differences, however, tend to decrease with time so that trends that appear during the first few years after establishment are not nearly so dramatic after 10 years.

No significant differences in soil disturbance, compaction levels or soil displacement between pre-planned and operator choice treatments within blocks were found. Given that operators and equipment used for skidroad construction and yarding were the same for both treatments and that slopes were similar, this result was perhaps to be expected. Also, after the third growing season no differences in seedling performance were detected by disturbance types between treatments within blocks. In all respects the operator choice and pre-planned treatments could be considered identical.

In areas where skidroads and skidtrails have not been rehabilitated, the inner track and cutbank and skidtrail tracks should not be planted. On deeply cut skidroads the between track and outer track disturbance types should be avoided as well.

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Table 1. Description of cutblocks

	Cutblock						
	117			Dainard		Small Business	
Treatment	OC+	PP+	ELI+	OC+	PP+	OC+	PP+
Total area (ha)*	25.4	48.2	46.1	5.5	2.6	13.4	12.9
Average elevation (m)*	1050	1000	1100	1750		1650	1800
Average slope (%)*	42	46	31	42		43	42
Aspect*	Sw	Sw	S	Sw		East	
Biogeoclimatic classification	ICHmw1			ESSFdk		ESSFwc2	
Soil classification	Orthic Eutric, Dystric Brunisol			Orthic Eutric Brunisol		Orthic and Gleyed Humo-Ferric Podzol	
Soil texture	silt loam – sandy loam			silt loam		loam – sandy loam	
Coarse fragments	30–40%			30–40%		50%+	
Harvesting completed	1988			1990		1990	
Plantations established	1990			1990		1991	
Number of trees in plantation trials (all species)	216	216	216	144	207	180	192
Species planted	western larch lodgepole pine Engelmann spruce			lodgepole pine Engelmann spruce		Engelmann spruce	

* From Kockx and Krag 1993
+ OC: Operator choice
+ PP: Pre-planned
+ ELI: Operator choice treatment harvested by a different contractor

Table 3. Soil chemistry by disturbance type and depth at Block 117

Category	Inner track	Outer track	Between track	Berm	Undisturbed
pH (H20)					
0–10 cm	6.22 a*	5.89 a	6.41 a	6.08 a	5.75 a
10–20 cm	6.25 a	5.92 a	6.49 a	6.12 a	6.24 a
20–30 cm	6.17 a	6.52 a	6.34 a	6.19 a	6.35 a
30–40 cm	6.03 a	—	—	—	6.39 a
pH ($CaCl_2$)					
0–10 cm	5.59 a	5.33 a	5.74 a	5.43 a	5.18 a
10–20 cm	5.43 a	5.29 a	5.68 a	5.48 a	5.53 a
20–30 cm	5.42 a	5.77 a	5.58 a	5.56 a	5.56 a
30–40 cm	5.30 a	—	—	—	5.57 a
% C (LOI)					
0–10 cm	3.78 a	6.78 a	2.69 a	4.57 a	3.39 a
10–20 cm	9.51 a	4.74 a	1.44 a	3.83 a	2.53 a
20–30 cm	0.47 c	2.05 b	0.58 c	3.43 a	1.47 bc
30–40 cm	0.53 a	—	—	—	1.02 a
% N (MICRO—KJELDAHL)					
0–10 cm	0.07 b	0.14 a	0.07 b	0.09 ab	0.09 ab
10–20 cm	0.17 a	0.10 a	0.05 a	0.10 a	0.07 a
20–30 cm	0.02 c	0.06 b	0.03 bc	0.09 a	0.05 bc
30–40 cm	0.03 a	—	—	—	0.04 a
C/N ratio					
0–10 cm	52.60 a	49.96 a	34.25 a	46.71 a	36.72 a
10–20 cm	30.68 a	44.83 a	27.21 a	39.67 a	37.82 a
20–30 cm	18.66 b	34.02 ab	17.20 b	39.46 a	30.36 ab
30–40 cm	16.26 a	—	—	—	26.42 a
Extractable P (mg/kg) (0.25 N HOAC+0.015 N NH_4F)					
0–10 cm	42.35 a	41.40 a	28.33 a	45.54 a	47.07 a
10–20 cm	21.19 a	57.77 a	34.55 a	33.34 a	53.61 a
20–30 cm	10.97 a	18.42 a	28.36 a	16.92 a	47.52 a
30–40 cm	45.92 a	—	—	—	46.08 a
Extractable K (mg/kg)					
0–10 cm	166.96 a	218.66 a	158.93 a	202.14 a	74.75 a
10–20 cm	271.70 a	149.30 a	89.90 a	215.40 a	72.30 a
20–30 cm	42.83 b	72.14 ab	83.38 ab	129.57 a	71.54 ab
30–40 cm	81.72 a	—	—	—	79.38 a

Table 3. (continued)

CATEGORY	INNER TRACK	OUTER TRACK	BETWEEN TRACK	BERM	UNDISTURBED
Extractable Ca (mg/kg)					
0–10 cm	580.6 a	741.8 a	537.8 a	627.2 a	416.0 a
10–20 cm	319.8 a	573.4 a	336.8 a	555.1 a	445.1 a
20–30 cm	171.6 a	444.8 a	209.6 a	632.2 a	352.4 a
30–40 cm	140.8 a	—	—	—	279.2 a
Extractable Mg (mg/kg)					
0–10 cm	53.41 a	71.81 a	44.11 a	59.23 a	27.32 a
10–20 cm	62.02 a	47.19 a	21.25 a	52.19 a	23.58 a
20–30 cm	29.58 a	33.32 a	16.96 a	49.63 a	21.16 a
30–40 cm	14.29 a	—	—	—	19.74 a

* Means within rows followed by the same letter are not significantly different at the 0.05 level.

