ALTERNATIVE SILVICULTURAL SYSTEMS FOR HARVESTING AND REGENERATING SPRUCE-DOMINATED BOREAL MINERAL WETLANDS

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ABSTRACT

Since 1995, the Canadian Forest Service, Natural Resources Canada has conducted collaborative research with Tolko Industries Ltd. to study alternative silviculture systems as a means of improving conifer reforestation success on mineral wetland sites. Regeneration on these sites is often poor, due to a rise in water table levels and establishment of heavy grass cover following harvest. Narrow clear-cut alternate strips and a patch clear-cut were tested in a white spruce (*Picea glauca* (Moench) Voss) – black spruce (*Picea mariana* (Mill.) B.S.P.) – larch (*Larix laricina* (Du Roi) K. Koch) stand north of Red Earth, Alberta. Performance of planted white spruce, black spruce, and larch, as well as seeded white spruce was monitored on mounded (scarified) and non-mounded (nonscarified) areas following harvest and site preparation in 1997. In addition, groundwater hydrology, microclimate, wind damage, and ground cover were monitored across the site. Five years after harvest, the best survival and growth has been with white spruce planted on mounded microsites. There has been only a small amount of water at the surface; consequently "watering-up" has not been a problem to date. Postharvest windthrow in the strip harvest system was minimal and occurred right after harvest with little subsequent blowdown. This research demonstrates a successful approach to harvesting and regenerating mineral wetland sites, with the objective of ensuring prompt reforestation. This requires prompt postharvest site preparation and planting with vigorous stock to avoid the problems of vegetation competition and partial retention of the overstory to ameliorate ground-level microclimate conditions following harvest.

RÉSUMÉ

Depuis 1995, en collaboration avec Tolko Industries Ltd., le Service canadien des forêts de Ressources naturelles Canada réalise des recherches sur les différents régimes sylvicoles afin d'améliorer le reboisement en conifères des stations minérotrophes. La régénération à ces endroits est souvent médiocre en raison de l'élévation de la nappe phréatique et de l'établissement d'un dense couvert végétal après la récolte. D'étroites bandes alternantes coupées à blanc et un secteur de coupe à blanc par trouées situé dans un peuplement d'épinette blanche (*Picea glauca* (Moench) Voss) – épinette noire (*Picea mariana* (Mill.) B.S.P.) – mélèze (*Larix laricina* (Du Roi) K. Koch) au nord de Red Earth, en Alberta, ont fait l'objet d'essais. On a comparé la performance des plants d'épinettes blanches, d'épinettes noires et de mélèzes ainsi que des semis d'épinettes blanches dans des secteurs scarifiés et non scarifiés après la récolte et la préparation du site en 1997. En outre, on a étudié l'hydrogéologie, le microclimat, les dommages causés par le vent et le couvert végétal sur le site. Cinq ans après la récolte, les épinettes blanches plantées sur les microsites scarifiés ont affiché les taux de survie et de croissance les plus élevés. Il n'y avait qu'une petite quantité d'eau en surface, de sorte que l'accumulation d'eau ne constitue pas un problème à ce jour. Les occurrences de chablis dans les secteurs de coupe en bandes ont été négligeables et se sont produites juste après la récolte, peu d'arbres ayant été renversés par le vent par la suite. Cette recherche décrit une approche efficace à la récolte et à la régénération des stations minérotrophes dans le but de garantir un reboisement rapide. À cette fin, il faut procéder à la préparation rapide du site après la récolte et utiliser des plants vigoureux pour éviter les problèmes de concurrence végétale et la rétention partielle de l'étage dominant afin d'améliorer le microclimat au niveau du sol après la récolte.

EXECUTIVE SUMMARY

The major difficulties in achieving successful reforestation on mineral wetlands are well known. The problems relate to competition due to ingress of wetland grasses and sedges and anaerobic conditions in the rooting zone of planted seedlings due to waterlogging and low soil temperatures. In 1995, the Canadian Forest Service, Natural Resources Canada, entered a multiyear collaborative research agreement with Tolko Industries Ltd., High Level Lumber Division (formerly High Level Forest Products Ltd.), to study alternative silviculture systems as a means of improving the success of conifer reforestation on a mineral wetland site.

A white spruce (*Picea glauca* (Moench) Voss) – black spruce (*Picea mariana* (Mill.) B.S.P.) – larch (*Larix laricina* (Du Roi) K. Koch) – Labrador tea (*Ledum groenlandicum* Oeder) – horsetail (*Equisetum* spp. L.) plant community (ecosite phase G-1) within the Central Boreal Mixedwood Subregion 110 km north of Red Earth, Alberta, was chosen for the study. Two harvesting systems were tested: narrow clear-cut strips alternating with uncut strips and a patch clear-cut. Performance of planted white spruce, black spruce, and larch, as well as that of seeded white spruce, was monitored on mounded (scarified) and non-mounded (nonscarified) areas. The study had six major components: assessing regeneration silviculture and ground cover, monitoring wind damage and wind firmness, monitoring soil temperature, determining groundwater hydrology, monitoring local meteorological conditions and microclimate conditions, and determining plant community response to harvesting. Preharvest measurements were taken in 1995 and 1996. The site was harvested, prepared, and planted during the first half of 1997. Postharvest monitoring has been conducted every year since 1997. The background information, objectives, site description, and experimental design for the study were provided in the establishment report (MacIsaac et al. 1998) and progress reports 2 and 4 years after harvest (MacIsaac et al. 1999, 2001). This publication details the postharvest response up to the fifth year after harvest.

As of 5 years after harvest, there was no evidence of mounding of the water table under the clear-cut strips in the strip-cut area. There has been only a small amount of water at the surface, so "watering-up" has not been a problem to date (i.e., water does not stay at maximum level for long after a precipitation event). Local topography and slope and proximity to alder channels have had the most effect on the depth to ground water, and these influences have overwhelmed the treatment (harvest) effects. Fifth-year seedling survival was significantly better for all species in the strip-cut area than in the patch-cut area. There has been better survival on mounded than on non-mounded microsites, in both the strip-cut and the patch-cut, for all species except black spruce in the patch-cut. Seedling growth (especially height growth) 5 years after harvest was better for all species in the strip-cut than the patch-cut. Growth of white spruce was better on mounded than on non-mounded microsites, but about equal for black spruce and larch on both types of microsite.

Postharvest windthrow was monitored in the strip-cut. In general, windthrow was minimal and occurred right after harvest, with little subsequent blowdown. The direction of windthrow was to the southeast for most trees and was concentrated at the east end of the uncut strips. The cutting pattern kept the wind below the threshold for large-scale windthrow, and the uncut strips buffered extreme winds. Vegetation water demand and interception were sufficient to limit flooding. The shading pattern in the strip has moderated the seedling environment.

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INTRODUCTION

Mineral wetlands within the Boreal Forest Natural Region of Alberta lie in the transition zone between uplands and fens or bogs. They carry a significant inventory of commercially valuable white spruce (*Picea glauca* (Moench) Voss) and black spruce (*Picea mariana* (Mill.) B.S.P.). Regeneration of stands of these trees is difficult when conventional clear-cutting silvicultural systems are applied, mainly because of excessively wet, anoxic conditions and competition from invading plants. These limitations have ramifications in determining the appropriate techniques for and relative success and costs of harvesting, regenerating, and growing spruce on these sites. In fact, mineral wetlands have been identified as sites with significant, poorly understood problems related to white spruce production (Brace Forest Services. 1994. Harvesting and regeneration concepts for white spruce and spruce-dominated mixedwoods in northern Alberta. Contract report to Daishowa-Marubeni International Ltd.).

"Watering-up," which occurs on both organic and mineral soils, refers to the rise in water table levels in response to reduced transpiration and interception after timber harvesting. Important factors controlling watering-up include precipitation and age of the harvested stand. In a comprehensive review of the subject, Dubé et al. (1995) indicated that watering-up is also governed by the average depth to the water table before harvest, tends to increase with the amount of wood cut, and is related to the time water is available near the soil surface. Intermediate cutting levels, such as those associated with thinning, cause less pronounced rises in water table levels.

Soil temperature is an important factor directly affecting the life processes of seeds, plants, and soil microbes. It is, in turn, affected by the presence or absence of a forest canopy or groundcover and by the amount of water in the soil. Soil temperature is a primary factor in determining the rates and directions of soil physical processes and of energy and mass exchange with the atmosphere, including evaporation and aeration. It also governs the types and rates of chemical reactions that occur in the soil and strongly influences biological processes, such as seed germination, seedling emergence and growth, root development, and microbial activity (Hillel 1980). The interactions between soil water content and soil temperature control the formation of soil frost, frost heaving, and the freeze–thaw cycle. Because water has a high heat capacity, when it is present in soil, it regulates the temperature so that the soil becomes neither too hot nor too cold.

Clear-cutting generally results in higher summer temperatures and lower winter temperatures than in the intact forest (Donnelly et al. 1991; Kubin and Kemppainen 1991). An increase in the number of frosty nights may also occur, which has implications for forest regeneration (Kubin and Kemppainen 1991). Recovery to preharvest temperature conditions may be rapid (2 years, Donnelly et al. 1991) or slow (12 years, Kubin and Kemppainen 1991). Evidently, latitude (Vermont compared with Finland) was a significant factor in the difference in recovery times between these two studies.

In light of these and other considerations described in MacIsaac et al. (1998), High Level Forest Products Ltd. (now Tolko Industries Ltd., High Level Lumber Division) and the Canadian Forest Service, Natural Resources Canada, initiated, in 1995, the present project on a mineral wetland located about 110 km north of the Red Earth townsite in Alberta.

The three overall objectives of this research project are as follows:

1. To test the effectiveness of narrow (15-m) alternating clear-cut and uncut strips (strip-cuts) and a small patch clear-cut in alleviating grass ingress and waterlogging problems and in improving survival and growth rates of regenerating trees.
2. To determine the survival and growth rates of seedlings of different species established by artificial regeneration (seeding and planting) and to explain the causal relationships between regeneration response and environmental variables (water table level, soil temperature, light levels, climate and microclimate variables, and ground cover ingress).
3. To determine the rate and spatial distribution of windthrow on the experimental site, patterns of wind behavior, and effectiveness of strips cut

parallel to the dominant wind direction in protecting residual uncut strips from windthrow after a partial cut.

To meet the main objectives specified at the start of the project (MacIsaac et al. 1998), particularly objectives 1 and 2, the following subobjectives were set for the groundwater hydrology and ground temperature components of the study:

1. To determine the effects of strip-cutting a wet site on groundwater table levels and to relate these effects to seedling survival and growth and to ground cover ingress.
2. To determine the effects of clear-cutting a peat plateau (peat with discontinuous permafrost) on groundwater table levels and to relate these effects to seedling survival and growth and to ground cover ingress.
3. To determine the soil temperature profiles in the rooting zones of seedlings across cut and uncut strips, on the patch clear-cut, and on the uncut areas, and to relate these temperature effects to seedling survival and growth and to ground cover ingress.
4. To characterize the interaction of wind with canopy trees.

SITE DESCRIPTION

The study site (Forest Management Unit F1, Block 34; Figs. 1 and 2) is situated in the Central Boreal Mixedwood Natural Subregion of Alberta (Alberta Environmental Protection 1994), about 110 km north of Red Earth, at 57°30′N and 115°20′W. The weather station with long-term records that is closest to the study site is located in Fort Vermilion, 110 km north of the site. It has a mean annual temperature of −1.2°C and mean January and July temperatures of −23.8 and 16.5°C, respectively (Atmospheric Environment Service 1982a). The area has a mean annual precipitation of 383 mm (Atmospheric Environment Service 1982b), about one-third of which falls as snow.

A reconnaissance survey of the area before timber harvesting indicated that two main ecotypes (according to Beckingham and Archibald [1996] and Beckingham et al. [1996]) existed on the site. On the first ecosite, the dominant components of the stand are black spruce (*Picea mariana* (Mill.) B.S.P.) and horsetail (*Equisetum* spp. L.), with a significant amount of white spruce (*Picea glauca* (Moench) Voss), more than is common on such a site. Labrador tea (*Ledum groenlandicum* Oeder) is the dominant shrub over much of the area. The moisture–nutrient regime is considered hygric/mesotrophic–submesotrophic. Soils are imperfectly or poorly drained and consist of a 40- to 70-cm-thick organic layer overlying glaciolacustrine mineral soil with silt–clay–loam textures. These soils are probably cold, because they are insulated by a thick organic layer. Most of the investigations were conducted on this site type.

The second ecosite on which vegetation and groundwater studies were done is a peat plateau, a slight but well-defined rise characterized by peat 50 cm deep supporting overmature white spruce and larch (tamarack) (*Larix laricina* (Du Roi) K. Koch). It contains pockets of permafrost at about the 60-cm depth. The area designated for clear-cutting contained both ecosite types described above.

In general, the research area is level to slightly undulating with a 0.7% slope to the northeast and a water table slope running nearly parallel to the topographic slope. (The water table slope was measured using data from 35 wells extending for 59 m along transects R1 and R2 [see “Groundwater” section in Methods]. Other transects were not used to calculate slope direction, because they were only 20 m in length.) Soils on the area belong to the Humic Gleysol and Humic Luvic Gleysol Soil subgroups (Agriculture Canada Expert Committee on Soil Survey 1987). Descriptions of soil profiles obtained from three locations on the study site in September 2000 are provided in Table 1.

Table 1. Soil profile descriptions[a]

Soil profile 1

Location of soil pit: Within residual strip between cut strips, 2 m southwest of hydrology well R1H (Fig. 2).

Vegetation: Horsetail, bog cranberry, sphagnum moss.

Depth to water table: 38 cm (range 33–40 cm); only organic horizons above water table.

Soil subgroup: Humic Gleysol.

Soil profile description:

Of	Fibric organic material, 23 cm thick (38–15 cm); clear wavy boundary; von Post scale of decomposition = 2–3, grading from almost undecomposed near surface to very weakly decomposed near lower boundary; plant structure distinct.
Om	Mesic organic material, 15 cm thick (15 cm to water table); moderately decomposed, von Post number = 5; seepage water at 0-cm level.
Ahg	Sampled 30 cm below water surface; very dark gray color (10YR 3/1); few indistinct mottles; silty clay to clay texture; weak, fine, platy structure; very friable consistence (moist).

Soil profile 2

Location of soil pit: Within uncut area of mature white spruce – black spruce forest, 20 m west of hydrology well R4B2 (Fig. 2).

Vegetation: Bog cranberry, bunchberry, prickly rose, horsetail, sphagnum moss.

Depth to water table: 47 cm (range 45–48 cm); only organic horizons above water table.

Soil subgroup: Humic Gleysol.

Soil profile description:

Of	Fibric organic material, 25 cm thick (70–45 cm); clear wavy boundary; von Post number = 2–3, grading from almost undecomposed near surface to weakly decomposed near lower boundary; plant structure distinct.
Om	Mesic organic material, 20 cm thick (45–25 cm); abrupt wavy boundary; von Post number = 5; seepage water at 25-cm level (water table); plant structure visible but becoming indistinct; point of seepage coincides with Om–Oh boundary.
Oh	Humic organic material, 25 cm thick (25–0 cm); very strongly decomposed, von Post number = 8.
Ahg	Sampled 25 cm below seepage point; very dark gray color (10YR 3/1); clay texture; weak, medium to fine, platy structure; friable consistence (moist); mottles distinct; gleyed.

Soil profile 3

Location of soil pit: Within mature white spruce – black spruce forest immediately east of the patch-cut area, 10 m west of hydrology well R5B (Fig. 2).

Vegetation: Labrador tea, bog cranberry, horsetail, prickly rose, kinnikinnick, sphagnum moss.

Depth to water table: 45–50 cm.

Soil subgroup: Humic Luvic Gleysol.

Soil profile description:

Of	Fibric organic material, 20 cm thick (50–30 cm); gradual wavy boundary; mostly undecomposed, von Post number = 2; plant structure distinct.
Om	Mesic organic material, 17 cm thick (30–13 cm); gradual wavy boundary; moderately decomposed, von Post number = 5; plant structure clear but becoming indistinct.
Oh	Humic organic material, 13 cm thick (13–0 cm); clear smooth boundary with mineral soil; very strongly decomposed, von Post number = 8; seepage water begins at top of this layer, open water at bottom of this layer.
Ahe	0 to 5 cm; boundary uncertain; very dark gray color (10YR 3/1); loamy texture; moderate, fine, platy structure; firm consistence (moist).
Bt	5+ cm (thickness uncertain); clayey texture; grayish brown color (10YR 5/2); moderate, fine, platy structure; firm consistence; bright, distinct mottles.

[a] Descriptions provided by Dr. I. Edwards and Mr. M. Blank, Canadian Forest Service.

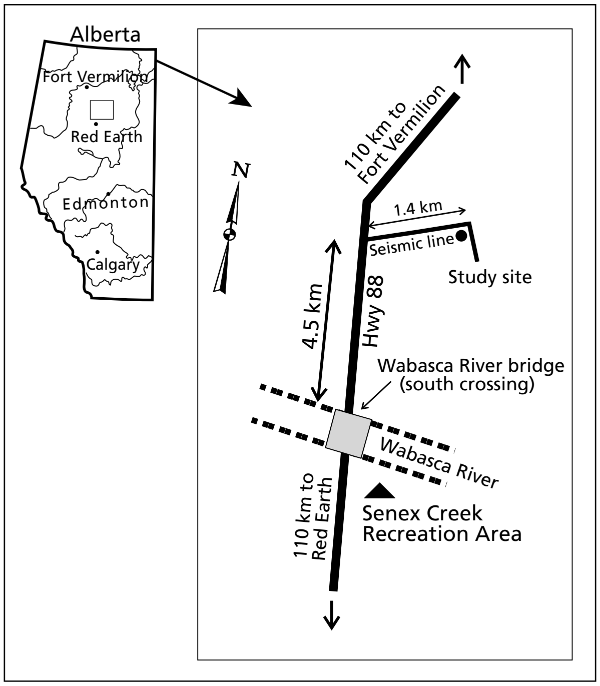


Figure 1. Location of study site in the province of Alberta.

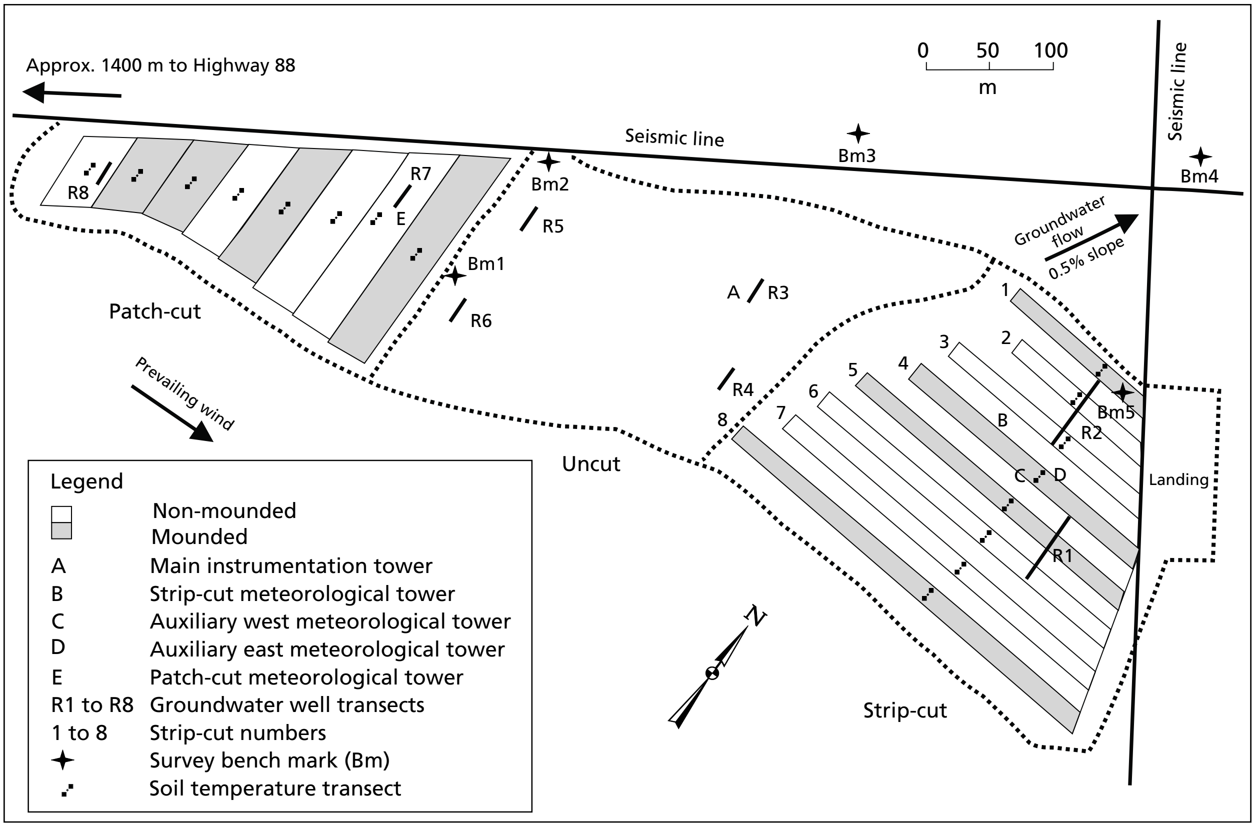


Figure 2. Site map with layout of uncut area, strip-cut, patch-cut, groundwater well and soil temperature transects, and meteorological towers.