Table 4. Soil chemistry by disturbance type and depth at Small Business Block

CATEGORY	INNER TRACK	OUTER TRACK	BETWEEN TRACK	SKIDTRAIL TRACK	BERM	UNDISTURBED
pH ($H_2$0)						
0–10 cm	5.24 a*	5.28 a	4.74 a	3.98 a	4.60 a	4.26 a
10–20 cm	4.88 a	4.92 a	4.54 a	4.02 a	4.56 a	4.38 a
20–30 cm	5.09 a	5.56 a	4.56 a	4.63 a	4.90 a	4.79 a
30–40 cm	4.93 a	5.59 a	4.69 a	4.96 a	5.13 a	5.24 a
40–50 cm	—	—	4.93 a	5.34 a	—	5.36 a
pH ($CaCl_2$)						
0–10 cm	4.45 a	4.34 a	4.05 a	3.59 a	3.90 a	3.54 a
10–20 cm	4.13 a	4.08 a	3.87 a	3.34 a	3.80 a	3.62 a
20–30 cm	4.15 a	4.52 a	3.82 a	3.92 a	4.04 a	3.91 a
30–40 cm	4.10 a	4.56 a	3.94 a	4.31 a	4.24 a	4.31 a
40–50 cm	—	—	4.10 a	4.23 a	—	4.42 a
% C (LOI)						
0–10 cm	2.43 a	4.14 a	18.23 a	38.99 a	7.19 a	20.20 a
10–20 cm	1.88 a	4.49 a	15.29 a	2.46 a	4.48 a	2.28 a
20–30 cm	0.65 b	0.52 b	1.25 b	1.86 b	3.28 a	1.12 b
30–40 cm	0.70 a	0.23 a	1.63 a	2.27 a	2.39 a	1.11 a
40–50 cm	—	—	1.50 a	1.15 a	—	1.18 a
% N (MICRO-KJELDAHL)						
0–10 cm	0.05 a	0.08 a	0.24 a	0.63 a	0.13 a	0.38 a
10–20 cm	0.04 a	0.09 a	0.28 a	0.07 a	0.09 a	0.06 a
20–30 cm	0.02 a	0.02 a	0.03 a	0.06 a	0.06 a	0.03 a
30–40 cm	0.02 b	0.01 b	0.05 ab	0.07 a	0.05 ab	0.05 ab
40–50 cm	—	—	0.05 a	0.04 a	—	0.03 a
C/N ratio						
0–10 cm	42.26 a	44.73 a	57.57 a	61.39 a	56.44 a	38.04 a
10–20 cm	33.32 a	46.68 a	45.81 a	33.16 a	48.94 a	38.90 a
20–30 cm	27.43 a	22.61 a	39.61 a	29.31 a	53.56 a	33.37 a
30–40 cm	35.00 a	20.91 a	35.43 a	33.58 a	46.67 a	22.66 a
40–50 cm	—	—	31.92 a	30.26 a	—	37.11 a
Extractable P (mg/kg)(0.25 N HOAC+0.015 N NH_4F)						
0–10 cm	7.72 a	10.23 a	10.83 a	20.78 a	12.29 a	15.98 a
10–20 cm	7.15 a	14.24 a	9.00 a	7.69 a	5.44 a	4.15 a
20–30 cm	3.66 a	2.10 a	3.18 a	10.22 a	4.59 a	2.77 a
30–40 cm	3.43 a	2.30 a	6.70 a	14.06 a	4.24 a	3.02 a
40–50 cm	—	—	6.44 a	3.75 a	—	2.57 a

Table 4. (continued)

Category	Inner track	Outer track	Between Track	Skidtrail track	Berm	Undisturbed
Extractable K (mg/kg)						
0–10 cm	186.14 a	90.25 a	102.34 a	163.90 a	81.10 a	92.63 a
10–20 cm	424.80 a	90.80 a	92.40 a	38.50 a	51.30 a	53.20 a
20–30 cm	138.30 a	74.10 a	56.16 a	60.32 a	59.00 a	41.70 a
30–40 cm	50.66 a	106.80 a	58.34 a	69.79 a	87.25 a	94.37 a
40–50 cm	—	—	56.97 a	48.43 a	—	69.53 a
Extractable Ca (mg/kg)						
0–10 cm	259.55 a	370.15 a	335.63 a	425.45 a	360.45 a	370.17 a
10–20 cm	180.55 b	324.90 a	234.27 b	143.05 b	206.65 b	145.49 b
20–30 cm	120.15 a	170.00 a	130.90 a	129.05 a	162.00 a	126.15 a
30–40 cm	120.20 a	166.90 a	105.20 a	118.00 a	135.90 a	206.20 a
40–50 cm	—	—	97.80 a	119.60 a	—	233.20 a
Extractable Mg (mg/kg)						
0–10 cm	56.68 a	73.02 a	46.54 a	59.49 a	62.25 a	43.72 a
10–20 cm	84.97 a	61.73 a	38.82 a	18.10 a	34.51 a	17.69 a
20–30 cm	35.27 a	37.70 a	20.75 a	13.01 a	25.43 a	18.16 a
30–40 cm	23.02 a	33.90 a	19.37 a	12.60 a	22.02 a	49.71 a
40–50 cm	—	—	19.87 a	19.77 a	—	55.67 a

* Means within rows followed by the same letter are not significantly different at the 0.05 level.