METHODS

In this study, two harvesting systems were tested and their results compared with those of an adjacent uncut stand: in a strip-cut system, in which 15-m-wide clear-cut strips alternated with 15-m-wide treed strips (the uncut treed strips are often referred to as "residual strips" or "leave strips"; in this document, they are referred to as "residual strips") and a patch clear-cut, referred to as a patch-cut. The harvest layout for the strip-cut and the patch-cut (Fig. 2) was done in summer 1995, in anticipation of a planned harvest in the winter of 1995–1996. However, the harvest was delayed for 1 year because of the need for High Level Forest Products Ltd. to salvage wood from areas burned in 1995. As a result of this delay it was possible to collect 2 years of preharvest data, rather than just 1 year of data. The site was logged in January 1997 and skidded 3 weeks later; site preparation occurred in March 1997. Mounding, the chosen site preparation, was carried out on both the strip-cut and the patch-cut areas (Fig. 2), with mounds spaced at a density of 1100–1200 per hectare.

Climate

Climate sensors were mounted on a 27-m (canopy height plus 3 m) triangular tower in the uncut stand (Fig. 2). Solar radiation was monitored from the south side of the tower at the 24-m level, with a silicon pyranometer. Temperature, precipitation, and humidity were monitored at screen height, initially 1.3 m but gradually increasing to 1.7 m over the course of the experiment, as foot traffic near the tower compressed the organic layer around the base. Precipitation was collected with a weighing gauge. All sensors were connected to a Campbell Scientific CR-10 (Campbell Scientific Canada, Edmonton, Alberta) data acquisition system that was programmed to report hourly averages.

Local climate data were compared with the 1964–2000 temperature and precipitation records taken from the Talbot Lake fire lookout station, 27 km southwest of the study site, which had reasonably continuous data for the months of May to September (days 120–270).

Groundwater

Groundwater was measured on two transects in the strip-cut, four transects in the uncut area, and two transects in the patch-cut (Fig. 2). In the strip-cut, transects R1 and R2 were oriented perpendicular to the strips and consisted of 17 and 20 wells, respectively. They showed the spatial position of the water table relative to the ground surface. Each of these transects contained two recording wells, one in a treed strip and one in a cut strip. The other transects each contained three or four wells, one of which was a recording well, spaced 10 m apart. For 2 years before harvest (1995 and 1996) and 5 years after harvest (1997–2002), groundwater hydrology data were obtained from a total of 10 recording and 48 nonrecording wells installed to a depth of 1 m in 1995. Ten R-XC Ultra-Logger data storage units (Lakewood Systems, Edmonton, Alberta) recording water levels every 2 h monitored the position of the water table during the growing season. Five data loggers were installed in 1995, and the other five were added in 1996. Most of the groundwater measurements were recorded during the period June through early October.

Between 1996 and 2001, well elevations were referenced to bench marks established on each transect. Each bench mark consisted of a nail fastened to the base of a mature tree. On 4 September 2002, five additional elevation bench marks were placed on the silvicultural treatments (Fig. 2). The networks of wells on the strip-cut, uncut, and patch-cut areas were surveyed for elevation with respect to these bench marks. The 10 continuously recording wells were surveyed with respect to the upper surface of the wooden platforms that housed the data loggers, which are located above the tops of the wells.

Near-Surface and Soil Temperature

Measurement of ground temperature commenced in June 1998 when 70 RXTP (Lakewood Systems Ltd., Edmonton, Alberta) temperature probes (factory-calibrated thermistors, accurate to within 0.5°C) were installed on the same sites as the recording groundwater wells, i.e., on all transects (two transects in the strip-cut, four transects in the uncut area, and two transects in the patch-cut) (Fig. 2). On each transect, temperature probes were connected to existing data recorders and inserted in the ground as follows: three at the ground surface, three at 10-cm depth, and one at 5-cm depth. Identical patterns of probes were installed along each of the eight transects. Each year, most of the ground temperature measurements were recorded during the period June through early October.

On 18 and 19 June 2002, the ground temperature measuring network was expanded by the addition of 32 HOBO H8 4-channel data loggers (Onset Computer Corporation, Pocasset, Massachusetts) and additional 128 TMC20-HA temperature probes (also from Onset Computer Corporation). Each data logger was housed in a small electrical junction box fastened to an aluminum stake about 1.5 m above the ground surface. In the strip-cut, these temperature transects were established down the center of each cleared strip (Fig. 2) for comparison between mounded and non-mounded microsites. Eight data loggers and 32 temperature probes were installed for each site-preparation treatment. The temperature probes were arranged so that 12 surface and 20 subsurface (all at the 5-cm depth) measurements were obtained for each treatment. On each transect in the strip-cut, two data loggers were spaced 5 m apart and temperature probes 2.5 m apart so that the effects of distance from treed strips (edge effects) on ground temperature could be determined. Distances were referenced from the northern edge of the cleared strips.

Eight data loggers and 32 temperature probes were also installed for each site-preparation treatment in the patch-cut (Fig. 2). In this case, because it was not necessary to take edge effects into account, the numbers of surface and subsurface temperature probes were equal, i.e., 16 surface and 16 subsurface temperature probes for each site-preparation treatment. All temperature probes were located close to coniferous seedlings, if possible, and were buried for protection. Exposed probe wires were protected with heavy-gauge nylon tubing.

Aboveground temperature patterns were evaluated over summer 1998 at 20 cm height, by means of shielded thermistors located on the sunny aspect on one of the clear-cut strips in the strip-cut area 1 m from the north edge, on the shady aspect 1 m from the south edge, in the middle of the patch-cut, and under the canopy of the uncut block. Hourly mean temperatures computed on 60-s sampling frequency were recorded over the growing season. The hourly data from 0600 and 1600 were chosen to represent conditions for the minimum and maximum of the daily temperature cycle.

The effect of shading on temperature was determined with silicon pyranometers mounted at the location of the temperature sensors. The difference between sunny and shady aspects was computed daily for solar radiation and temperature, for the 0600 and 1600 time points.

Seedling and Germinant Survival and Growth

Given the overall experiment design, the strip-cut and patch-cut silvicultural systems were laid out as separate experiments (MacIsaac et al. 1998). Both experiments used a randomized split-plot design with four replicates laid out in detail after harvest; scarification was completed in March 1997.

In the strip-cut area, the eight strip-cuts were grouped into adjacent pairs for four replicates (Fig. 2). One of the two strips within each replicate was randomly chosen for the main treatment (scarification by mounding), whereas the other was left unscarified. Within each treatment (strip), five subtreatments were randomly assigned: planted larch, planted black spruce, planted white spruce, seeded white spruce, and a control area with no planting or seeding. Thus, a total of 40 treatment units were created in the strip-cut area (a treatment unit [plot] is defined in this study as a combination of species × site type × replication). The subtreatments (planted and seeded plots) were laid out after the strips were harvested.

In the patch-cut area, sections of the treatment were grouped into adjacent pairs for four replicates (Fig. 2). The location of the four replicates was laid out after the patch clear-cut was harvested. One of the two sections within each replicate was randomly chosen for the main treatment (scarification by mounding), whereas the other was left unscarified. Within each treatment area, four subtreatments were randomly assigned: planted larch, planted black spruce, planted white spruce, and a control area with no planting or seeding (the seeded white spruce subtreatment was not used here). Thus a total of 32 treatment units were created in the patch-cut area. Both the main treatment (mounded and non-mounded) and the subtreatments (planted plots) were laid out after the strips were harvested.

In July and August 1997, the larch, black spruce, and white spruce seedlings were planted in the strip-cut and patch-cut areas. Each replicate in each planted subtreatment was planted with 50 seedlings of each species. The seedlings were planted on both mounded and non-mounded treatment microsites with a 2.7-m planting grid (approximately 1400 stems per hectare).

In the strip-cut area, a total of 1200 seedlings were planted (50 seedlings per species × 3 species × 2 site types [mounding or no mounding] × 4 replicates). The plot length within each strip varied in direct proportion to the overall strip length, but the space between planted seedlings was kept constant at 2.7 m. In the shortest strips (strips 1 and 2), with plot lengths of 15 m, there was sufficient space to plant 50 seedlings at a 2.7-m spacing grid. In the longest strips (strips 7 and 8) the plots were 50 m long. The white spruce seeding replicates were hand-seeded in the strip-cut area on 4 June 1997; 10 stratified white spruce seeds were planted within a 7.5-cm radius of the 50 pinned locations in each seeding treatment unit.

In the patch-cut area, a total of 1200 seedlings were planted (50 seedlings per species × 3 species × 2 site types [mounding or no mounding] × 4 replicates).

In both the strip-cut and patch-cut areas, all the seedlings in the plots were marked with numbered pigtails immediately after planting. At that time, each marked tree was measured for total height (from the ground to the leader tip), and treatment, species, replicate, plot, and position within the plot were recorded. In addition, the planting microsite for each seedling was given a subjective evaluation (good, medium, or poor), and microsite type was recorded as mounded or non-mounded. For example, a microsite adjacent to an existing stump or on a mound with well-humified material exposed at the surface was classified as good.

Follow-up seedling measurements and assessments of white spruce seed germination were performed at 1 year (June 1998), 3 years (July 2000), and 5 years (August 2002). At those times, total height, root collar diameter, seedling mortality, vigor, and damage were assessed for each planted seedling in the strip-cut and patch-cut areas. Vigor was assessed according to a subjective four-class code (high, medium, low, dead) based on visible signs such as needle length and foliage color. Visible signs of seedling damage were assessed according to the following categories: chlorosis, animal damage, crushed (by humans), disease, insect damage, and microsite destroyed or flooded. Competition from aboveground vegetation within a 30-cm radius of each seedling was assessed on the basis of foliage cover of combined grasses, forbs, and shrubs according to the following cover classes: none, low (<20%), moderate (20–75%), and high (>75%). For the white spruce seeded treatment plots within the strip-cut, the number of germinants from the 10 seeds planted on 4 June 1997 were recorded at 1, 3, and 5 years.

Postharvest Vegetation and Ground Cover

Separate plots were established in August 1997 for postharvest monitoring of ground cover strata, vegetation competition, and tree canopy conditions. As with the seedling plots described above, these new plots were located in all treatment units within the strip-cut and patch-cut areas within the mounded and non-mounded subtreatments.

Strip-Cut Area

In each of the 40 treatment units, a 15-m line was set perpendicular to the strip-cut. This line was placed adjacent to the central row of seedlings in the treatment unit, as indicated on the seedling map. The start (south end) of this 15-m line was permanently marked.

Five seedling-centered 1 m × 1 m vegetation quadrats were placed along this line at the following distances from the south edge of the strip-cut: 1.5, 4.5, 7.5, 10.5, and 13.5 m. The nearest seedling to the line was selected as the quadrat center. The plot center was defined in this way to obtain seedlings at the prescribed distance from the strip edge. Data for the seedling in the center of each vegetation plot was collected as part of the overall seedling assessment described in the previous section.

At establishment (in 1997) and at 1 (1998), 3 (2000) and 5 (2002) years after harvest, vegetation and ground cover were assessed. These assessments were made during the period of maximum leaf area development in the summer of each respective measurement year. Soil moisture class in the vegetation quadrats were recorded according to the classification system of Luttmerding et al. (1990). Moisture was assessed at the seedling rooting zone (5–10 cm depth) because some sites that appeared quite dry on the surface contained substantial moisture underneath. Microsite position was recorded, using the following classes: (1) outside skid track, (2) skid track, (3) skid center, (4) location on mound (4.1 top or upper, 4.2 middle, 4.3 lower) (skid track refers to the area of ground disturbance created by the harvesting equipment, the feller buncher and grapple skidders; two parallel skid tracks are created in each harvest path). The assessment of microsite location was based on the point where the seedling was planted. Plant abundance was also recorded, according to the following cover classes: 0.1%, 0.5%, 1–20% (to nearest 1%), >20% to nearest 5%. This estimate was based on foliage cover, including plants and trees that were rooted outside the plot but that hung over the plot. Overall cover was measured for each of the following growth-form strata: tree, tall shrub (>1.5 m), low shrub (<1.5 m), forb, graminoid, moss, and lichen. Cover of individual vascular species was estimated for the five most dominant plants in each growth-form strata. The cover of individual nonvascular plant species was not recorded.

Patch-Cut Area

The type and timing of plot measurements for the patch-cut were identical with those for the strip-cut, except for the arrangement of the five 1 m × 1 m plots within each treatment unit. The 32 treatment units were each divided into five sections, on the basis of seedling location maps created for each treatment unit after planting. To ensure unbiased selection of seedlings, a random number table was used to locate a vegetation plot in each of the five sections.

Solar Radiation Levels

One year after harvest (in July 1998), hemispherical ("fish-eye") photographs were taken within each of the 40 treatment units in the strip-cut area, during uniformly overcast sky conditions, following the recommendations of Frazer et al. (1997). In each treatment unit, three photo points were set up (along the vegetation monitoring line, which was perpendicular to the strip-cut), with the camera located in the middle of the seedling-centered vegetation plots. These points were positioned as follows: south edge (1.5 m inside the strip from the south edge), center (center of the strip-cut, 7.5 m from either edge), and north edge (1.5 m inside the strip-cut from the north edge). A total of 120 photo points were used (40 treatment units × 3 photo points across each unit). At each photo point, a set of four photos were taken at 1.3 m above the ground. Kodak Multispeed film was used, and the ISO on the camera was set to 400. Prime exposure was determined using the light meter. Four photos were taken to produce f/stop bracketing: one at the prime exposure, two underexposed and one overexposed (e.g., prime, f/11; two under, f/16, f/22; and one over, f/8).

These images were used to quantify the amount of radiation (defined as the solar radiation across all wavelengths; Frazer et al. 1997) reaching the earth's surface. The 120 photos were scanned by computer and analyzed with the gap light index software package (Canham 1988, 1995) (GLI/C Version 2, Institute of Ecosystem Studies, Millbrook, New York). This program provides an estimate of the light transmission through forest canopies over an entire growing season, including incident diffuse and direct-beam radiation. These calculations require certain types of information, including the latitude and longitude of the site, length of the growing season, and amount of incident radiation received as direct beam over the growing season (i.e., proportion of days that are sunny). This information was obtained for this area from publically available, long-term atmospheric records.

Values for the following variables were calculated: open sky (percentage open sky visible through canopy openings), beam radiation (percentage of direct-beam radiation passing directly through openings in the canopy), diffuse radiation (percentage of seasonal total diffuse-beam radiation that penetrated directly through openings in the canopy), and global radiation (the percentage of combined diffuse and direct seasonal radiation that penetrated directly through canopy openings). This latter variable corresponds to the gap light index measure as defined by Canham (1989). Additional information on image analysis was presented by MacIsaac et al. (1998).

Wind Interactions

Experiment-wide, above-canopy wind was monitored from the top of the climate tower at 27-m height with a three-dimensional array of anemometers, aligned north, east, and upward, and fitted with fast-response expanded styrofoam propellers. Basic wind data were logged as hourly horizontal mean speed and direction and as a daily wind rose (a weather map showing the frequency and strength of winds from different directions over a period of time). Turbulent flux density, hereafter referred to as drag, on the uncut canopy surrounding the tower was determined from the covariance of vertical and horizontal winds measured at 2-s intervals multiplied by air density (the resulting unit for drag is watts per square meter).

Penetration of the wind into the understory was monitored with two-dimensional anemometer arrays on 6-m masts in the uncut area and in residual strips in the strip-cut area. Tree sway was monitored by means of biaxial clinometers mounted at 6-m height on the main stem of canopy-height trees in the uncut stand and in residual strips in the strip-cut area. Three stems in each of two representative size categories (smaller and larger, on the basis of diameter at breast height [dbh]) were measured in each treatment unit to determine whether trees of different thicknesses had different sensitivities to wind. These trees were within 10 m of the main wind tower (in the uncut area) or the auxiliary wind towers (in the strip-cut and patch-cut areas). Sway was quantified as hourly standard deviation of stem angle calculated from measurements obtained at a 15-s sampling frequency.

Linearity of the sway response was evaluated by comparison of sway and drag measurements in the uncut stand. Sway (as a proxy for drag), experienced by trees of similar thickness but in the residual canopy of the strip-cut, was compared to the uncut area. The mean and maximum sway and other wind results were reported for the measurement period. The directional sensitivity of response to wind was tested by comparing sway on the north–south and east–west channels of the clinometer for individual trees.

The three-dimensional propeller array was replaced by a more durable RM Young (R.M. Young Company, Traverse City, Michigan) wind speed and direction monitor in 1999, after completion of the detailed evaluations of the interaction between wind drag and stem sway.

The trend in wind speed along the east–west axis of the cut strips (parallel to the residual strips) was evaluated by means of fast-response two-dimensional propeller anemometers with axes oriented parallel to (on-axis), and perpendicular to (off-axis) the long axis of the cut. These anemometers were placed 6 m above the ground on the center line 60, 90, and 120 m from the west end of the fourth strip-cut (Fig. 2). Hourly means of the on-axis and off-axis components and above-canopy (actual) wind speeds were recorded. Data were later sorted for intervals when the on-axis component represented most of the actual wind. The wind speed at each of the towers was compared for these periods of relatively pure on-axis winds to determine whether wind speed increased along the direction of travel.

Wind drag at the vertical edge of the residual strips in the strip-cut area was monitored by two-dimensional propeller arrays. Arrays were placed at the 90- and 120-m positions at 6-m height and 1 m inside the strip edge on the north and south faces. Covariance of the on-axis and off-axis wind vectors was computed by the data loggers. Magnitude and sign of drag were compared for periods with west and east winds.

Windthrow

Windthrow (the uprooting [root failure] or breakage [stem failure] of trees by wind; Mitchell et al. 2001) in the residual strips of the strip-cut area was periodically mapped and measured at the following intervals after harvest: 5 months (June 1997), 1 year and 8 months (September 1998), 2 years and 8 months (September 1999), 3 years and 6 months (July 2000), and 5 years and 7 months (August 2002). In each survey, all new windthrown trees were marked and tagged, and the following data were recorded: windthrow type (uprooting or stem failure), tree species, tree location, direction of fall, basal diameter, dbh, root plate measurements (horizontal and vertical dimensions, thickness), and proximity to other windthrown trees.

RESULTS AND DISCUSSION

Climate

An important question in this study was whether climate (specifically air temperature) during the period since seedling establishment (after 1997) was similar to the longer-term regional record. At the Talbot Lake fire lookout station, 27 km southwest of the study site, growing season temperatures for 1997–2000 were similar to those for the longer term (1965–2000) (Fig. 3). There were greater differences for September, because early closure of the fire lookout in wet and cool years during the 1990s skewed the longer-term mean by overrepresenting warm and dry years. The records for June to August support the assumption that the experimental years were not exceptional.

The next question was whether the air temperature data collected at the study site corresponded to the regional data (i.e., were the Talbot Lake records similar enough to represent the conditions at the experimental site?). Comparison of temperature records from the Red Earth experimental site and Talbot Lake suggested similar conditions (Fig. 4). The wider daily temperature range at Red Earth can be accounted for by the lower elevation at that site and by terrain and vegetation differences. However, the close coupling of the temperature trends indicates that the two sites are part of the same regional climate cell.

Notwithstanding the fact that the air temperatures at the study site over the 1997–2000 period were within regional climatic norms, there were some year-to-year variations in seasonal averages for temperature (Table 2) and precipitation (Table 3). These variations had ramifications for water table levels, vegetation response, and seedling performance.

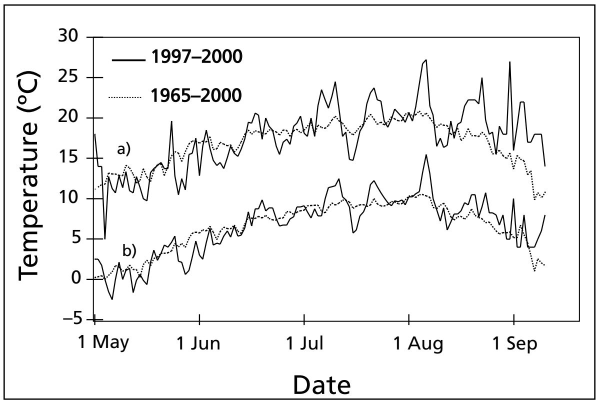


Figure 3. Short-term (1997–2000) and long-term (1965–2000) air temperatures during the growing season (1 May to 15 September) for Talbot Lake. (a) Mean daily maximum. (b) Mean daily minimum.

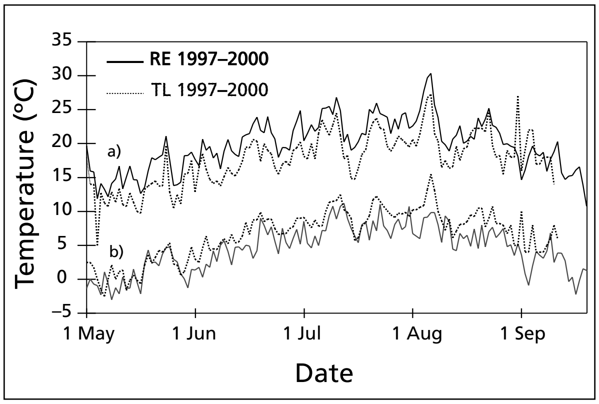


Figure 4. Short-term (1997–2000) air temperatures during the growing season (1 May to 15 September) at Red Earth (RE) and Talbot Lake (TL). (a) Mean daily maximum. (b) Mean daily minimum.

Table 2. Yearly and growing season temperatures (°C) at study site following harvest[a]

	Annual					Growing season (1 May to 30 September)				
Year	Mean max	Max	Mean min	Min	Mean mean	Mean max	Max	Mean min	Min	Mean mean
1997	NA	NA	NA	NA	NA	18.6	32.0	5.1	–3.7	11.9
1998	NA	NA	NA	NA	NA	21.0	32.2	4.4	–6.0	12.7
1999	NA	NA	NA	NA	NA	18.7	33.3	8.7	–5.5	13.7
2000	5.3	28.7	–6.6	–38.6	–0.7	16.7	28.7	4.4	–7.0	10.6
2001	7.0	31.6	–5.5	–37.0	0.8	19.5	31.6	5.2	–4.1	12.4
2002	5.1	30.5	–7.2	–39.6	–1.1	18.3	30.5	3.6	–16.5	7.4

[a] Temperature taken at 1.3 m in uncut area.

Note: Mean max = mean of daily maximum temperatures, mean min = mean of daily minimum temperatures, mean mean = mean of daily mean temperatures, NA = complete yearly record not available.

Table 3. Yearly and summer precipitation (mm) at study site following harvest[a]

	Annual		Summer (16 June to 19 September)	
Year	Total	Daily mean	Total	Daily mean
1997	NA	NA	291	3.1
1998	NA	NA	121	1.3
1999	NA	NA	168	1.8
2000	273.9	0.7	160	1.7
2001	231.1	0.6	161	1.7
2002	150.9	0.4	93	1.0

[a] Precipitation collected at 2.5 m at weather station in the patch-cut.

Note: NA = complete yearly record not available.

Groundwater

Immediate Postharvest Period (1997–2001)

Precipitation contributes to groundwater and influences fluctuations in the water table. Water table levels were noticeably higher during the growing seasons of the second (1996), third (1997), and sixth year (2000) of the study than in other years (Table 4). They reached a maximum in 1997, when precipitation was greatest, and a minimum in 1998 and 1999, when precipitation was low. For the first 3 years after harvest, on all three treatments, there was a general inverse correspondence between precipitation and depth to water table, i.e., the depth to the water table increased as seasonal precipitation decreased.

Data for the year 2000, when total precipitation for June to September was relatively low, did not follow this trend. Instead, high water table levels prevailed, approaching those of 1997, when almost twice as much rain fell. Although more rain fell during the growing season in 1997, the frequency of rainfall during the same period in 2000 was far greater—65 days of rain in 2000 and only 37 days in 1997. The shorter time spans between rainfalls in 2000 apparently prevented the water table levels from dropping to the low levels recorded in 1998 and 1999 (Table 4). In general, mean depth to the water table tended to be less on the patch-cut and strip-cut areas and greater on the uncut area. Similarly, mean water table levels in the treed strips were lower than in the cut (open) strips. Although not statistically proven, these results are consistent with greater evapotranspiration, and hence lower water tables, occurring under the trees than in the open strips or the patch-cut.

The position of the water table relative to the ground surface over strip-cut transect R1 was characterized by data from the 17 wells along the transect (Figs. 2 and 5). Except in two instances, the water table did not emerge above the ground surface. The water table appears to run roughly parallel to the ground surface, evincing a gentle slope to the north, an indication that groundwater moves from south to north. The true direction of groundwater flow could not be determined from the well installations, because all of the groundwater well transects were oriented north–south, and data from these wells provided only a two-dimensional perspective. It was assumed, however, that groundwater flow in the experimental area follows the slope of the land, i.e., in approximately the northeast direction (Fig. 2). Studies elsewhere (Dubé et al. 1995) have documented the occurrence of water table "mounds" in the soil below wide strips cut in the forest. In the current study, the water table remained planar (except for minor deviations) under both the open and the cut strips (Fig. 5), which indicates that groundwater mounding did not occur.

Some ponding of surface water was observed near the seismic line adjacent to the patch-cut where wood was decked during harvest (Fig. 2), probably as a result of blading along the line and soil compaction by machinery during harvest. Groundwater levels frequently registered above the ground surface at the south end of transect R2, where the first six wells were located (Fig. 6). At these locations, groundwater was observed flowing above ground for the entire year in 1996 and 1997. During the other years, the water table reached the surface only in the lowest positions of the land surface (Fig. 6a). On average, water table levels for these years remained below the surface (Fig. 6b).

The ground surface area through which groundwater flows is called the seepage face, and the aboveground flow is open channel flow. On the strip-cut area, as the groundwater emerged above ground it flowed perpendicular to the line of wells, in a westerly direction. The cross-section occupied by the first six wells on the south end of transect R2 is a topographic low; the wetness of the site combined with the abundance of river alder (*Alnus tenuifolia* Nutt.) on the strip running perpendicular to this cross-section characterized the site as an alder swamp. Open channel flow was observed before and after timber harvest. In addition, when groundwater was discharging into the topographic low, the water table along the transect sloped from north to south. Otherwise, it usually sloped from south to north, as along transect R1 (Fig. 5). In general, the water table along transect R2 was planar and showed no evidence of mounding under the open strips (Fig. 6).

Although near-surface water tables were frequently observed during wet periods, the water levels receded as soon as the rain stopped. The hydrographs (plots of water table level as a function of time) for 1997, the wettest year during the study period, clearly illustrate this pattern (Fig. 7a). They show a quick response to rainfall, manifested as a sudden rise in water table levels, followed by a slower recession or drainage rate. The recession continues until interrupted by another rainfall event, during which water table levels rise again. In three of the hydrographs for 1997 (Fig. 7a) the water table remained in the top 15 cm of soil for almost the entire measuring period. However, water table levels in well R5B (on the uncut area) remained below the 20-cm depth for the entire 1997 measuring period. The time response patterns for all four wells were the same, regardless of depth to the water table.

Hydrographs for two wells on transect R1 and one well on the uncut area during a dry year (1998; Fig. 7b) show that, in the absence of significant precipitation, water table levels declined by 40 to 50 cm. It is clear, then, that frequent precipitation is necessary to maintain near-surface water table levels at the study site, because natural drainage causes the water table to drop at a rate of about 5 or 6 mm × day^{-1}. When water table levels are near the surface, evapotranspiration may also be instrumental in lowering the water table.

Of the two sets of hydrographs presented, the set for the dry year (Fig. 7b) probably more closely resembles the norm. It shows high water tables in the spring, when the ground may be primed with water from melted snow, and low water tables in the fall, when precipitation tends to be low.

Five Years after Harvest (2002)

The position of the groundwater table along transects R1 and R2 on the strip-cut (Fig. 2) are shown for three days in 2002 (Fig. 8). Generally, the water table under the strip-cut remained at 35 cm below the surface or deeper (Fig. 9). The water table position on 19 July was close to the lowest level recorded in the strip-cut in 2002. The undulating appearance of the 19 July water table profile was attributed to ice in some of the wells. On 5 September, the water table on the strip-cut rose to its highest level following rainfall of 16 mm over the previous 3 days. Only 4 mm of rain fell in the next 18 days and consequently the water table dropped to the intermediate level recorded on 23 September (Fig. 8).

Water tables on the patch-cut and uncut areas came close to the surface in late July and early August (Fig. 9), but on no occasion did the water table rise above the ground surface on any of the treatment areas. Although the water table rose rapidly in response to significant rainfall, it started to decline as soon as the rain ceased (Fig. 9). The rate of rise in the water table on all treatment areas was a function of the amount, frequency, and intensity of rainfall. The rate of decline in the water table was generally greater near the surface than at depth. The decline for the site averaged about 6–8 mm × day^{-1}; thus, during a summer month without rain the water table might drop 250 mm.

Table 4. Mean depth to water table in 10 wells on three treatment areas and precipitation during the period 16 June to 19 September 1995–2000[a]

	Mean depth to water table (cm)										
	Strip-cut										
	Transect 1		Transect 2								
					Uncut area				Patch-cut		
Year[b]	R1B (open)	R1O (treed)	R2L2 (open)	R2P2 (treed)	R3A	R4B2	R5B	R6B2	R7D	R8B	Precipitation (mm)
1995	28	36	NA[c]	NA	23	NA	45	NA	NA	30	143
1996	19	30	17	9	23	20	41	16	EF[d]	16	228
1997	11	18	11	19	9	17	31	13	11	8	291
1998	35	43	37	48	39	43	60	30	37	22	121
1999	22	38	34	47	37	34	54	20	30	22	168
2000	11	24	EF	22	12	20	48	14	17	10	160

[a] Designations such as R1B refer to groundwater well locations; the first number identifies the transect and the following characters refer to a specific well on the transect (see Fig 2).
[b] 1995 and 1996 = preharvest; 1997–2000 = postharvest.
[c] NA = not available. Only five wells were installed in 1995, and there were no data from the other five wells for that year.
[d] EF = Data not available, due to equipment malfunction.

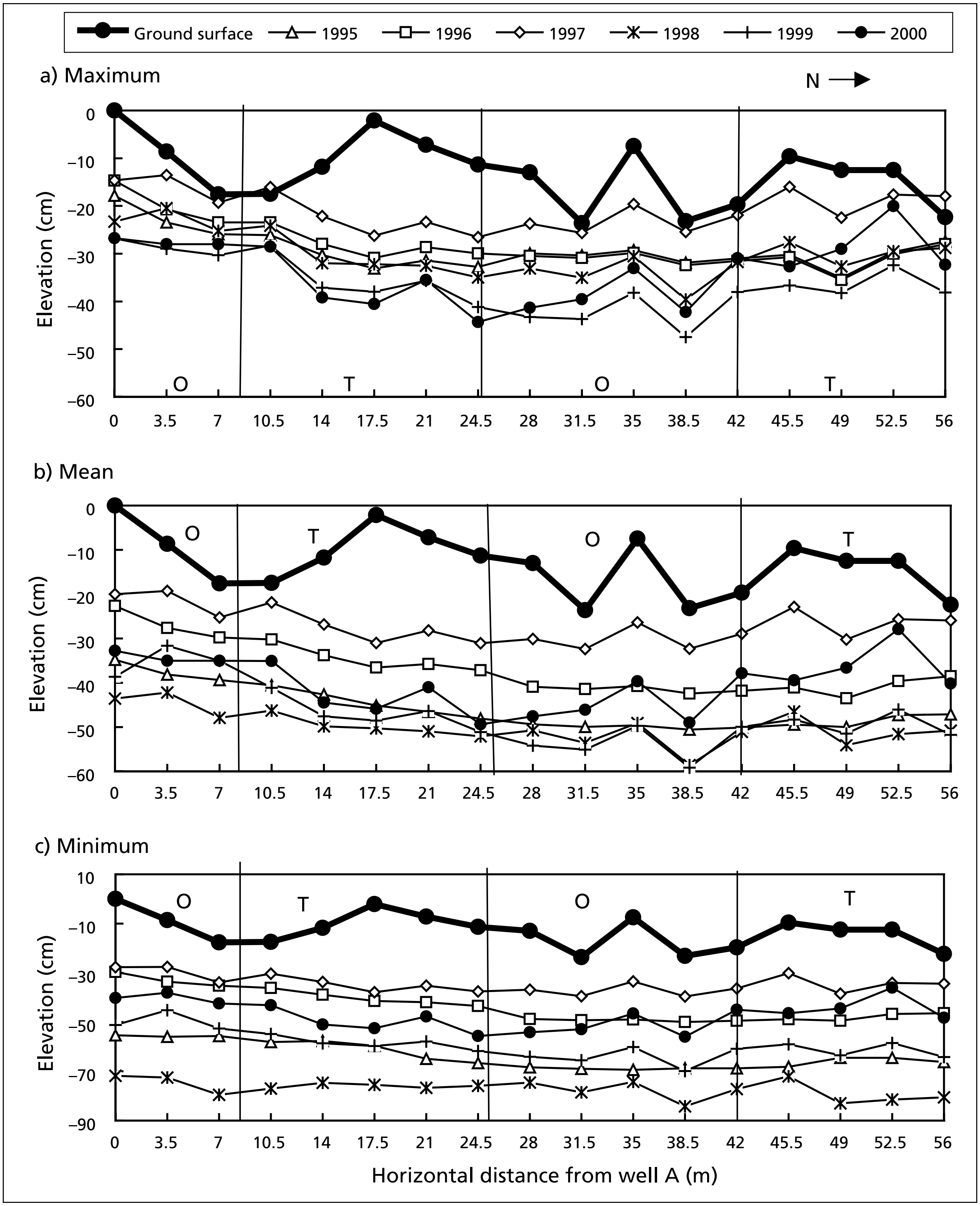


Figure 5. Groundwater table profiles on strip-cut transect R1 during the preharvest (1995 and 1996) and postharvest (1997–2000) periods. (a) Maximum. (b) Mean. (c) Minimum. O and T indicate open and treed strips, respectively. The elevations are referenced to the ground surface at well A on this transect.

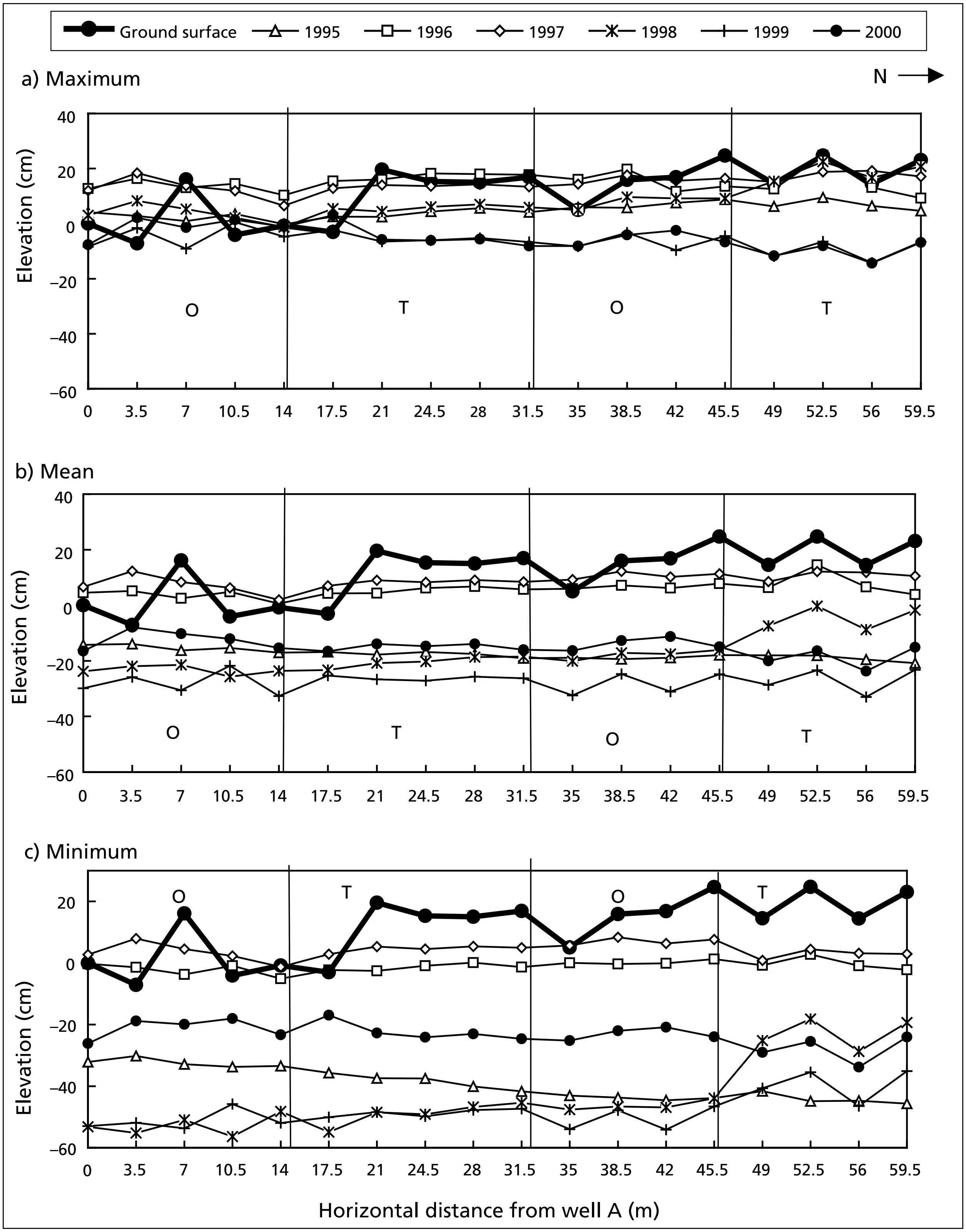


Figure 6. Groundwater table profiles on strip-cut transect R2 during the preharvest (1995 and 1996) and postharvest (1997–2000) periods. (a) Maximum. (b) Mean. (c) Minimum. O and T indicate open and treed strips, respectively. The elevations are referenced to the ground surface at well A on this transect.