Table 5. Soil chemistry by disturbance type and depth at the Dainard Block

Category	Inner track	Outer track	Between Track	Skidtrail track	Berm	Undisturbed
pH (H_20)						
0–10 cm	7.31 a*	6.87 a	6.20 a	5.17 a	7.15 a	5.28 a
10–20 cm	5.60 a	5.62 a	5.11 a	5.07 a	7.19 a	6.11 a
20–30 cm	5.22 a	5.32 a	5.62 a	5.34 a	6.35 a	6.17 a
30–40 cm	—	4.82 a	5.10 a	5.10 a	—	7.11 a
40–50 cm	—	—	7.04 a	5.72 b	—	8.12 a
pH ($CaCl_2$)						
0–10 cm	6.95 a	6.53 a	5.77 ab	3.89 b	6.80 a	4.61 ab
10–20 cm	4.89 a	4.88 a	4.44 a	4.15 a	6.90 a	5.42 a
20–30 cm	4.15 a	4.37 a	4.75 a	4.38 a	5.88 a	5.41 a
30–40 cm	—	3.87 a	4.19 a	4.16 a	—	6.55 a
40–50 cm	—	—	6.41 a	4.84 b	—	7.48 a
% C (LOI)						
0–10 cm	4.62 a	4.58 a	3.37 a	2.76 a	4.54 a	3.02 a
10–20 cm	5.50 a	2.13 a	2.12 a	2.02 a	4.66 a	1.63 a
20–30 cm	1.22 a	1.10 b	1.49 b	1.57 b	3.86 a	1.14 b
30–40 cm	—	0.66 a	0.90 a	0.93 a	—	1.00 a
40–50 cm	—	—	0.75 a	0.81 a	—	0.73 a
% N (MICRO-KJELDAHL)						
0–10 cm	0.11 a	0.12 a	0.11 a	0.10 a	0.14 a	0.11 a
10–20 cm	0.16 a	0.08 a	0.08 a	0.07 a	0.19 a	0.08 a
20–30 cm	0.06 a	0.06 a	0.06 a	0.06 a	0.11 a	0.06 a
30–40 cm	—	0.05 a	0.05 a	0.06 a	—	0.06 a
40–50 cm	—	—	0.06 a	0.06 a	—	0.06 a
C/N ratio						
0–10 cm	41.71 a	37.31 a	28.35 a	27.52 a	33.16 a	27.10 a
10–20 cm	34.38 a	27.67 a	25.52 a	27.16 a	31.22 a	21.72 a
20–30 cm	21.79 b	19.96 b	23.59 b	25.33 b	35.05 a	18.55 b
30–40 cm	—	12.94 a	16.84 a	15.93 a	—	16.11 a
40–50 cm	—	—	12.30 a	13.54 a	—	12.79 a
Extractable P (mg/kg) (0.25 N HOAC+0.015 N NH_4F)						
0–10 cm	8.19 a	10.51 a	9.38 a	13.37 a	11.86 a	4.07 a
10–20 cm	13.37 a	5.13 a	5.53 a	5.84 a	9.76 a	2.54 a
20–30 cm	4.20 a	4.69 a	3.92 a	4.23 a	9.02 a	2.01 a
30–40 cm	—	2.13 a	2.19 a	2.32 a	—	1.58 a
40–50 cm	—	—	2.15 a	2.24 a	—	1.77 a

Table 5. (continued)

CATEGORY	INNER TRACK	OUTER TRACK	BETWEEN TRACK	SKIDTRAIL TRACK	BERM	UNDISTURBED
Extractable K (mg/kg)						
0–10 cm	55.89 a	80.97 a	43.28 a	48.95 a	90.00 a	33.94 a
10–20 cm	58.01 a	33.71 a	29.56 a	27.73 a	68.05 a	19.25 a
20–30 cm	22.34 a	18.91 a	23.72 a	20.09 a	54.55 a	17.43 a
30–40 cm	—	17.51 a	15.20 a	14.55 a	—	14.28 a
40–50 cm	—	—	12.07 a	13.98 a	—	6.74 a
Extractable Ca (mg/kg)						
0–10 cm	2490.0 a	2109.5 a	1051.8 ab	178.5 b	2002.8 a	422.6 b
10–20 cm	692.6 a	336.0 a	184.3 a	113.7 a	1458.0 a	917.5 a
20–30 cm	334.0 a	189.0 a	390.0 a	193.0 a	929.0 a	1115.00 a
30–40 cm	—	254.0 a	348.0 a	258.0 a	—	1046.70 a
40–50 cm	—	—	772.0 a	442.0 a	—	2159.40 a
Extractable Mg (mg/kg)						
0–10 cm	41.99 a	53.83 a	33.91 a	33.61 a	56.85 a	44.02 a
10–20 cm	53.07 a	30.26 a	22.60 a	23.08 a	47.94 a	37.68 a
20–30 cm	28.47 a	30.89 a	24.83 a	34.42 a	47.25 a	65.93 a
30–40 cm	—	27.18 a	22.83 a	31.03 a	—	53.30 a
40–50 cm	—	—	15.59 a	21.30 a	—	81.17 a

* Means within rows followed by the same letter are not significantly different at the 0.05 level.

Table 6. Percent skidroad and skidtrail related soil disturbance by treatment unit and disturbance type

TREATMENT	DISTURBANCE TYPE							
	CUTBANK	INNER TRACK	BETWEEN TRACK	OUTER TRACK	BERM	SIDECAST	SKIDTRAIL TRACK	TOTAL
	....%							
Block 117								
ELI*	1	5	4	5	3	3	—	21
OC*	1	5	3	5	4	4	—	22
PP*	1	5	3	5	3	3	—	20
Dainard								
OC	1	4	2	4	3	2	2	18
PP	1	4	3	4	3	2	2	19
Small Business								
OC	1	5	3	5	3	3	1	21
PP	1	5	3	5	3	3	—	20

* ELI - Operator choice treatment harvested by a different contractor
* OC - Operator choice treatment
* PP - Pre-planned treatment

Table 7. Area (ha) occupied by disturbance type by treatment at Block 117

TREATMENT	DISTURBANCE TYPE					
	CUTBANK	INNER TRACK	BETWEEN TRACK	OUTER TRACK	BERM	SIDECAST
OC*	0.25	1.27	0.76	1.27	1.02	1.02
PP*	0.48	2.41	1.45	2.41	1.45	1.45
ELI*	0.46	2.30	1.80	2.30	1.38	1.38
Total	1.19	5.98	4.01	5.98	3.85	3.85

* OC - Operator choice treatment
* PP - Pre-planned treatment
* ELI - Operator choice treatment harvested by a different contractor

Table 8. Mean bulk densities (Mg/m^3) of total and fine soil fractions by disturbance type and soil depths at Block 117

	Disturbance type				
Depth (cm)	Inner track	Outer track	Between track	Berm	Undisturbed
Total bulk density					
0–10	1.540 a*	1.246 ab	1.444 a	1.034 bc	0.846 c
10–20	1.714 a	1.205 b	1.663 a	1.046 b	1.110 b
20–30	1.844 a	1.516 ab	1.805 a	1.063 c	1.372 bc
30–40	1.883 a	1.610 b	1.868 a	—	1.601 b
40–50	1.860 a	1.721 a	1.875 a	—	1.747 a
Fine bulk density					
0–10	1.225 a	0.954 ab	1.168 a	0.775 bc	0.678 c
10–20	1.483 a	0.945 b	1.385 a	0.792 b	0.865 b
20–30	1.624 a	1.284 ab	1.502 a	0.771 c	1.122 b
30–40	1.629 a	1.282 a	1.606 a	—	1.300 a
40–50	1.556 a	1.469 a	1.605 a	—	1.329 a

* Means within rows followed by the same letter are not significantly different at the 0.05 level.