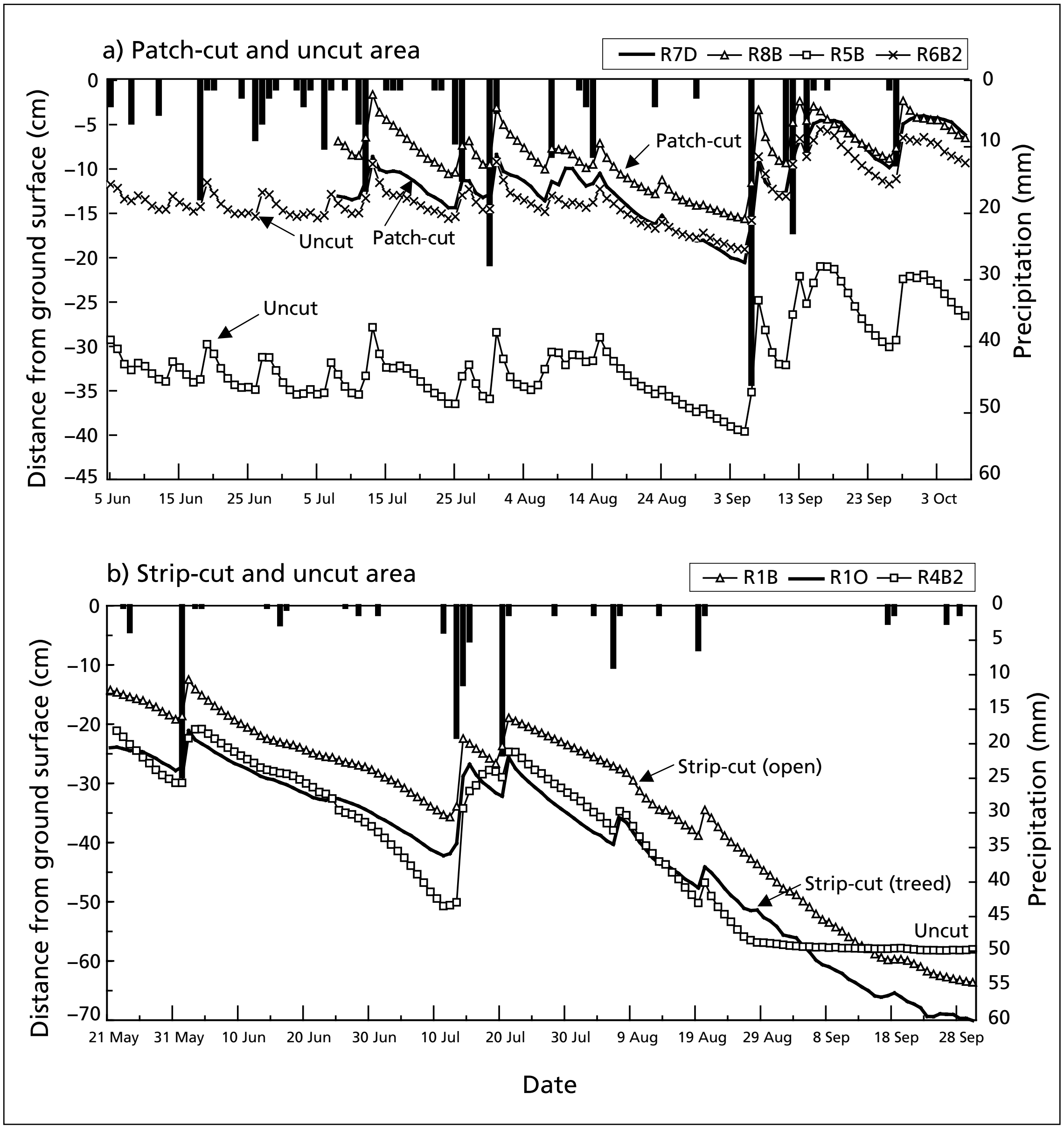


Figure 7. Precipitation (vertical bars) and groundwater hydrographs in the study area. (a) Two wells on the patch-cut (R7D and R8B) and two wells on the uncut area (R5B and R6B2) (5 June to 7 October 1997). (b) Two wells on strip-cut transect R1 (R1B and R1O) and one well on the uncut area (R4B2) (21 May to 29 September 1998).

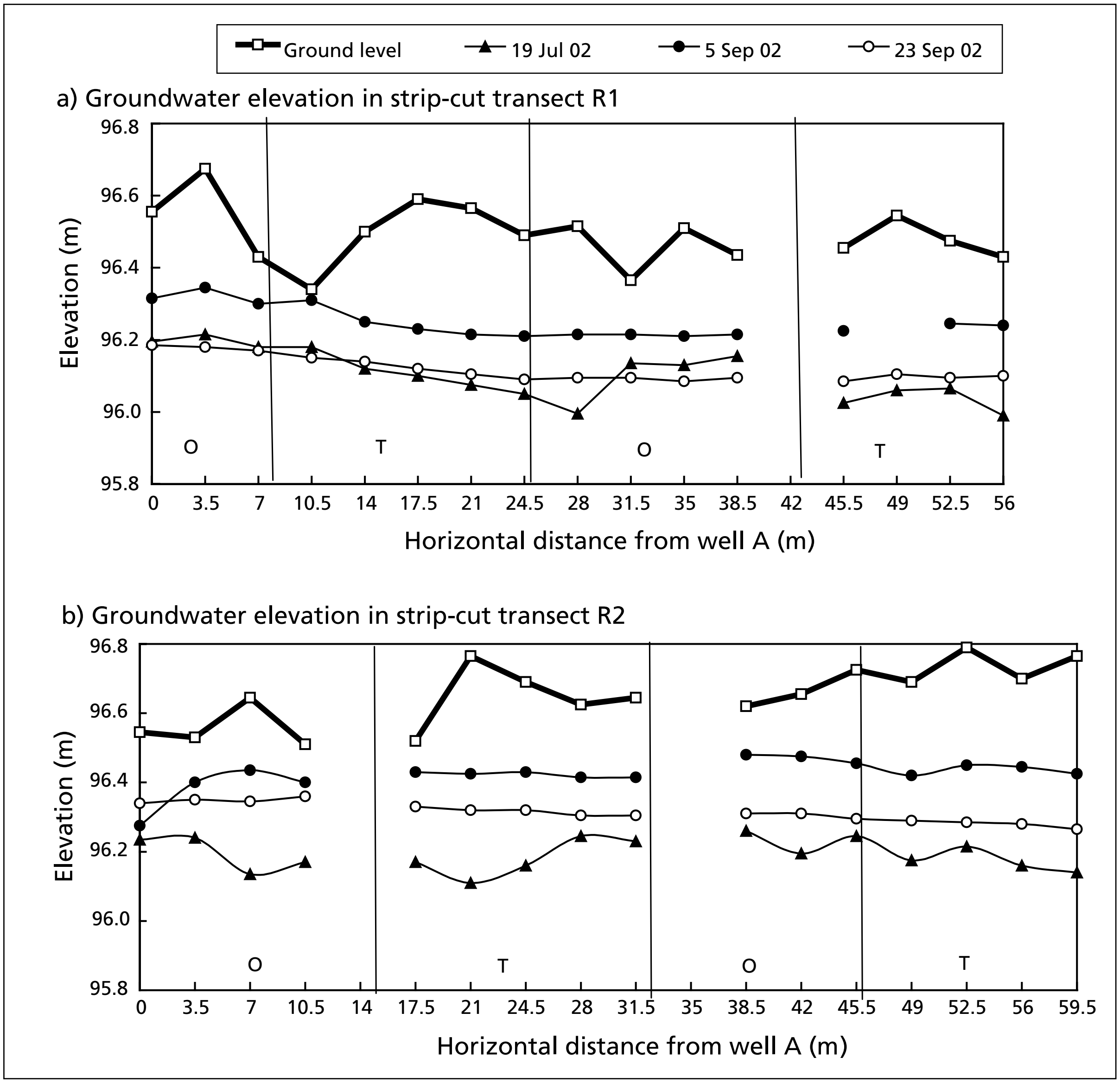


Figure 8. Groundwater table elevations on 3 days in 2002 along (a) strip-cut transect R1 and (b) strip-cut transect R2. O and T indicate open and treed strips, respectively. Note: For Figures 8a and 8b, elevation is relative, based on an arbitrary benchmark of 100 m.

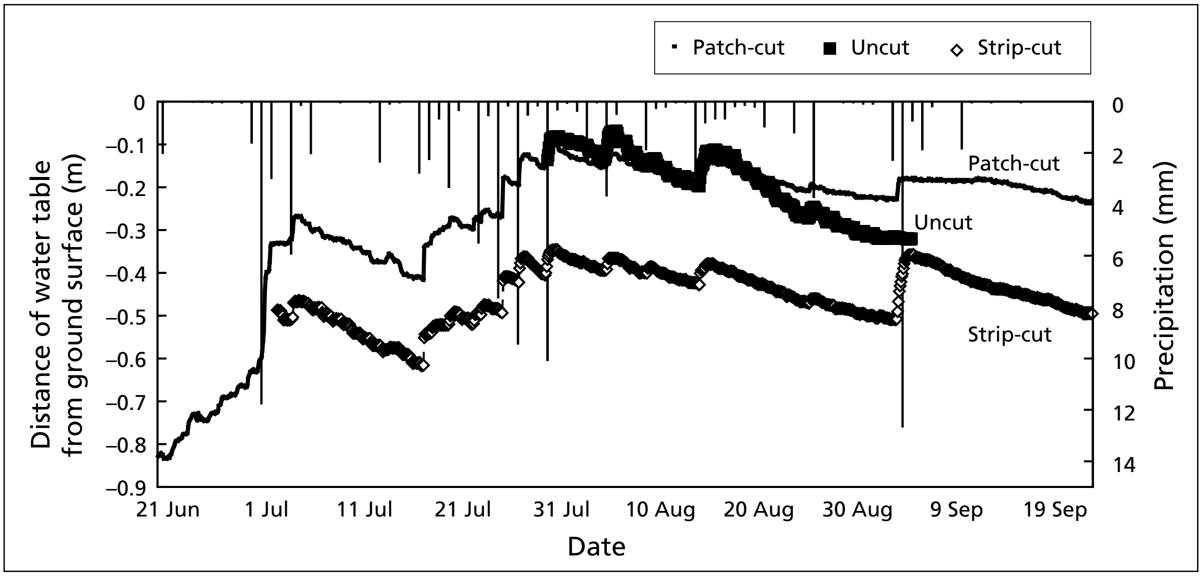


Figure 9. Hydrograph for the uncut, strip-cut, and patch-cut areas (21 June to 21 September 2002).

Near-Surface and Soil Temperature

Immediate Postharvest Period (1997–2001)

The ground surface is the plane most significantly affected by weather because it forms the interface between the atmosphere and the soil. Solar radiation impinges directly upon it, it loses heat to the atmosphere at night and on cool days, and its physical condition controls entry of heat with precipitation or snowmelt into the soil.

Table 5 summarizes near-surface, morning temperature averages for summer 1998. At 0600, the uncut area was noticeably different from the others, because it was less subject to radiative cooling. The exposed microsites were on average 1.2°C cooler than those under canopy at dawn. The offset, while small, was sufficient to yield 13 frost events at these sites, whereas only 8 such events occurred under the canopy.

Afternoon high temperatures were related to exposure to direct-beam solar radiation, such that the patch-cut and the north edge of the strip-cut were relatively warmer, whereas the uncut understory and shaded south edge were correspondingly cooler. Comparisons of the sunny (south-facing) and shady (north-facing) aspects of the strip-cut demonstrated a strong influence of incoming radiation on late afternoon air temperature at 20 cm above the surface. The sunny (south-facing) aspect was almost 1°C warmer for every 100 W × m^{-2} of additional solar radiation at 1600 compared with the shady (north-facing) aspect (Fig. 10).

Summaries of maximum, mean, and minimum temperatures for the ground surface, the 5-cm depth, and the 10-cm depth at 10 locations are provided in Tables 6, 7, and 8, respectively. These data are representative of temperature conditions on the experimental area as a whole. Maximum, mean, and minimum air temperatures are provided for comparison.

The thermal discontinuity at the air–soil boundary is clearly shown by the differences in maximum temperatures at the surface (Table 6) and at the 5-cm depth (Table 7). At the surface, maximum temperatures were on average 5°C higher than maximum air temperatures, whereas at the 5-cm depth maximum temperatures were 11°C to 14°C lower than the maximum air temperatures. At the 10-cm depth, maximum temperatures were on average 14°C to 18°C lower than the maximum air temperatures (Table 8).

Mean ground surface and air temperatures for the measurement period were approximately the same for all 3 years of record (Table 6). Mean soil temperatures were slightly less than mean air temperature at the 5-cm depth (0°C to 6°C lower; Table 7) and at the 10-cm depth (2°C to

7°C lower; Table 8). Minimum temperatures tended to be higher in the soil than in the air, the difference tending to increase with depth. Thus, soil surface temperatures were usually 1°C to 5°C higher (Table 6), the 5-cm depth temperatures 5°C to 9°C higher (Table 7), and the 10-cm depth temperatures 5°C to 10°C higher (Table 8) than air temperatures.

Ground surface data (Table 6) indicate that the greatest extremes in surface temperature tended to occur on the harvested sites, i.e., the strip-cut and the patch-cut. This is to be expected, because the stand was opened up in the case of the strip-cut, and the protective tree cover completely removed to create the patch-cut. Examples of treated sites, where maximum daily surface temperatures consistently exceeded maximum daily air temperatures, are given for the strip-cut (Fig. 11a) and the patch-cut (Fig. 12a). In contrast, a different pattern was observed on the uncut area (Fig. 13a), where maximum daily ground surface temperatures were consistently less than maximum daily air temperatures. This difference can be related to the presence of a forest canopy and an undisturbed forest floor across the uncut area.

The daily data (Figs. 11, 12, and 13) reveal features common to all three sites. First, oscillations in the mean and minimum daily ground surface temperature closely followed those of air temperature in both time and magnitude. This pattern is also evident from the statistical data for these sites (Table 9): means, standard deviations, and ranges for ground surface temperature were similar to those for air temperature. Second, ground temperature fluctuations were greatest at the surface and least at the 10-cm depth, which implies that the temperature damping effect in the upper 10-cm of soil was greater at the 10-cm depth than at the 5-cm depth. This effect is reflected in the means, standard deviations, and ranges, which decreased with depth on the three sites (Table 9). Third, air temperature and ground temperature at the three depths were synchronized, so that all four temperature cycles were in phase. This result is not surprising, because the ground temperature was measured at relatively shallow depths.

At the 5-cm depth on the treated sites, maximum and mean temperatures were intermediate between surface values and values at the 10-cm depth (Figs. 11 and 12). This was not the case on the uncut area at R5B, where temperatures at the 5-cm depth were very similar to those at the 10-cm depth (Fig. 13). The difference suggests that removing part or all of the canopy results in temperature effects down to at least the 5-cm depth.

At the 10-cm depth, the temperature profiles of all three sites were remarkably similar: temperature increased from a minimum of 5°C to 6°C in mid-June to a maximum of 12°C to 14°C in early August, and declining to 8°C to 9°C by mid-September. The similarity in temperature profiles suggests that treatment effects on temperature were minimal at the 10-cm depth. Air and surface temperatures occasionally dropped below freezing, but temperatures at the 5- and 10-cm depths remained above 4°C throughout the measuring period (Figs. 11, 12, and 13).

Five Years after Harvest (2002)

Data for ground temperatures at different locations within the cleared strips were first obtained in 2002. In the summer months, noticeable differences in the mean daily surface temperatures at different locations usually occurred when ambient temperatures were increasing (Fig. 14). On 8 and 24 August 2002, mean daily surface temperatures 5 m from the northern edge of the cut strips were 4°C higher than at the 12.5-m mark (in the middle of the cut strips). Surface temperature peaks did not always occur concurrently. For example, surface temperatures in the northern section of the cut strips, at distances of 2.5, 5, and 7.5 m from the edge, peaked on 8 August, whereas surface temperatures at the 10- and 12.5-m locations peaked on the following day. During times of falling ambient temperatures, differences in surface temperatures within the cut strips were less noticeable. A more useful display of the spatial variation across the strips was obtained by presenting surface temperature as a function of distance from the north edge of the strip-cuts (Fig. 14b).

The surface temperature patterns across the clear-cut strips were related to the orientation of the strips, the presence of nearby trees, and the time of year. Because the clear-cut strips run east and west, the southern edge of the strips tends to remain in the shade longer than the northern portion of the strips. The combination of greater exposure to the sun and higher back-radiation from the trees on the northern edge of the cut strips caused surface temperatures at the northern side of the strip-cuts to be higher than at the southern side, consistent with the near-surface temperatures. Differences in surface temperature between the two edges decreased when a greater proportion of solar radiation was received as diffuse light on cloudier days.

During the growing season, mean daily surface temperatures on the patch-cut were usually higher than on the strip-cut, particularly during times of increasing ambient temperatures (Fig. 14c). At such times, mean daily surface temperatures were 3°C to 5°C higher on the patch-cut than on the strip-cuts. The differences were less marked at lower temperatures.

In summer 2002, the surface temperature conditions on the strip-cut and patch-cut treatments were markedly different from those on the uncut area (Fig. 15). Occasionally, maximum surface temperatures were more than 25°C higher on the patch-cut than on the uncut area (Fig. 15a). Maximum surface temperatures on the strip-cut were also considerably higher than on the uncut area, but they did not reach the levels attained on the patch-cut (Fig. 15a). The differences in maximum temperatures fluctuated noticeably over the summer on both the strip-cut and patch-cut treatments.

Mean daily surface temperatures during 2002 on the patch-cut ranged from 0°C to 6°C higher than on the uncut area and were characterized by abrupt fluctuations (Fig. 15b). On the strip-cut, mean daily surface temperature ranged from 0°C to 3°C higher than on the uncut area, without wide fluctuations (Fig. 15b). Minimum (usually nighttime) surface temperatures were almost always lower on the strip-cut and patch-cut than on the uncut area (Fig. 15c). On the patch-cut, minimum surface temperatures frequently dropped 4°C to 7°C lower than on the uncut area. The differences between the strip-cut and the uncut area were usually less than 2°C, although occasionally the difference reached 3°C (Fig. 15c).

The 2002 data summarized above suggest that the temperature environment on the patch-cut treatment was hostile to the growth and survival of tree seedlings. Maximum ground surface temperatures on the patch-cut frequently exceeded 50°C and occasionally reached 65°C, a temperature considered lethal to tree seedlings (Baker 1929). Minimum ground surface temperatures often declined to or dipped below 0°C and sometimes dropped to −5°C. Thus, during the growing season, the patch-cut area was not only susceptible to high ground surface temperatures during the day but was also prone to frost at night. The openness of the patch-cut facilitates the impact of radiant solar energy on the ground during the day and intensifies the loss of energy, through long-wave radiation, at night.

Mean and minimum ground surface temperatures on the strip-cut were not very different from those on the uncut area (Figs. 15b, 15c), although maximum ground surface temperatures were significantly higher on the strip-cut (Fig. 15a), exceeding 60°C in a few instances. The presence of treed strips in the strip-cut treatment prevented maximum surface temperatures from reaching the levels attained on the patch-cut. It appears that maximum surface temperatures attained on both the patch-cut and the strip-cut can be hazardous to tree seedlings growing on these areas. It is not known how long boreal tree seedlings can survive at these extreme temperatures before succumbing to sun-scald and dehydration. This topic merits further research.

Temperatures at the 5-cm depth tended to mimic surface temperatures on all three treatments (Figs. 11, 12, and 13). Thus, mean and minimum daily temperatures for the strip-cut and the uncut treatments at the 5-cm depth were similar, whereas minimum daily temperatures on the patch-cut approached 0°C more frequently than did temperatures on the other two treatments. Maximum daily temperatures at the 5-cm depth rarely exceeded 20°C on the uncut area, whereas they registered primarily within the 20°C to 30°C range on the strip-cut and patch-cut. On particularly warm days, maximum temperatures at the 5-cm depth ranged between 30°C and 40°C.

There were no significant differences between the mounded and non-mounded treatments in terms of ground temperatures at the surface and at 5-cm depth on either the strip-cut or the patch-cut. However, surface temperatures were higher on the patch-cut than on the strip-cut for both site preparation treatments.

Seedling and Germinant Survival and Growth

Seedling and germinant survival, growth, and vigor were assessed 5 years after planting in the strip-cut and patch-cut areas (Table 10). Five-year survival of all planted species was greater on the strip-cut (67–92%) than on the patch-cut (53–67%) (Table 10, Fig. 16). On the patch-cut, where the water table was closest to the surface, seedlings may succumb to anoxia. Furthermore, on the patch-cut, the seedlings were exposed to the full effects of sun, wind, extremes of temperature, and snow press. On the strip-cut, the presence of treed strips prevented the water table from rising as much as on the patch-cut, thereby providing root zones more conducive for shoot growth. The 15-m-wide treed strips alternating with the 15-m-wide cleared strips, all running east–west, also provided a measure of protection for the seedlings against sun, wind, temperature extremes, and snow press.

On the patch-cut, seedlings may be exposed to the sun for most of the day during summer, whereas on the strip-cut, the trees of the uncut strips shade the seedlings early and later in the day. A high incidence of solar radiation reaching the ground surface is usually accompanied by high ground surface temperatures, high evaporation, and plant water stress. Although the strip-cut treatment did provide better protection for the seedlings than was available with the patch-cut treatment, there was significant mortality at both locations. Microclimate measurements indicated that the seedlings could be under drought stress for much of the day, even on wet sites. In general, solar radiation dominates microclimatic conditions. The east–west cut-strip orientation directly affected midday light levels, and dryness of the air (atmospheric drought) is affected by temperature.