Table 9. Mean total soil porosity (%) by disturbance type and soil depth at Block 117

	Disturbance type				
Depth (cm)	Inner track	Outer track	Between track	Berm	Undisturbed
0–10	40.1 c*	51.6 bc	43.9 c	59.8 ab	67.3 a
10–20	33.3 b	53.2 a	35.3 b	59.4 a	57.0 a
20–30	28.2 c	41.1 bc	29.7 c	58.7 a	46.7 ab
30–40	26.7 b	37.4 a	27.3 b	—	37.8 a
40–50	27.6 a	33.0 a	27.0 a	—	32.0 a

* Means within rows followed by the same letter are not significantly different at the 0.05 level.

Table 10. Mean bulk densities (Mg/m^3) of total and fine soil fractions by disturbance types and soil depths at the Small Business Block

Depth (cm)	Disturbance Type					
	Inner track	Outer track	Between Track	Skidtrail track	Berm	Undisturbed
Total bulk density						
0–10	1.845 a*	1.491 a	1.109 a	0.723 a	1.056 a	1.006 a
10–20	1.949 a	1.528 a	1.258 a	1.283 a	1.299 a	1.376 a
20–30	1.964 a	1.779 a	1.812 a	1.445 a	1.400 a	1.668 a
30–40	2.272 a	1.925 ab	1.733 ab	1.505 ab	1.246 b	1.587 ab
40–50	—	1.695 a	1.682 a	1.549 a	—	1.766 a
Fine bulk density						
0–10	1.495 a	1.121 ab	0.857 ab	0.504 b	0.754 ab	0.702 ab
10–20	1.474 a	1.178 a	0.999 a	0.880 a	0.968 a	0.890 a
20–30	1.404 a	1.372 a	1.406 a	1.010 a	1.010 a	1.003 a
30–40	1.253 a	1.643 a	1.210 a	0.720 a	0.934 a	1.185 a
40–50	—	1.392 a	1.350 a	1.148 a	—	1.337 a

* Means within rows followed by the same letter are not significantly different at the 0.05 level.

Table 11. Mean total soil porosity (%) by disturbance type and soil depth at the Small Business Block

Depth (cm)	Disturbance Type					
	Inner track	Outer track	Between Track	Skidtrail track	Berm	Undisturbed
0–10	30.1 a*	43.5 a	58.0 a	72.6 a	59.9 a	61.9 a
10–20	26.1 a	42.8 a	52.3 a	51.3 a	50.8 a	47.8 a
20–30	25.6 a	32.6 a	31.3 a	45.0 a	46.9 a	37.1 a
30–40	13.9 b	27.0 ab	34.3 ab	43.0 ab	52.8 a	36.0 ab
40–50	—	35.7 a	36.2 a	41.3 a	—	34.9 a

* Means within rows followed by the same letter are not significantly different at the 0.05 level.

Table 12. Mean bulk densities (Mg/m3) of total and fine soil fractions for disturbance types and soil depths at the Dainard Block

Depth (cm)	Disturbance Type					
	Inner track	Outer track	Between Track	Skidtrail track	Berm	Undisturbed
Total bulk density						
0–10	1.285 a*	1.148 ab	1.144 ab	1.070 ab	0.901 b	0.858 b
10–20	1.509 a	1.348 ab	1.254 ab	1.220 ab	0.878 b	1.147 ab
20–30	1.609 a	1.486 ab	1.379 abc	1.138 c	1.241 bc	1.329 abc
30–40	—	1.486 a	1.516 a	1.391 a	—	1.355 a
40–50	—	—	1.509 a	1.486 a	—	1.421 a
Fine bulk density						
0–10	1.053 a	0.862 a	1.016 a	0.666 a	0.667 a	0.725 a
10–20	1.170 a	1.075 a	0.871 a	0.754 a	0.745 a	1.009 a
20–30	1.051 a	1.295 a	1.047 a	0.936 a	0.943 a	1.137 a
30–40	—	1.155 a	1.014 a	0.789 a	—	1.145 a
40–50	—	—	0.578 a	0.637 a	—	1.153 a

* Means within rows followed by the same letter are not significantly different at the 0.05 level.

Table 13. Mean total soil porosity (%) by disturbance type and soil depth at the Dainard Block

Depth (cm)	Disturbance Type					
	Inner track	Outer track	Between Track	Skidtrail track	Berm	Undisturbed
0–10	50.7 b*	56.0 ab	56.1 ab	58.7 ab	65.4 a	67.5 a
10–20	42.1 b	48.3 ab	51.9 ab	50.9 ab	65.0 a	55.9 ab
20–30	38.3 b	43.0 b	47.1 ab	56.4 a	50.6 ab	49.2 ab
30–40	—	43.0 a	41.8 a	46.6 a	—	48.1 a
40–50	—	—	42.1 a	43.0 a	—	45.3 a

* Means within rows followed by the same letter are not significantly different at the 0.05 level.