The mortality rate of all tree species was greatest the first year after planting (Fig. 16). On the strip-cut treatment, there was better survival on the mounded microsites than on the non-mounded microsites. On the patch-cut treatment, the survival rates of the three species on the two types of microsites were not significantly different. For all seedling species, the steepest declines in survival occurred in the first 3 years after planting, with only minor mortality in the last 2 years. On the strip-cut, the survival rates tended to stabilize faster on the mounded than on the non-mounded microsites. Five years after planting, the survival of all seedling species on the strip-cut was 15% to 23% greater on the mounded than on the non-mounded microsites (Table 10); however, for black spruce and white spruce on the patch-cut, mounding did not affect survival. Larch on the non-mounded microsites on the patch-cut had the greatest overall mortality. The 5-year survival of white spruce germinants on the strip-cut was 6.9% and 0.7% on the mounded and non-mounded microsites, respectively (Table 10).

After 5 years, all species showed the best vigor on mounded sites within the strip-cut (Table 10). The vigor of all species on the non-mounded microsites on the strip-cut was better than on either the mounded or the non-mounded microsites on the patch-cut. In addition to having greater mortality than spruce, larch had slightly lower vigor overall (averaged across all treatments) than did the spruce species. Mounding on the patch-cut had less effect on seedling survival and growth than it did on the strip-cut, perhaps because the harsher climatic environment on the patch-cut overrode any beneficial effects of mounding.

After 5 years, total height was consistently greater on the strip-cut than on patch-cut for all three species (Fig. 17, Table 10). However, while analysis of variance for each harvest treatment showed that total height was significantly different between species at an á value of 0.01 (P = 0.0001), it was not significantly different within species for seedlings on the mounded and non-mounded microsites (Appendix 1). As expected, height increment (based on sequential measurements of total height) mirrored total height results, with a clear separation in growth rate between the strip-cut and patch-cut areas (Fig. 18, Table 10). While the effect of mounding was most pronounced for black spruce, followed by white spruce (based on mean values), this difference was not significant at an á value of 0.01 (P = 0.2807) (Appendix 1). Unlike height and height increment, mean root collar diameter 5 years after planting was similar for both harvest treatments (Fig. 19, Table 10). Although it was slightly greater on the mounded than the non-mounded microsites, root collar diameter was not significantly influenced by site preparation at an á value of 0.01 (P = 0.7380) (Appendix 1). Diameter increment for the period 3 to 5 years after harvest was also slightly greater with the mounded treatment (Fig. 20), but again, there was no significant difference between site preparation treatments at an á value of 0.01 (P = 0.8241) (Appendix 1).

Table 5. Mean temperature (morning and afternoon) near the ground during the 1998 growing season (1 May to 30 September)[a]

Microsite type	Mean temperature (°C)	
	0600	1600
Patch-cut	5.9	20.9
Strip-cut - North strip edge (sunny)	5.7	20.4
Strip-cut - South strip edge (shady)	5.8	19.2
Uncut area	6.7	19.0

[a] Data collected at "seedling height" (20 cm).

Table 6. Air and ground surface temperatures on three treatment areas during the period 25 June to 19 September 1998–2000[a]

Year	Air temperature (°C)	Ground surface temperature (°C)									
		Strip-cut									
		Transect 1		Transect 2							
						Uncut area				Patch-cut	
		R1B (open)	R1O (treed)	R2L2 (open)	R2P2 (treed)	R3A	R4B2	R5B	R6B2	R7D	R8B
Maximum											
1998	32.2	NA[b]	48.9	33.9	45.2	31.1	25.8	39.9	42.0	45.9	39.7
1999	33.3	41.4	42.8	35.5	44.1	29.4	29.0	32.6	33.2	45.8	35.6
2000	28.7	34.7	34.9	25.3	41.7	24.3	21.8	30.0	25.5	34.5	30.5
Mean											
1998	14.7	NA[b]	16.2	14.3	15.7	13.7	12.4	14.2	13.8	16.0	14.4
1999	13.7	14.4	14.5	13.3	14.5	13.1	12.0	13.3	12.6	15.2	13.5
2000	13.1	9.8	12.6	11.8	13.4	11.5	9.9	12.4	11.0	13.2	13.0
Minimum											
1998	–5.7	NA[b]	–4.7	–2.2	–4.3	–2.7	–1.0	–2.6	–3.4	–5.9	–5.9
1999	–1.5	–0.1	–0.4	–2.4	0.0	1.2	1.8	1.7	1.3	–2.0	–1.0
2000	–2.5	–2.4	–0.2	–0.9	–0.2	1.3	2.6	1.1	1.7	–0.7	–0.7

[a] The temperature sensors were located near groundwater well sites. Designations such as R1B refer to groundwater well locations; the first number identifies the transect and the following characters refer to a specific well on the transect (see Fig. 2).

[b] NA = Data not available.

Table 7. Air temperature and temperature at the 5-cm soil depth on three treatment areas during the period 25 June to 19 September 1998–2000[a]

		Ground temperature at 5-cm depth (°C)									
		Strip-cut									
		Transect 1		Transect 2		Uncut area				Patch-cut	
Year	Air temperature (°C)	R1B (open)	R1O (treed)	R2L2 (open)	R2P2 (treed)	R3A	R4B2	R5B	R6B2	R7D	R8B
Maximum											
1998	32.2	NA[b]	20.4	21.2	21.4	22.7	24.3	13.3	21.0	23.2	18.3
1999	33.3	15.2	20.9	19.4	19.9	23.7	16.0	13.9	19.1	23.6	18.1
2000	28.7	14.3	18.7	18.2	17.3	22.3	14.2	14.3	18.1	22.3	18.9
Mean											
1998	14.7	NA[b]	11.9	12.1	11.9	12.3	10.1	9.0	11.7	13.7	10.4
1999	13.7	11.1	12.2	11.6	12.0	12.4	9.7	9.8	11.7	13.7	10.9
2000	13.1	9.4	11.1	11.1	10.8	11.6	7.9	8.5	10.5	12.9	10.7
Minimum											
1998	–5.7	NA[b]	1.7	1.7	2.3	1.2	2.2	3.7	2.4	1.0	1.4
1999	–1.5	6.4	4.8	4.9	5.9	3.9	3.2	5.6	5.1	4.2	4.2
2000	–2.5	4.7	2.9	3.8	4.2	2.7	2.4	4.0	4.3	2.6	3.1

[a] The temperature sensors were located near groundwater well sites. Designations such as R1B refer to groundwater well locations; the first number identifies the transect and the following characters refer to a specific well on the transect (see Fig. 2).

[b] NA = Data not available.

Table 8. Air temperature and temperature at the 10-cm soil depth on three treatment areas during the period 25 June to 19 September 1998–2000[a]

		Ground temperature at 10-cm depth (°C)									
		Strip-cut									
		Transect 1		Transect 2		Uncut area				Patch-cut	
Year	Air temperature (°C)	R1B (open)	R1O (treed)	R2L2 (open)	R2P2 (treed)	R3A	R4B2	R5B	R6B2	R7D	R8B
Maximum											
1998	32.2	NA[b]	19.8	14.5	18.9	20.4	16.6	14.0	13.4	16.9	16.6
1999	33.3	15.7	15.0	13.2	18.4	19.9	12.2	13.8	12.8	16.1	12.3
2000	28.7	14.7	14.2	13.0	17.3	16.3	11.4	13.7	12.2	14.1	13.2
Mean											
1998	14.7	NA[b]	10.9	10.3	11.1	11.7	9.4	9.1	8.8	10.1	8.1
1999	13.7	11.1	10.6	9.6	11.5	11.7	8.5	9.9	8.5	10.7	8.7
2000	13.1	9.7	9.2	8.9	10.7	9.9	7.4	8.4	7.5	9.9	8.9
Minimum											
1998	–5.7	NA[b]	4.2	4.2	3.1	1.9	3.7	3.0	3.9	3.9	3.7
1999	–1.5	6.1	6.2	5.5	6.0	5.1	4.8	5.7	4.0	6.4	3.7
2000	–2.5	3.9	4.5	4.6	4.6	3.4	3.1	4.1	3.2	5.1	3.9

[a] The temperature sensors were located near groundwater well sites. Designations such as R1B refer to groundwater well locations; the first number identifies the transect and the following characters refer to a specific well on the transect (see Fig. 2).

[b] NA = Data not available.

Table 9. Air and ground temperature statistics for selected sites in the uncut, strip-cut, and patch-cut areas between 17 June and 18 September 2000[a]

	Temperature (°C)			
Treatment	Air	Surface	5-cm depth	10-cm depth
Uncut area (near well R5B)				
Maximum	28.7	30.0	14.3	13.7
Mean[b]	13.0 (3.9)	12.4 (5.1)	8.5 (2.0)	8.4 (1.9)
Minimum	–2.5	1.1	4.0	4.1
Range	31.2	28.9	10.3	9.6
Strip-cut (near well R1O)				
Maximum	30.0	34.9	18.7	14.2
Mean[b]	13.4 (3.9)	12.6 (6.7)	11.1 (3.1)	9.2 (2.0)
Minimum	–2.3	–0.2	2.9	4.5
Range	32.3	35.1	15.8	9.7
Patch-cut (near well R7D)				
Maximum	31.5	34.5	22.3	14.1
Mean[b]	13.3 (3.9)	13.2 (7.0)	12.9 (4.2)	9.9 (2.2)
Minimum	–5.0	–0.7	2.6	5.1
Range	36.5	35.2	19.7	9.0

[a] The temperature sensors were located near groundwater well sites. Designations such as R5B refer to groundwater well locations; the first number identifies the transect and the following characters refer to a specific well on the transect (see Fig. 2).

[b] Standard deviation in parentheses.

Table 10. Seedling height, height increment, root collar diameter (rcd), vigor, and survival 5 years after harvest[a]

	Strip-cut		Patch-cut	
Characteristic	Mounded	Non-mounded	Mounded	Non-mounded
Height (cm)				
White spruce	72.9 ± 1.6 (170)	69.4 ± 1.9 (139)	56.6 ± 1.8 (132)	50.4 ± 1.8 (123)
Black spruce	75.9 ± 1.8 (184)	65.1 ± 2.2 (138)	57.1 ± 2.0 (125)	58.9 ± 1.9 (131)
Larch	119.8 ± 3.8 (170)	116.6 ± 4.6 (133)	94.6 ± 3.5 (112)	93.7 ± 3.9 (106)
White spruce seed	22.8 ± 1.7 (57)	14.1 ± 2.9 (8)	–	–
Height increment at 5 years (cm)				
White spruce	53.2 ± 1.5 (170)	48.9 ± 1.9 (139)	34.5 ± 1.8 (132)	27.9 ± 1.8 (123)
Black spruce	53.5 ± 1.8 (184)	44.5 ± 2.1 (138)	34.4 ± 2.0 (125)	35.6 ± 1.9 (131)
Larch	90.7 ± 3.7 (170)	87.6 ± 4.5 (133)	65.1 ± 3.3 (112)	64.6 ± 3.7 (106)
Rcd (mm)				
White spruce	11.9 ± 0.2 (170)	10.4 ± 0.3 (139)	11.3 ± 0.3 (132)	10.0 ± 0.4 (123)
Black spruce	11.8 ± 0.3 (184)	10.5 ± 0.3 (138)	11.6 ± 0.4 (125)	12.0 ± 0.4 (131)
Larch	17.8 ± 0.5 (170)	16.7 ± 0.6 (133)	18.2 ± 0.5 (112)	18.1 ± 0.7 (106)
White spruce seed	3.6 ± 0.2 (57)	2.0 ± 0.4 (8)	–	–
Vigor[b]				
White spruce	2.2 ± 0.08 (200)	1.8 ± 0.09 (200)	1.7 ± 0.09 (198)	1.4 ± 0.09 (200)
Black spruce	2.5 ± 0.06 (200)	1.5 ± 0.08 (199)	1.4 ± 0.09 (200)	1.7 ± 0.10 (200)
Larch	2.2 ± 0.08 (200)	1.6 ± 0.09 (197)	1.4 ± 0.10 (194)	1.3 ± 0.09 (200)
Survival (%)				
White spruce	85.0 ± 3.7 (200)	69.5 ± 2.9 (200)	66.7 ± 10.5 (198)	61.5 ± 5.5 (200)
Black spruce	92.0 ± 2.1 (200)	69.3 ± 5.4 (199)	62.5 ± 6.7 (200)	65.5 ± 6.7 (200)
Larch	85.0 ± 5.8 (200)	67.5 ± 6.2 (197)	57.7 ± 9.1 (194)	53.0 ± 4.7 (200)
White spruce seed	6.9 ± 1.0 (200)	0.7 ± 0.3 (200)	–	–

[a] Mean± standard error, with sample size in parentheses. Sample sizes for height, height increment, and rcd are less than 200 because data are based on live trees only; in addition, in some cases, a few trees were missing. Sample sizes for vigor and survival are less than 200 in some cases because of a few missing trees.

[b] Vigor classes: 0 = dead, 1 = low, 2 = medium, 3 = high.

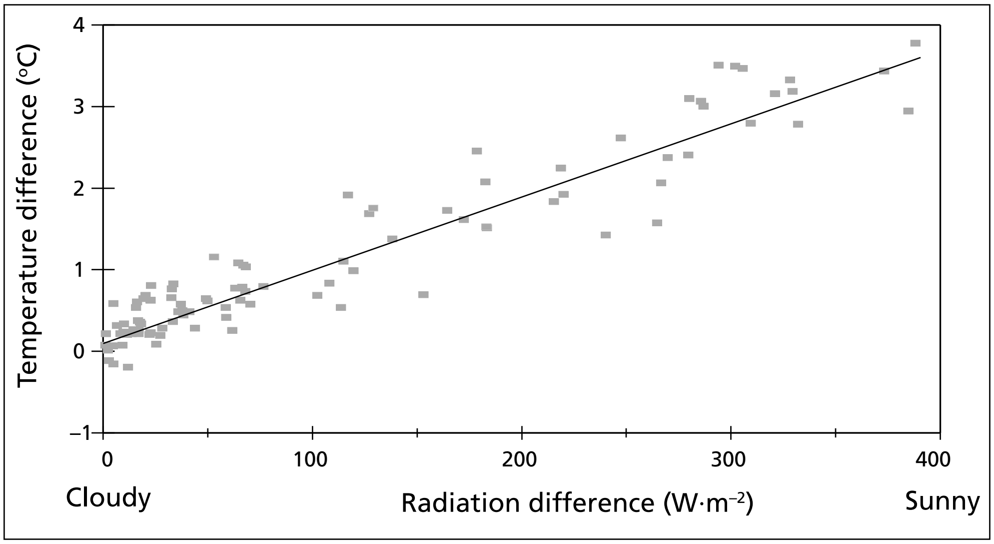


Figure 10. Difference in afternoon (1600) temperature between sunny and shady aspects of strip-cuts related to the difference in solar radiation measured by silicon pyranometers. (The difference is small on overcast days.)

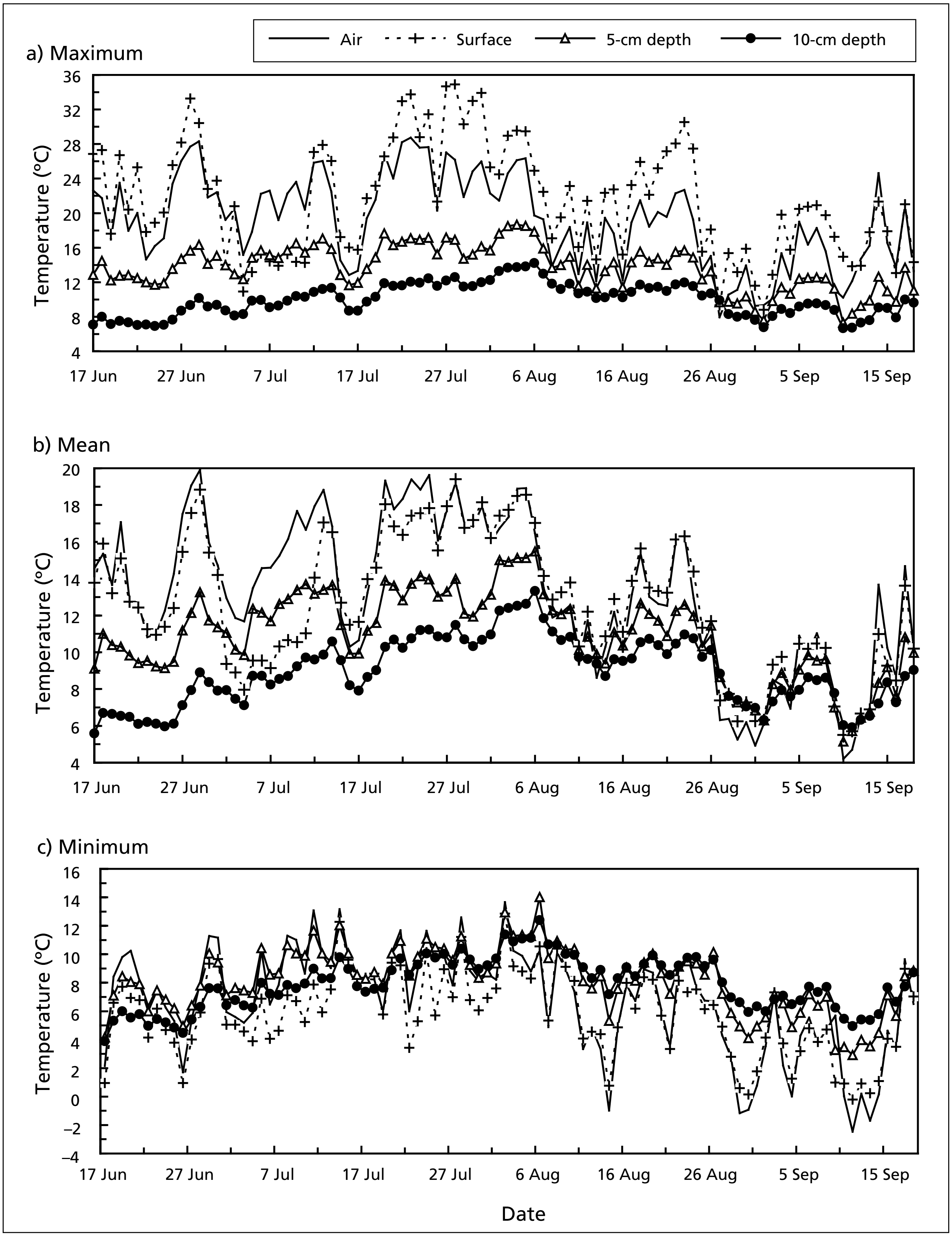


Figure 11. Daily air and soil temperatures, 17 June to 18 September, 2000, on treed strip-cut site R10. (a) Maximum. (b) Mean. (c) Minimum.

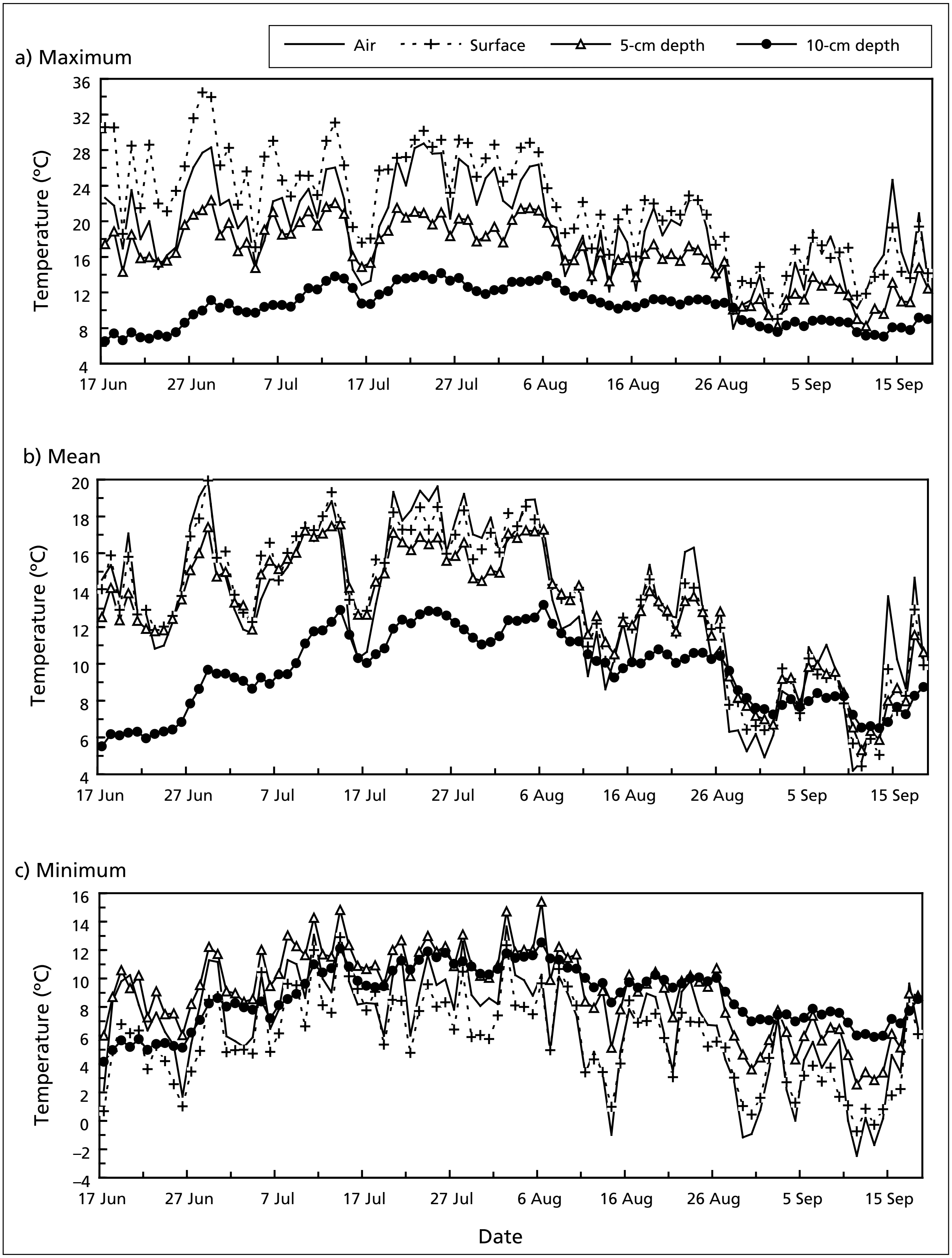


Figure 12. Daily air and soil temperatures, 17 June to 18 September, 2000, on patch-cut site R7D. (a) Maximum. (b) Mean (c) Minimum.

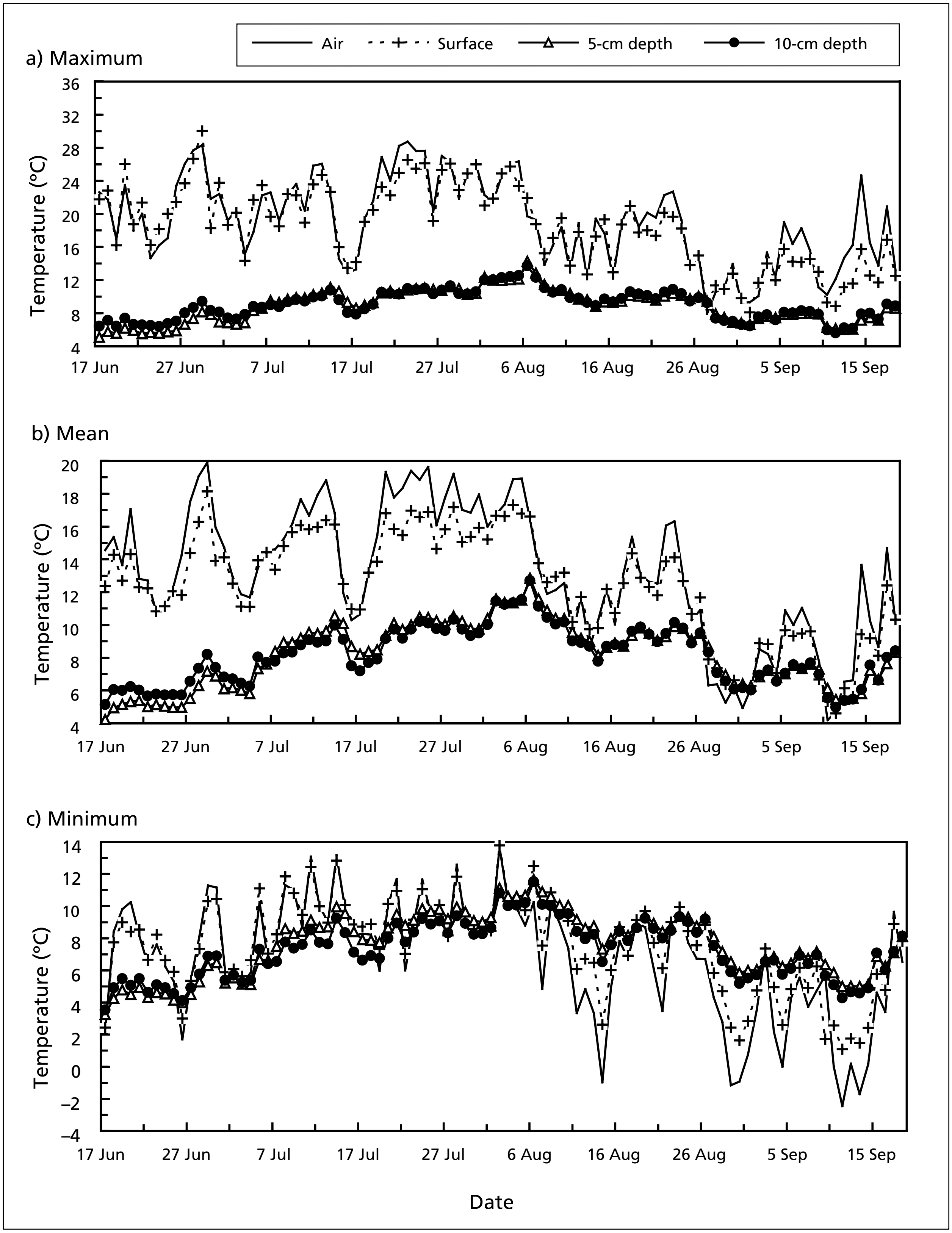
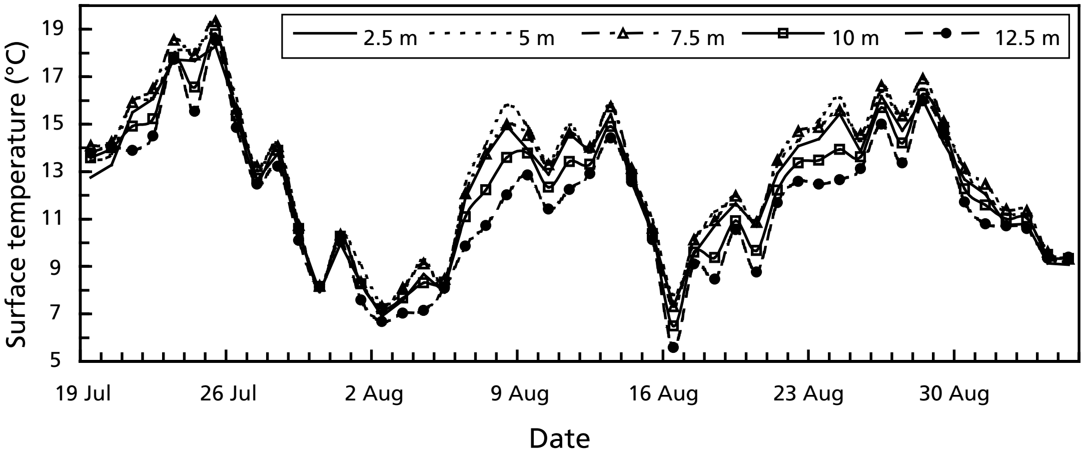
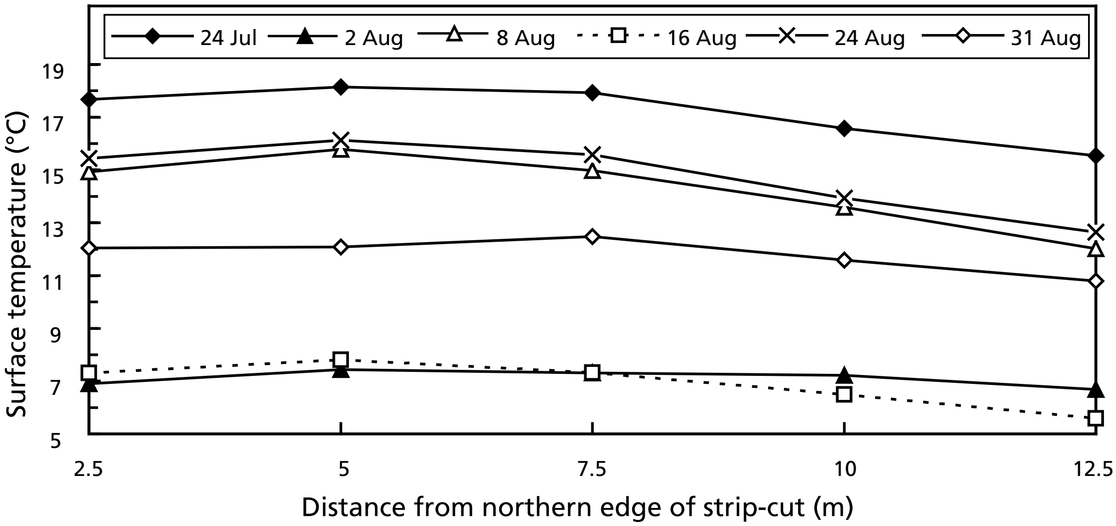


Figure 13. Daily air and soil temperatures, 17 June to 18 September, 2000, on site R5B of the uncut area. (a) Maximum. (b) Mean. (c) Minimum.


a) Strip-cut temperature as a function of time


b) Strip-cut temperature as a function of distance

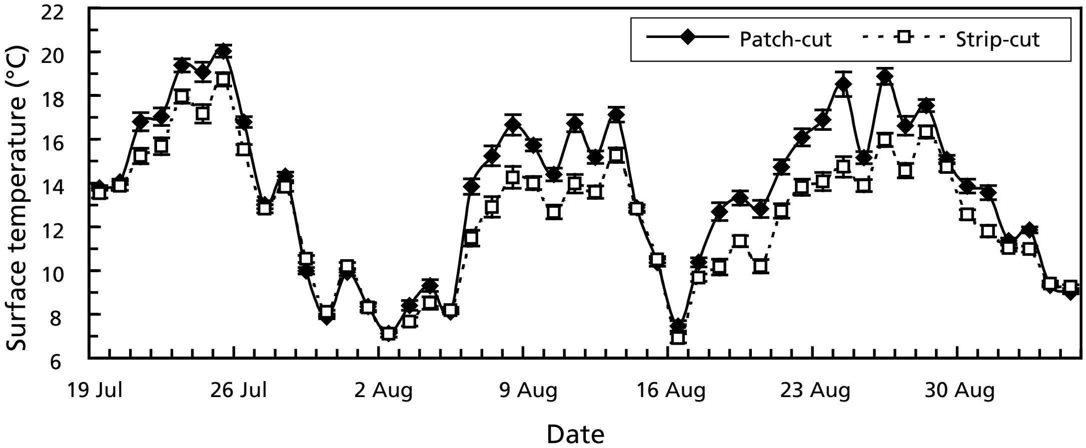

c) Strip-cut and patch-cut temperatures

Figure 14. Mean daily surface temperatures, 19 July to 4 September, 2002, 5 years after harvest. (a) Across strip-cut as a function of time at different distances from the northern edge of the strip-cut (*n* = 23). (b) Across strip-cut as a function of distance from the northern edge of the strip-cut for 6 days in the 2002 growing season. (c) In strip-cut (*n* = 23) and patch-cut (*n* = 29) (standard errors shown) over a 48 day period in 2002.

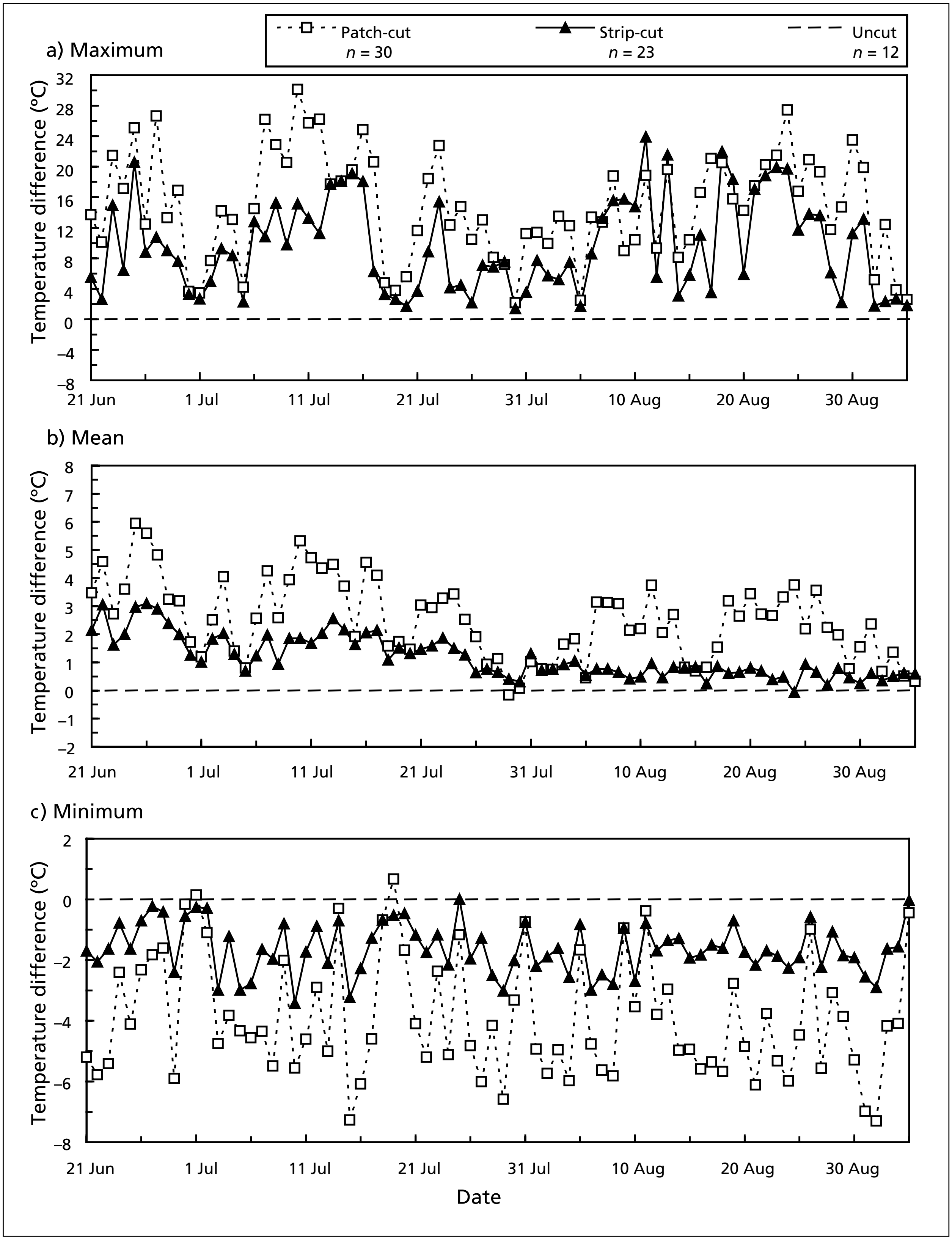


Figure 15. Daily temperature difference at the ground surface (ΔT) between the uncut area and the two harvest treatments between 21 June and 4 September, 2002. (a) Maximum. (b) Mean. (c) Minimum.

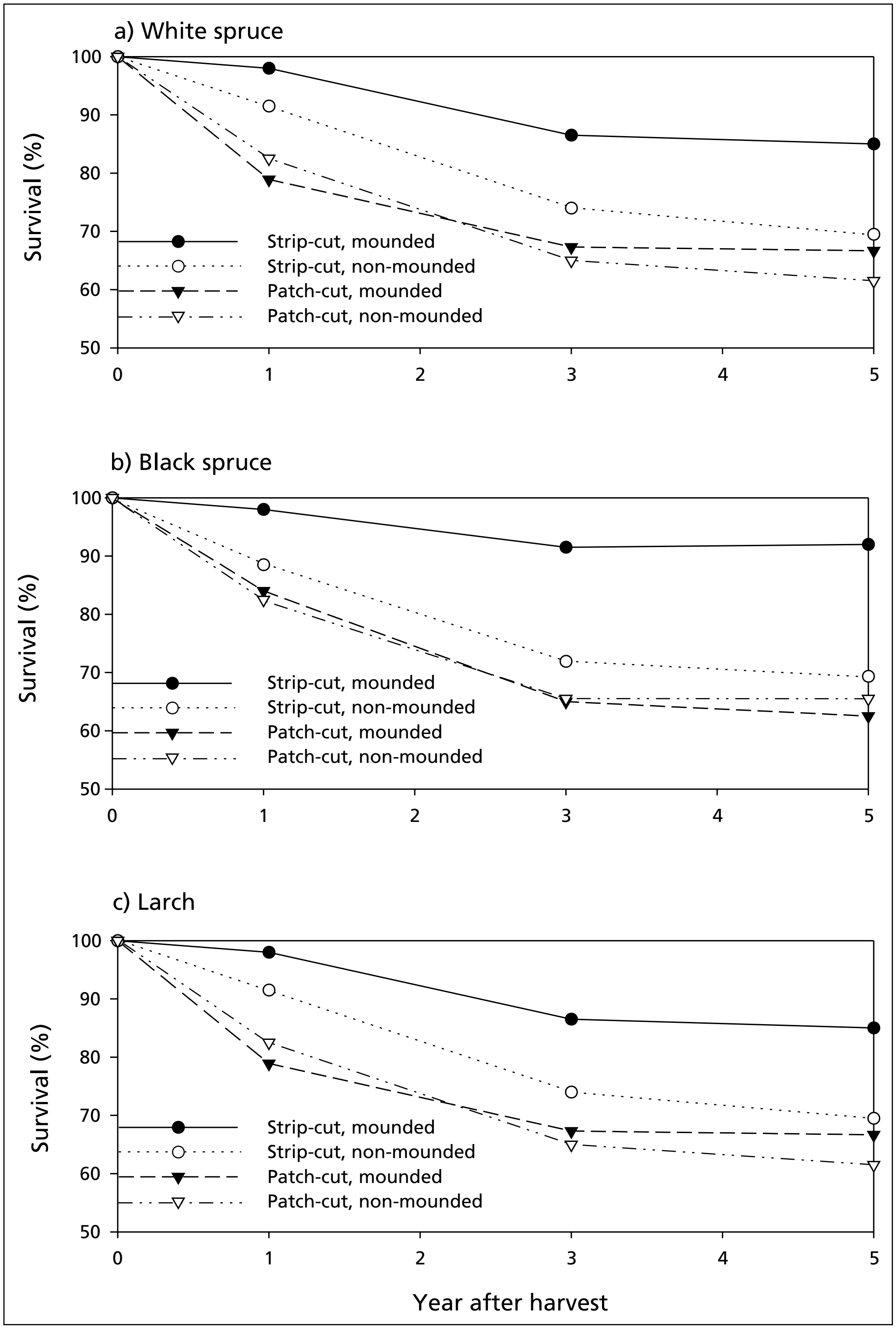


Figure 16. Survival of planted trees at 1 year (1998), 3 years (2000), and 5 years (2002) after planting. (a) White spruce. (b) Black spruce. (c) Larch.