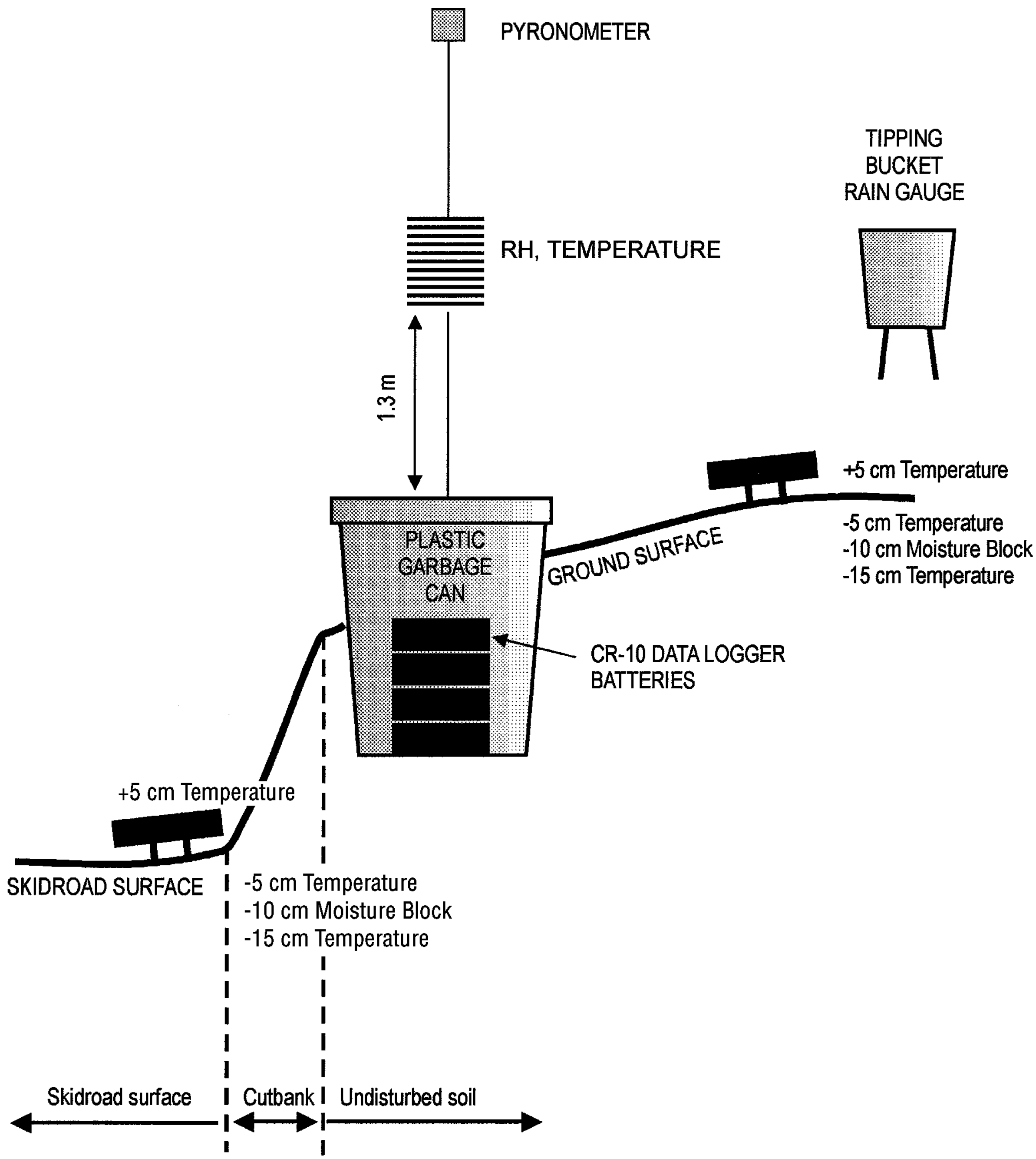


Figure 3.
Climate data logger (showing location of sensors).

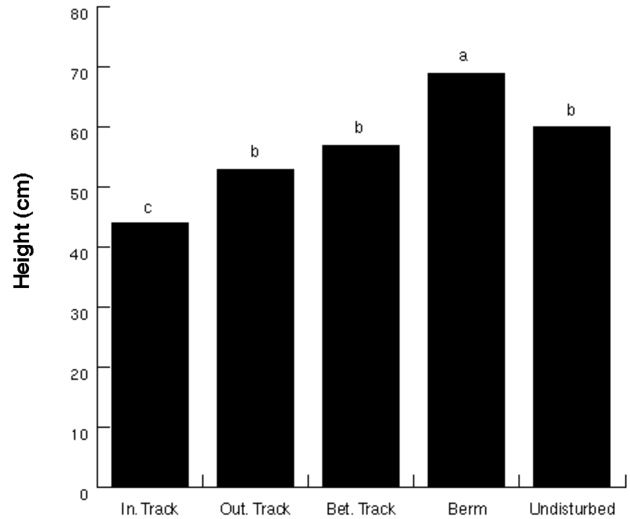


Figure 4.
Height of Engelmann spruce seedlings by disturbance type after three growing seasons at Block 117. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

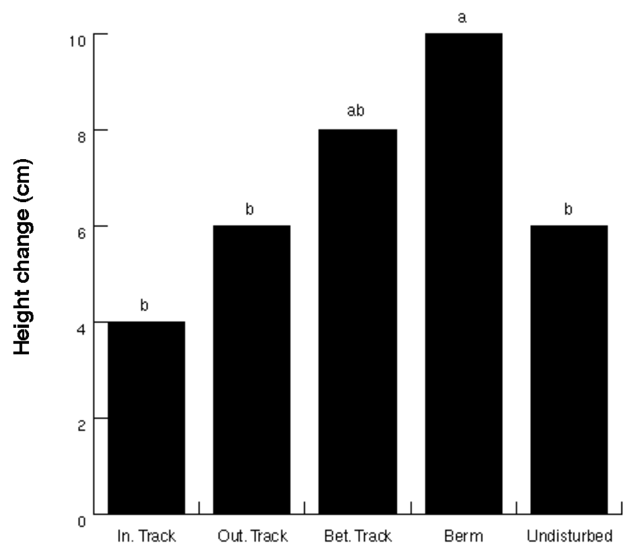


Figure 5.
One-year change in height of Engelmann spruce seedlings by disturbance type at Block 117. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

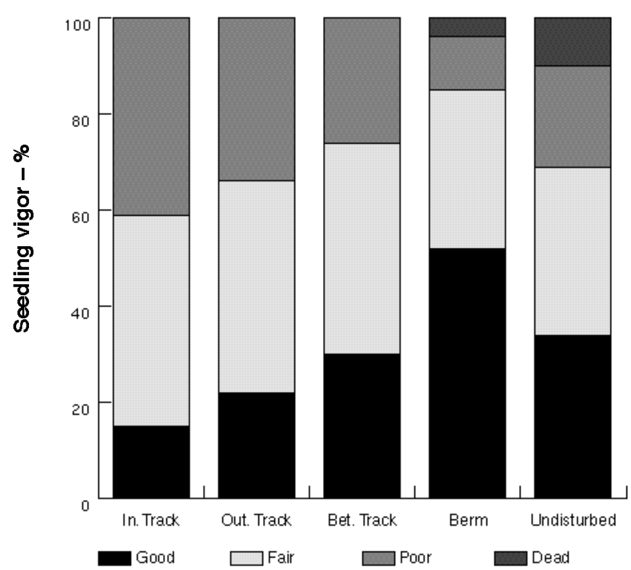


Figure 6.
Engelmann spruce seedling vigor by disturbance type at the end of the third growing season at Block 117.