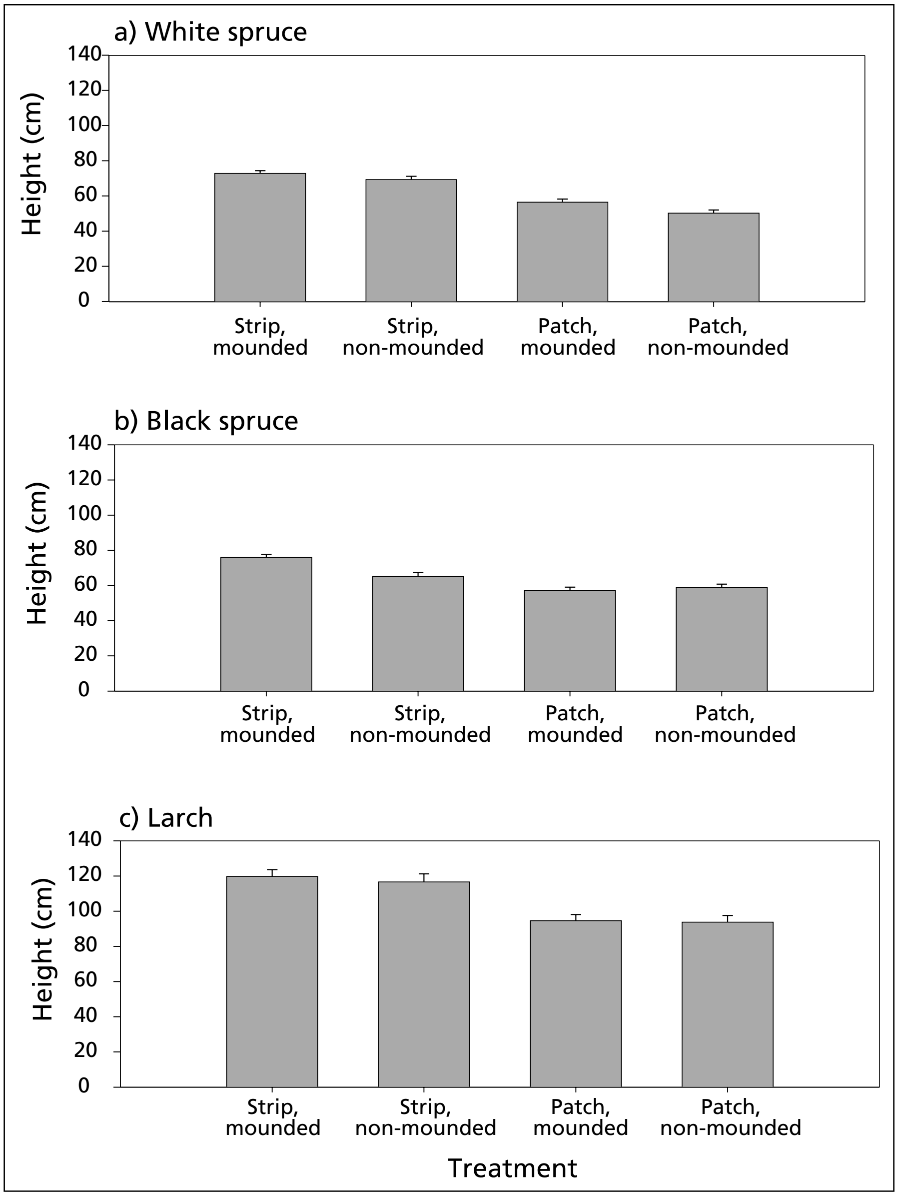


Figure 17. Fifth-year height of planted trees by treatment. (a) White spruce. (b) Black spruce. (c) Larch. Mean and standard error of the mean are shown.

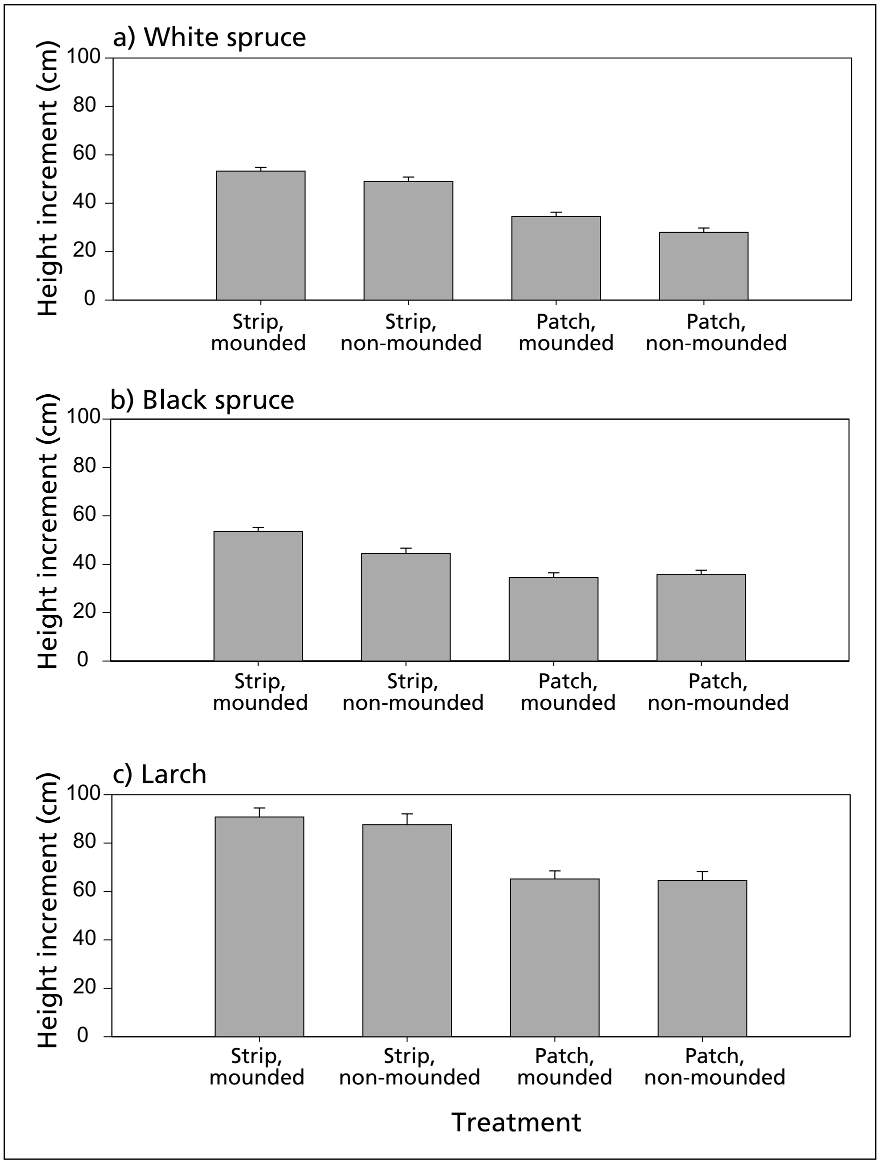


Figure 18. Five-year (1997–2002) height increment of planted trees by treatment. (a) White spruce. (b) Black spruce. (c) Larch. Mean and standard error of the mean are shown.

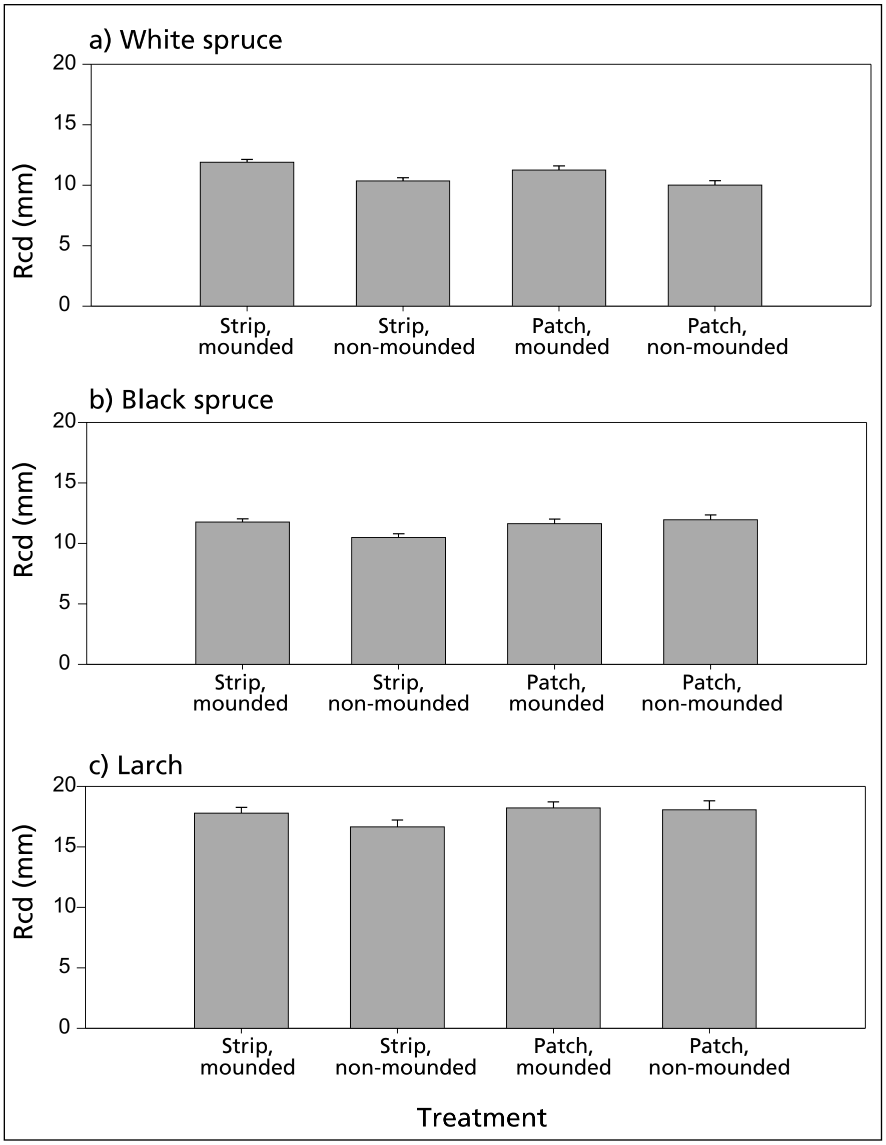


Figure 19. Fifth-year root collar diameter (rcd) of planted trees by treatment. (a) White spruce. (b) Black spruce. (c) Larch. Mean and standard error of the mean are shown.

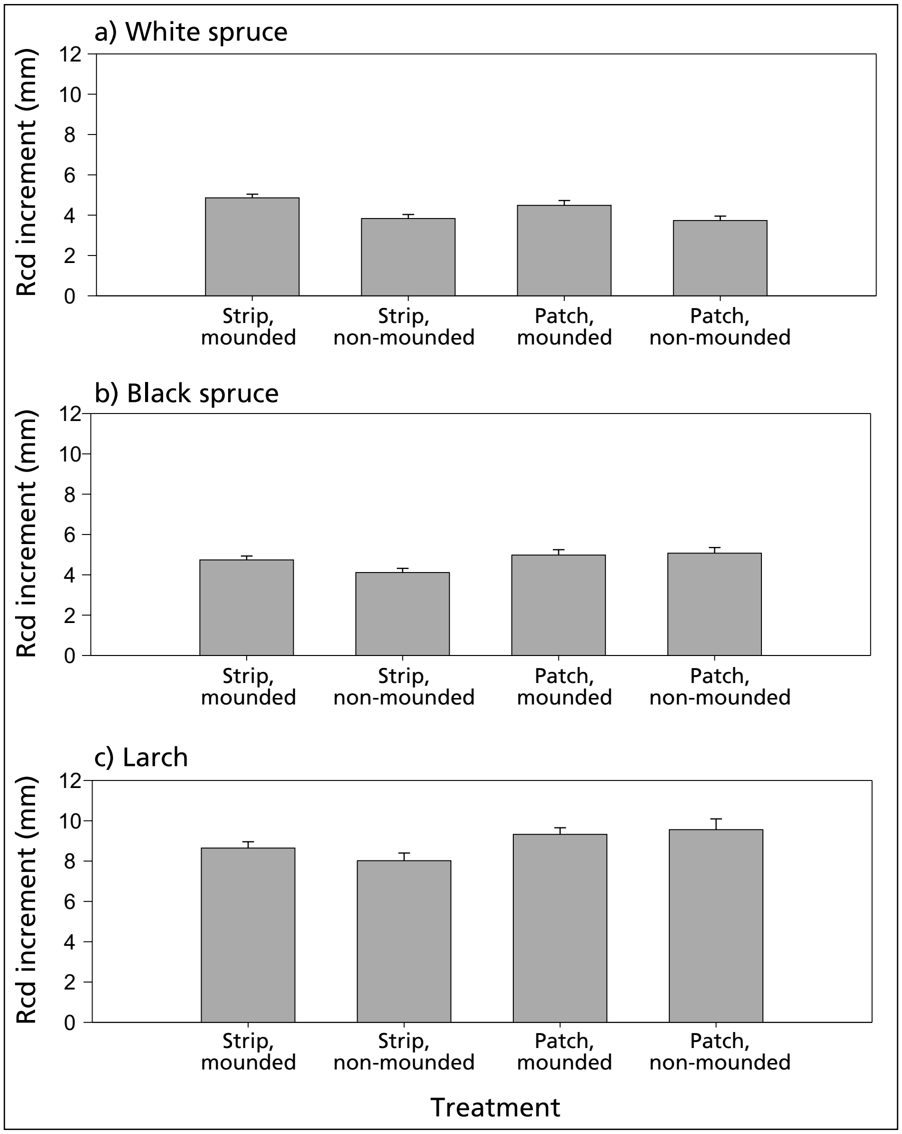


Figure 20. Two-year (2000–2002) root collar diameter (rcd) increment of planted trees by treatment. (a) White spruce. (b) Black spruce. (c) Larch. Mean and standard error of the mean are shown.

Postharvest Vegetation and Ground Cover

Five years after harvest, the ground cover in both the patch-cut and the strip-cut was dominated by forbs and low shrubs (Fig. 21, Table 11). For all strata, there was greater vegetation cover in the strip-cut than the patch-cut. There are several possible reasons for this pattern. The year 2002 had the least precipitation recorded during the growing season since the project started (Table 3), and low rainfall would reduce soil moisture to a different extent in the patch-cut and strip-cut areas. The residual strips would provide partial shade for the cut strips, which would result in more retained moisture and a reduction in the drying of the top organic layer, which in turn would result in better vegetation growth and retention of preharvest moss cover. In addition, the strip-cut area had less disturbance than the patch-cut area, with heavy disturbance restricted to the one machine track in each strip. Third, adjacent residual strips would provide a proximate source of propagules to recolonize the cut strips, which would lead to quicker postharvest vegetation response for some species, especially shrubs.

For the most part, abundance levels and height of regenerating understory plants were low and deemed not to affect seedling growth through overtopping and shading. The dominant species in each vegetation growth form were as follows: grass—marsh reed grass (bluejoint) (*Calamagrostis canadensis* (Michx.) Beauv.); forbs—dewberry (*Rubus pubescens* Raf.), common horsetail (*Equisetum arvense* L.), twinflower (*Linnaea borealis* L.), and fireweed (*Epilobium angustifolium* L.); low shrubs—wild red raspberry (*Rubus idaeus* L.) and common Labrador tea (*Ledum groenlandica* Oeder); tall shrubs—river alder, white birch (*Betula papyrifera* Marsh.), and willow (*Salix* spp. L.) (Table 12). No single species had an individual cover greater than 4% (Table 12). When all species in a particular stratum were combined, it was possible to identify areas of more abundant vegetation cover (especially for forbs), which corresponded to wetter areas, especially in the strip-cut area.

In terms of vegetation response to treatment, mounding resulted in less cover, especially for the grass stratum (Table 11, Fig. 21). On the strip-cut, non-mounded microsites tended to be dominated by predisturbance species such as Labrador tea (Table 13). Also on the strip-cut, mounding favored the growth of raspberry and was less favorable for Labrador tea, whereas on the patch-cut, mounding favored establishment of black spruce and willow species (Table 13).

Grass cover (mostly marsh reed grass) increased from preharvest levels of less than 1% to 5–10% and 2–3% cover on the strip-cut and patch-cut areas, respectively (MacIsaac et al. 1998). Given the known potential for raspberry and marsh reed grass to rapidly increase in abundance following disturbance (Hogg and Lieffers 1991; Oleskevich et al. 1996), it is expected that cover of these species will increase substantially over the next few years on this site if there is sufficient precipitation.

Table 11. Mean percent cover of vegetation in each stratum and all strata combined, by harvest and scarification type, 5 years after harvest

	Strip-cut		Patch-cut	
Stratum	Mounded	Non-mounded	Mounded	Non-mounded
Tree[a]	0.8	0.6	0.3	0.9
Tall shrub	4.3	6.1	0.7	1.2
Low shrub	13.3	15.3	7.1	7.3
Forbs	20.9	23.6	7.8	9.2
Graminoids	4.7	10.7	1.8	2.9
Mosses	5.5	8.6	0.0	0.0
Total	49.4	64.9	17.7	21.4

[a] Tree cover occurred in five of the plots. These are cases where trees in the uncut residual strips were leaning over the plot.

Table 12. Percent cover of the five most abundant species in each stratum, 5 years after harvest, all treatments combined

Stratum	Rank	Scientific name	Common name	% cover
Tree	1	*Larix laricina*	larch, tamarack	0.26
	2	*Salix* spp.	willow	0.19
	3	*Betula papyrifera*	white birch	0.15
	4	*Picea mariana*	black spruce	0.06
Tall shrub	1	*Alnus tenuifolia*	river alder	1.83
	2	*Betula papyrifera*	white birch	0.99
	3	*Salix* spp.	willow	0.28
	4	*Larix laricina*	larch, tamarack	0.09
	5	*Picea mariana*	black spruce	0.07
Low shrub	1	*Rubus idaeus*	wild red raspberry	3.07
	2	*Ledum groenlandicum*	common Labrador tea	2.28
	3	*Rosa acicularis*	prickly rose	1.53
	4	*Salix* spp.	willow	0.63
	5	*Betula papyrifera*	white birch	0.59
Forbs	1	*Rubus pubescens*	dewberry, trailing or running raspberry	3.49
	2	*Equisetum arvense*	common horsetail	3.39
	3	*Linnaea borealis*	twinflower	1.89
	4	*Epilobium angustifolium*	fireweed	1.69
	5	*Vaccinium vitis-idaea*	lingonberry, bog cranberry	1.18
Graminoids	1	*Calamagrostis canadensis*	marsh reed grass, bluejoint	2.02
	2	*Carex capillaris*	hair-like sedge	1.28
	3	*Carex disperma*	soft leaved sedge	0.98
	4	*Carex* spp.	sedge	0.59
	5	*Carex vainata*	sheathed sedge	0.19
Mosses	1	*Musci*	moss	1.63
	2	*Pleurozium schreberi*	big red stem, red stemmed feathermoss	0.96
	3	*Hylocomium splendens*	stair-step moss	0.65
	4	*Ptilium crista-castrensis*	knight's plume	0.53
	5	*Sphagnum* spp.	sphagnum	0.12
Lichen	1	*Peltigera aphthosa*	freckle pelt, studded leather lichen	0.01

Table 13. Percent cover of the five most abundant species in each stratum, by harvest and scarification type, 5 years after harvest

		Patch-cut				Strip-cut			
		Mounded		Non-mounded		Mounded		Non-mounded	
Stratum	Rank	Species	% cover	Species	% cover	Species	% cover	Species	% cover
Tall shrub	1	*Picea mariana*	0.31	*Betula papyrifera*	0.65	*Alnus tenuifolia*	2.57	*Alnus tenuifolia*	3.95
	2	*Salix* spp.	0.13	*Larix laricina*	0.23	*Betula papyrifera*	0.99	*Betula papyrifera*	2.02
	3	*Populus balsamifera*	0.10	*Salix* spp.	0.18	*Salix* spp.	0.74	*Larix laricina*	0.13
	4	*Picea glauca*	0.08	*Alnus tenuifolia*	0.10	*Populus balsamifera*	0.03	*Salix* spp.	0.04
	5	*Populus tremuloides*	0.04						
Low shrub	1	*Rubus idaeus*	2.31	*Rubus idaeus*	2.70	*Rubus idaeus*	4.71	*Ledum groenlandicum*	4.07
	2	*Ledum groenlandicum*	1.68	*Ledum groenlandicum*	0.99	*Rosa acicularis*	2.23	*Rosa acicularis*	2.33
	3	*Salix* spp.	1.05	*Rosa acicularis*	0.83	*Ledum groenlandicum*	2.01	*Rubus idaeus*	2.33
	4	*Ribes oxyacanthoides*	0.40	*Ribes triste*	0.68	*Betula papyrifera*	1.02	*Ribes oxyacanthoides*	1.02
	5	*Rosa acicularis*	0.36	*Ribes oxyacanthoides*	0.48	*Salix* spp.	0.98	*Betula papyrifera*	0.96
Forbs	1	*Rubus pubescens*	1.50	*Epilobium angustifolium*	2.23	*Equisetum arvense*	5.49	*Rubus pubescens*	6.84
	2	*Epilobium angustifolium*	1.46	*Rubus pubescens*	1.56	*Rubus pubescens*	3.29	*Equisetum arvense*	5.21
	3	*Equisetum arvense*	1.10	*Rubus idaeus*	1.26	*Linnaea borealis*	3.16	*Linnaea borealis*	3.61
	4	*Rubus idaeus*	1.03	*Equisetum arvense*	0.79	*Epilobium angustifolium*	2.25	*Vaccinium vitis-idaea*	1.70
	5	*Ledum groenlandicum*	0.73	*Vaccinium vitis-idaea*	0.66	*Vaccinium vitis-idaea*	1.86	*Mitella nuda*	1.41
Graminoids	1	*Calamagrostis canadensis*	0.73	*Calamagrostis canadensis*	1.38	*Calamagrostis canadensis*	1.48	*Calamagrostis canadensis*	4.11
	2	*Carex capillaris*	0.43	*Carex capillaris*	0.90	*Carex capillaris*	1.31	*Carex disperma*	2.30
	3	*Carex vaginata*	0.39	*Carex vaginata*	0.45	*Carex disperma*	1.13	*Carex capillaris*	2.25
	4	*Carex disperma*	0.06	*Poa palustris*	0.10	*Carex* spp.	0.35	*Carex* spp.	1.74
	5	*Carex leptalea*	0.05	*Carex disperma*	0.04	*Carex canescens*	0.15	*Carex limosa*	0.14

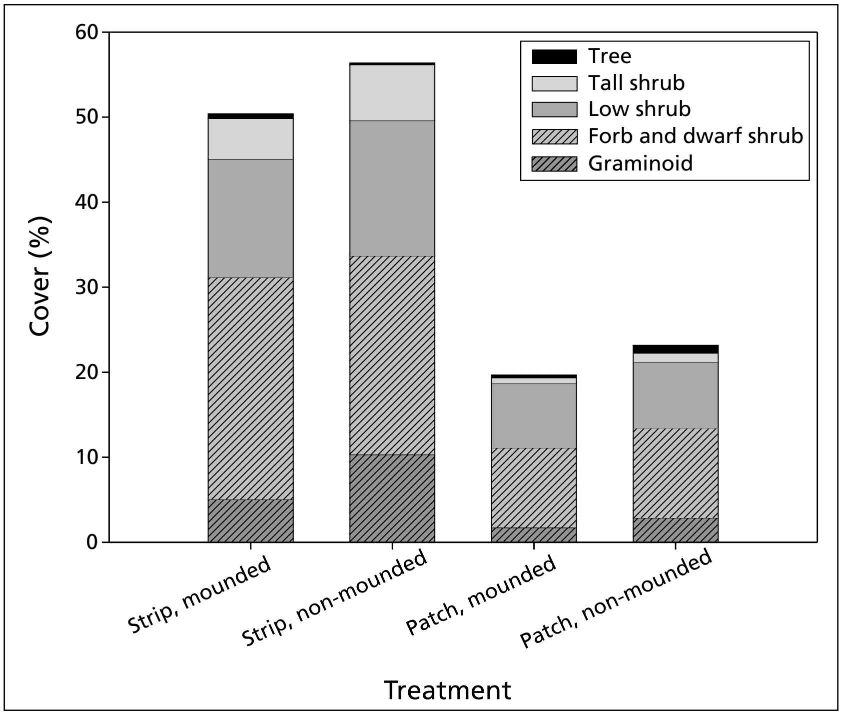


Figure 21. Vegetation cover of vascular species by strata, for each treatment, 5 years after harvest (2002).