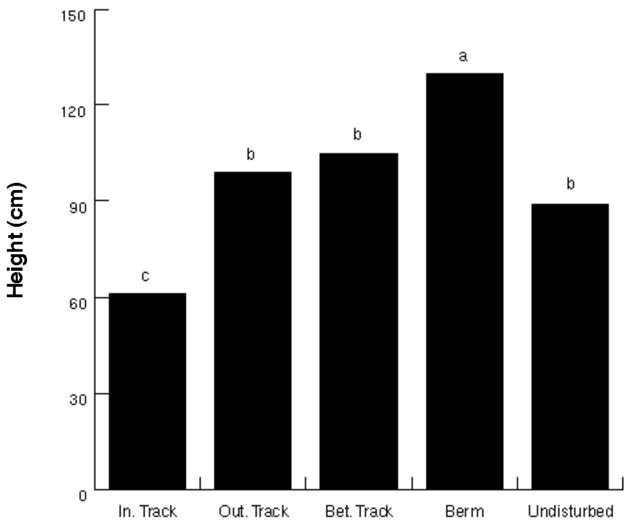


Figure 7.
Height of western larch seedlings by disturbance type after three growing seasons at Block 117. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

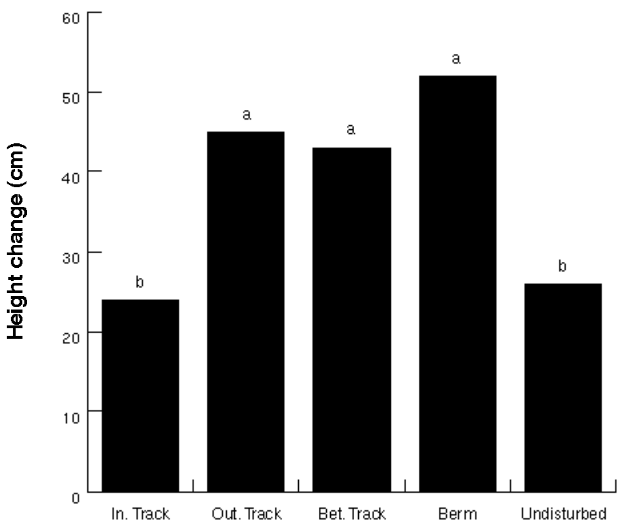


Figure 8.
One year change in height of western larch seedlings by disturbance type at Block 117. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

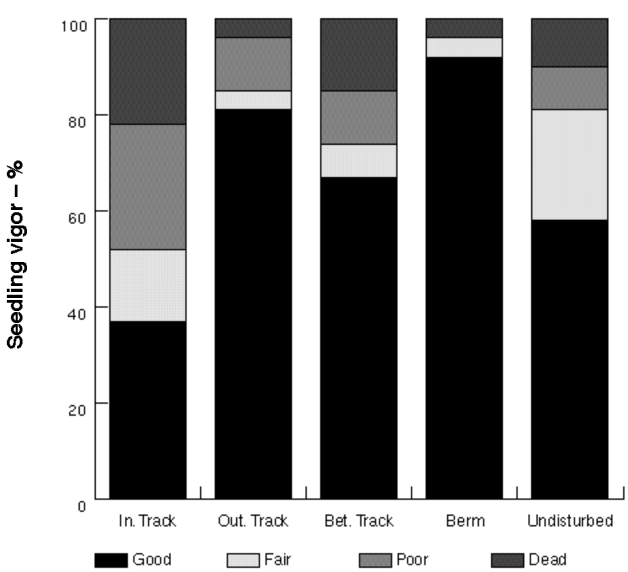


Figure 9.
Western larch seedling vigor by disturbance type at the end of the third growing season at Block 117.

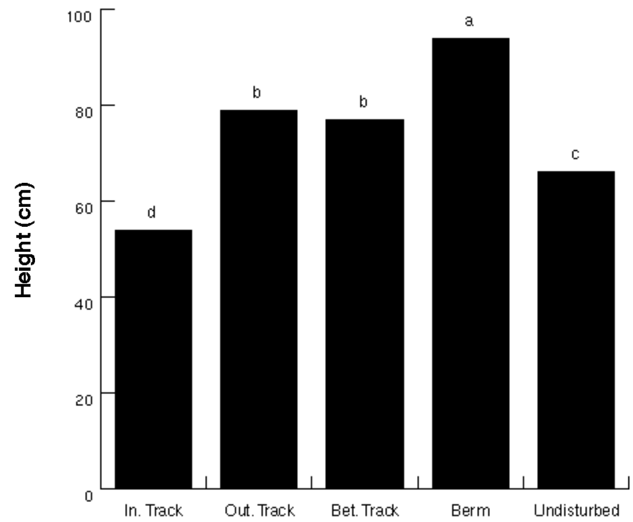


Figure 10.
Height of lodgepole pine seedlings by disturbance type after three growing seasons at Block 117. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

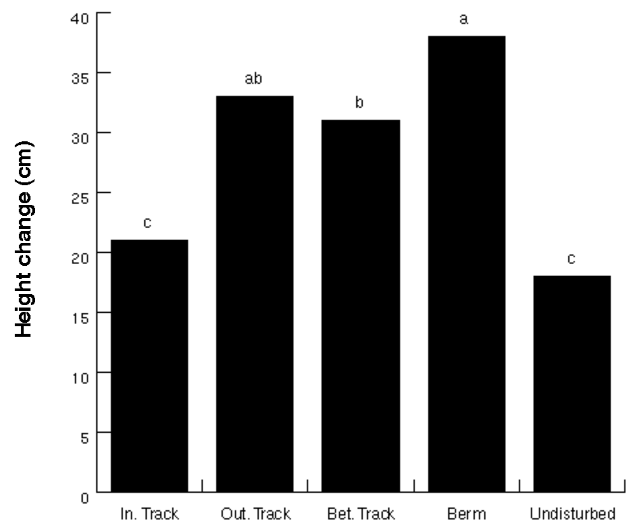


Figure 11.
One-year change in height of lodgepole pine seedlings by disturbance type at Block 117. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

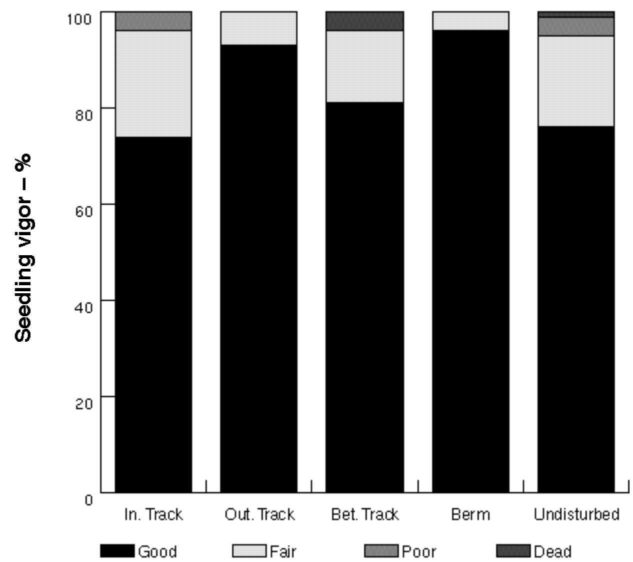


Figure 12.
Lodgepole pine seedling vigor by disturbance type at the end of the third growing season at Block 117.

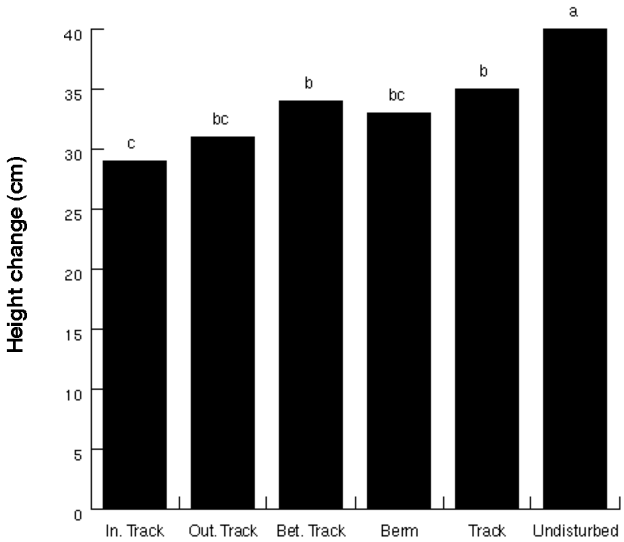


Figure 13.
Height of Engelmann spruce seedlings by disturbance type after three growing seasons at the Small Business Block. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

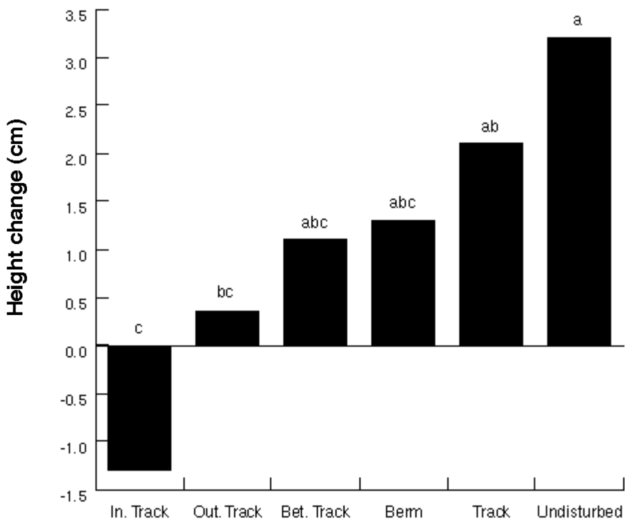


Figure 14.
One year change in height of Engelmann spruce seedlings by disturbance type at the Small Business Block. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

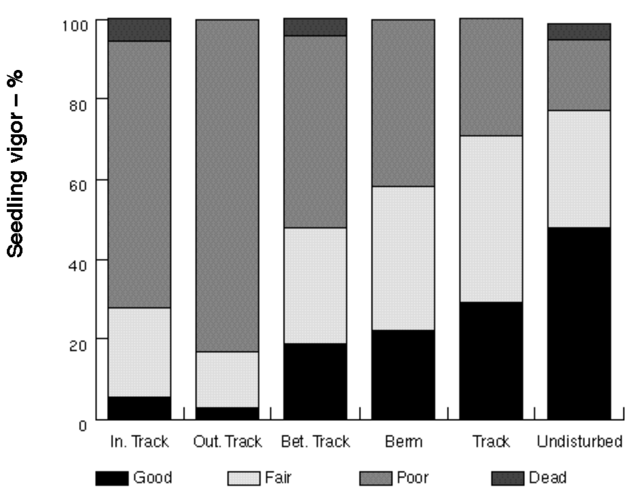


Figure 15.
Engelmann spruce seedling vigor by disturbance type at the end of the third growing season at the Small Business Block.

Figure 16.
Height of Engelmann spruce seedlings by disturbance type after three growing seasons at the Dainard Block. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

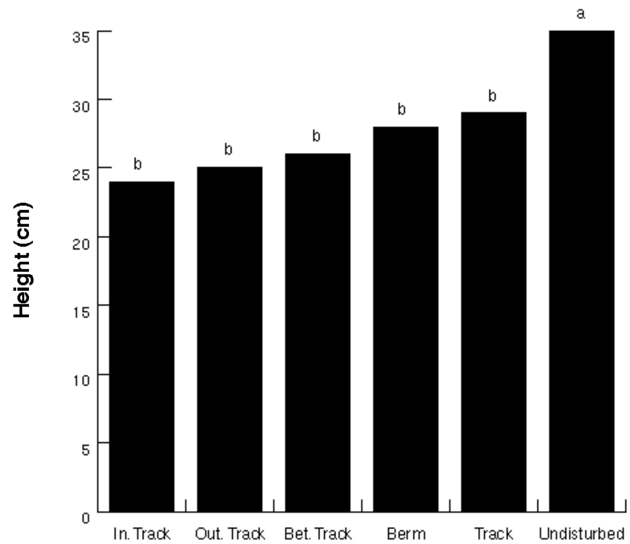


Figure 17.
One-year change in height of Engelmann spruce seedlings by disturbance type at the Dainard Block. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

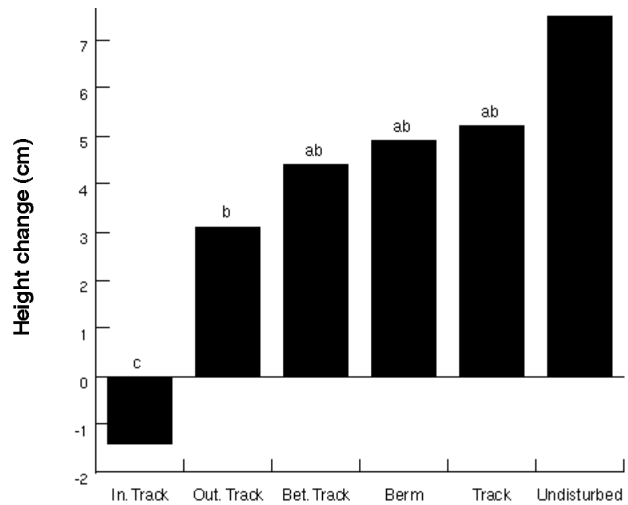
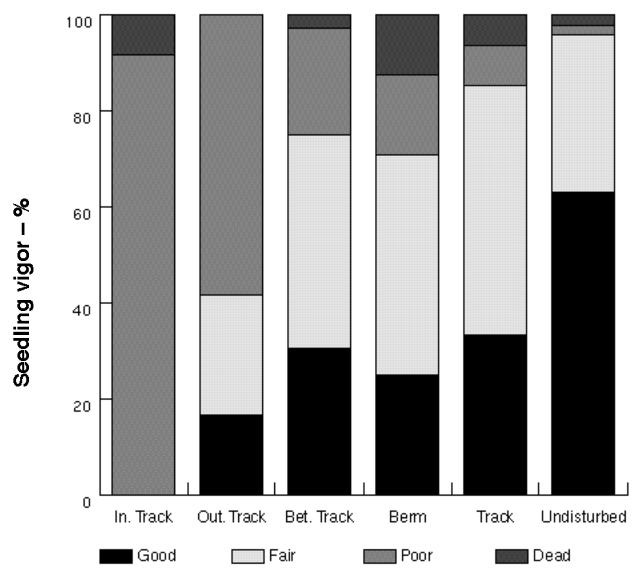


Figure 18.
Engelmann spruce seedling vigor by disturbance type at the end of the third growing season at the Dainard Block.



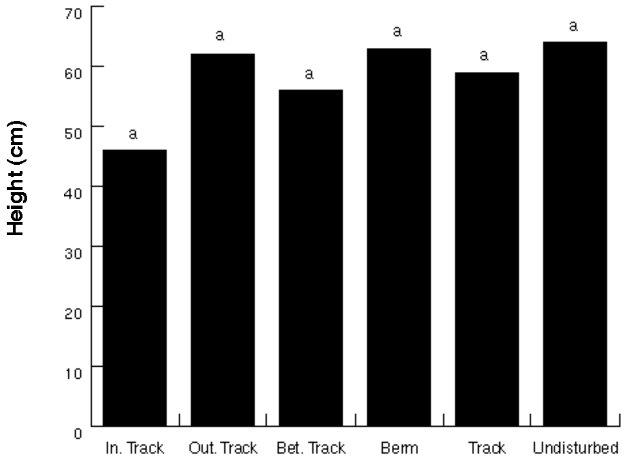


Figure 19.
Height of lodgepole pine seedlings by disturbance type after three growing seasons at the Dainard Block. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

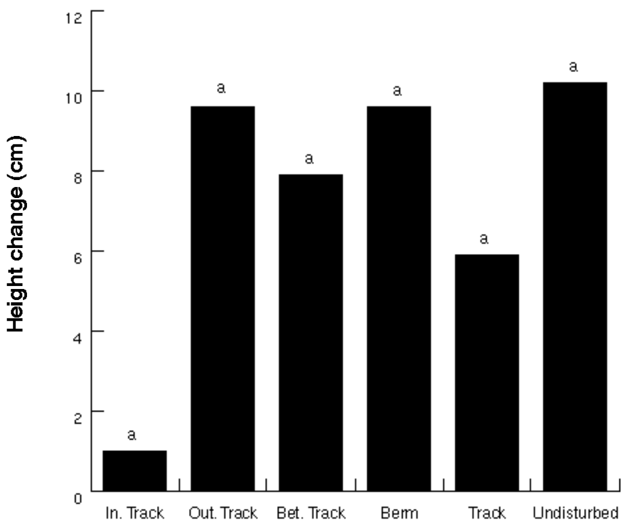


Figure 20.
One-year change in height of lodgepole pine seedlings by disturbance type at the Dainard Block. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

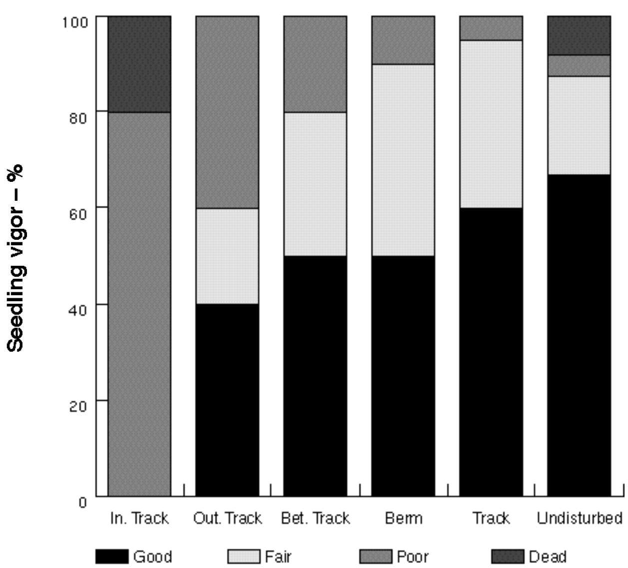


Figure 21.
Lodgepole pine seedling vigor by disturbance type at the end of the third growing season at the Dainard Block.