Effect of Groundwater Levels and Ground Temperatures on Seedling Survival and Growth

The seedlings were planted in 1997, the wettest year of the 8-year measurement period. Between 4 June and 10 October 1997, rainfall on the experimental area totaled 323 mm. One-third of this amount fell during July, the month when the seedlings were planted, and about half fell after planting. Groundwater table levels in June through early October remained in the upper 15 cm of soil on the patch-cut (Fig. 7a, Table 4) and the upper 20 cm of soil on the strip-cut (Table 4), but they did not emerge above the ground surface.

A combination of factors contributed to the high groundwater table levels recorded on the strip-cut and the patch-cut in 1997. Snowmelt runoff and frequent input of rain to the soil rarely allowed the water table to fall below the 20-cm depth during the growing season, and the capillary fringe associated with the high water tables further contributed to near-surface soil wetness. In addition, the rise in water table levels in response to reduced transpiration and interception following timber harvesting (watering-up) also increased soil wetness near the surface. Watering-up is usually most pronounced in the first year after timber harvest, before plants have had time to become established on the harvested sites. Harvesting on the experimental site was completed in January 1997.

The combined effect of these factors produced very wet, anoxic conditions in the plant rooting zone on the strip-cut and the patch-cut. Consequently, anoxia is probably the most likely cause of seedling mortality during the first growing season after planting. Although soil temperature was not measured until 1998, it can be inferred from the prolonged wetness of the soil in 1997 and the generally high heat capacity associated with wet soils that soil temperatures in 1997 were less than favorable for survival and growth of the tree seedlings.

Over the next 5 years, survival rates for the three planted species were greater on the mounded microsites than on the non-mounded microsites (Fig. 16), except for black spruce in the patch-cut area. The better survival rates on the mounds may be attributed to the seedlings being raised above the anoxic conditions that existed below ground level in 1997. Capping the mounds with mineral soil may also have been a mitigating factor.

On the patch-cut, seedling survival rates were less than on the strip-cut, and differences in survival between the mounded and non-mounded microsites were less pronounced than on the strip-cut (Fig. 16). The lower survival rates and the relative ineffectiveness of mounding on the patch-cut treatment may be related to the patch-cut being wetter (higher water table) than the strip-cut in 1997. Lower minimum temperatures on the patch-cut treatment (Fig. 15c) might also have contributed to lower survival rates.

The lowest precipitation (Table 4) and the lowest water table levels (Figs. 5 and 6) on the experimental area were recorded in the 1998 and 1999 growing seasons. In the same growing seasons, maximum soil surface temperatures (Table 6) approached or exceeded 40°C, temperatures that may be lethal to tree seedlings. These data suggest that water might have been a limiting factor near the surface and that low plant water availability during these years contributed to the greater mortality rate recorded in 2000 (Fig. 16). Although these sites would have been considered wet over the duration of the study, a small drop in groundwater levels (although still within 40 cm from the surface), coupled with the nature of the surface organic material (undecomposed needles and feathermoss), could have resulted in a relatively dry surface horizon overlying a wet profile.

The observed mortality would have been caused by a combination of atmospheric drought near the surface and low temperatures in the rooting zone, because of the insulating effect of the dry surface organic layer. Notwithstanding this effect, because of the periodic anoxic conditions described earlier, the mounded microsites provided, on average, the best environment for seedling survival and growth over a range of conditions. These microsites are similar to the uprooted pits and mounds created by windthrow in other boreal old growth forests. In one Scandinavian study, the majority of regenerating spruce (63%) was found on mounded microstites, even though these sites covered only 28% of the stand (Kuuluvainen 2003).

Data on the relation between heat injury and mortality of boreal coniferous seedlings are scarce, although Baker (1929) investigated this relation for 13 nonboreal coniferous species. He considered 46°C the minimum temperature causing mortality of conifer seedlings. In the study reported here, surface temperature on the patch-cut and strip-cut treatments approached or exceeded this level (Table 6). The length of time that lethal temperatures are sustained is also important. Because the highest temperatures occur at the soil surface, heat injury to the seedling stem occurs at ground level. Baker (1929) found that slightly injured seedlings usually succumbed to secondary factors such as fungi entering the wound. He also found that the most extensive heat damage occurred when the soil was dry and loose. In a wet soil, the high volumetric heat capacity of water ameliorates the extremes of temperatures. Seedlings able to provide their own shade are best protected from heat injury. Thus, seedlings with large stems, many cotyledons, and short stems that bring the tops close to the ground and those that rapidly develop true leaves above the cotyledons are best equipped to provide their own shade (Baker 1929). Shade-tolerant species tend to be more prone to heat injury than shade-intolerant species.

In the Acadian Forest Region of New Brunswick, McInnis and Roberts (1995) used Baker's (1929) threshold of potentially lethal temperature (46°C) to determine the effects of slash cover on tree seedling microenvironment. They found an inverse relation between peaks in ground surface temperature and slash cover. With low levels of slash on a new clear-cut, regenerating black spruce and red spruce (*Picea rubens* Sarg.) seedlings were exposed to ground surface temperatures greater than 46°C on 31 occasions (based on hourly measurements between 29 June and 27 August 1990). The authors suggested that the exposure of small conifer seedlings to these conditions could result in increased mortality through direct heat damage.

The surface temperature data collected from the Red Earth experimental site so far (1998–2002) indicate that temperatures lethal to coniferous seedlings are possible on both the strip-cut and the patch-cut treatments. However, these extremes are generally not sustained beyond 2 h (the sampling interval). It is proposed that in subsequent years the temperature sampling frequency be increased to hourly or half-hourly and that temperature sensors be placed close to seedlings on the mounds and on non-mounded microsites on both the patch-cut and the strip-cut treatments. Such measurements should be continued year-round to determine when seedlings are exposed to unseasonable frost conditions.

Mounding has been proposed as a solution for a number of forest regeneration problems, namely competition from other vegetation, cold soil in the rooting zone, deficient soil aeration on wet sites, insufficient soil water on dry sites, and nutrient deficiency in the rooting zone of outplants (Sutton 1993). On this study site, where the organic horizons are 40 to 70 cm thick, it is also necessary to use mounding to elevate mineral soil as a planting medium. McMinn (1983), building on the work of Edlund (1980) and Sutton (1983), suggested that mounds consisting of inverted organic matter capped by mineral soil may enhance white spruce seedling performance in the Boreal and Sub-Boreal zones. He found that survival of white spruce seedlings was best on mounds created by inverting organic matter and capping with 12 cm of mineral soil. Most of the mounds at the site used for the present study consisted primarily of organic matter, but a number had caps of mineral soil.

A study conducted on a cleared and drained peatland in central Alberta (Takyi and Hillman 2000) showed that mounding can result in good survival and growth of the three species planted on the current study site. Six growing seasons after planting, 84% of the larch seedlings and 95–96% of the spruce seedlings had survived. Larch typically grew better than either of the spruce species.

Seedling and Vegetation Response to Solar Radiation and Temperature Levels

The temperature trends for the sunny aspect of the strip-cut and the patch-cut were similar in the afternoon (Table 5). The shaded portion of the cut strips and the uncut understory were also very similar at this time of day. Plotting the difference in temperature between the shady and sunny sides of the cut strips against the difference in incoming solar radiation revealed a remarkably strong correlation (Fig. 10), given that these areas were separated by only 13 m of open space. On a sunny afternoon, the temperature difference related to seedling height would be sufficient to increase the moisture-holding capacity of the air from 2.3 kPa at 20°C under partial shade to 2.9 kPa at 24°C in full sunshine, sufficient to create atmospheric drought stress. With the onset of such water stress (vapor pressure deficit greater than 1 kPa), stomatal closure begins, limiting photosynthesis (Hogg and Hurdle 1997).

As expected, direct-beam radiation (integrated over the whole growing season) increased across the strip-cut, from about 50% at the south edge to over 70% adjacent to the north side (Fig. 22). Other components of radiation, including diffuse and global radiation, increased sharply from the south edge to the center, and then flattened out. Percent open sky had lower values across the whole strip-cut, at about 50%. Light helps seedlings to grow, but the associated higher temperatures also dries them out. The interaction of these two factors leads to postulation that overall survival, vigor, and growth of seedlings would be best in the middle of the strip, depending on the species (a trend also seen in the other understory species; Fig. 23).

Five-year seedling survival and vigor across the strip-cut are shown in Figs. 24 to 26, for the three species, respectively. For all species and response variables, there was a trend toward greater vigor and growth in the center of the strip. Survival and vigor of white spruce was greatest 10.5 m from the south edge of the strip-cut (Fig. 24). Height and root collar diameter had a flatter trend but also showed a slightly better response in the center of the strip. Black spruce had more variable survival and vigor across the strip, but exhibited maximal growth response at 10.5 m from the south edge of the strip-cut (Fig. 25), similar to white spruce. Larch height and root collar diameter showed a similar but more marked trend (Fig. 26), although survival was best on the shaded south edge of the strip. The trend toward more growth in the center of the strip was also exhibited by the other vascular species (Fig. 23).

Overall, these results provide further evidence of the response of seedlings to understory light levels created by fine-scale canopy distribution. Although the shading regime could have been quantified by calculations involving tree height, sun angle, and distance to the edge of residual trees between the strip-cuts, the fact that the canopy is open (because of the old-growth status of the stand), the use of hemispherical images to quantify radiation levels was the most appropriate approach.

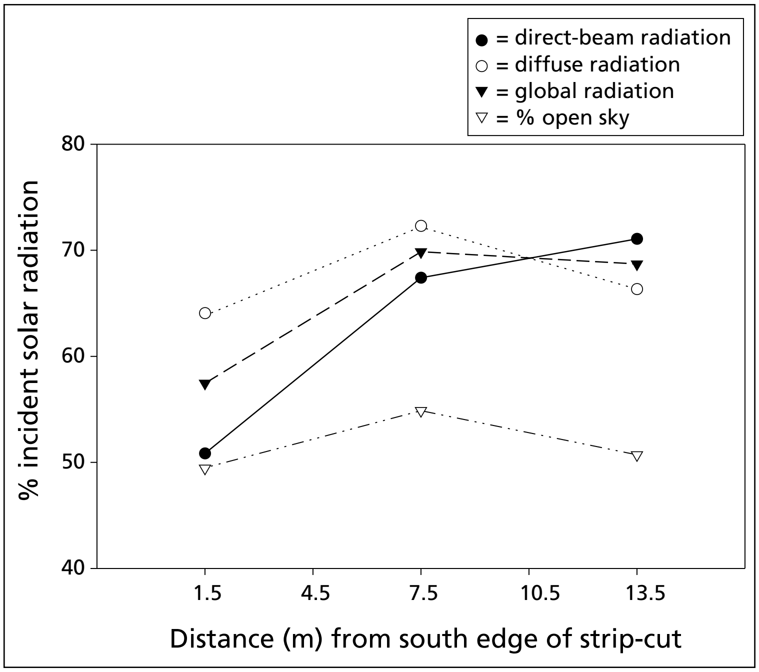


Figure 22. Changes in the components of solar radiation across the strip-cut area 1 year after harvest. Percent incident solar radiation is the percentage received in the understory at 1.3 m height, compared with a totally open area with no tree canopy. The percent global radiation is the mean of the percent direct and diffuse radiation. Radiation values are integrated over the growing season (1 May to 30 September).

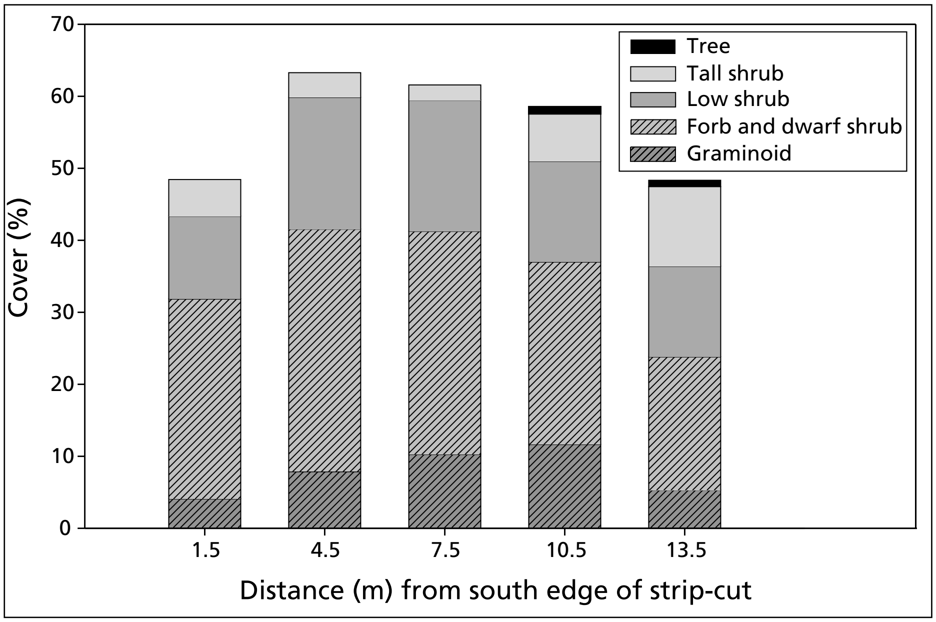


Figure 23. Vegetation cover of vascular species by strata, across the strip-cut area, 5 years after harvest (2002).

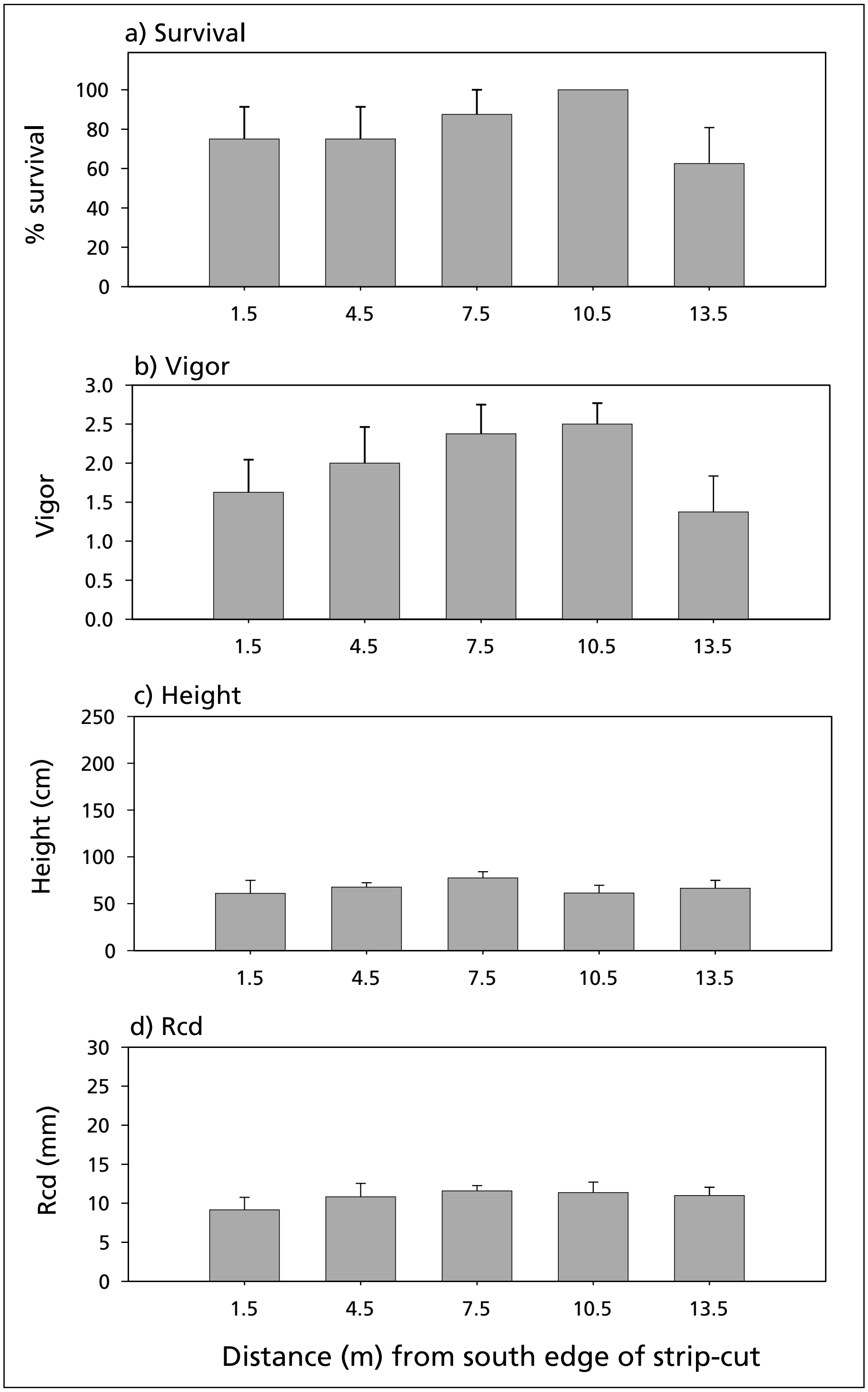


Figure 24. White spruce seedling response across the strip-cut area, for all plots combined, in the fifth year after harvest (2002). (a) Survival. (b) Vigor. (c) Height. (d) Root collar diameter (rcd). Data are based on seedlings located in the vegetation plots. Vigor is based on the following numeric assignments: 0 = dead, 1 = low, 2 = medium, 3 = high. Mean and standard error of the mean are shown. There is no error bar for survival at 10.5 m, as the standard error was 0 (i.e., no dispersion from the mean) at that distance.

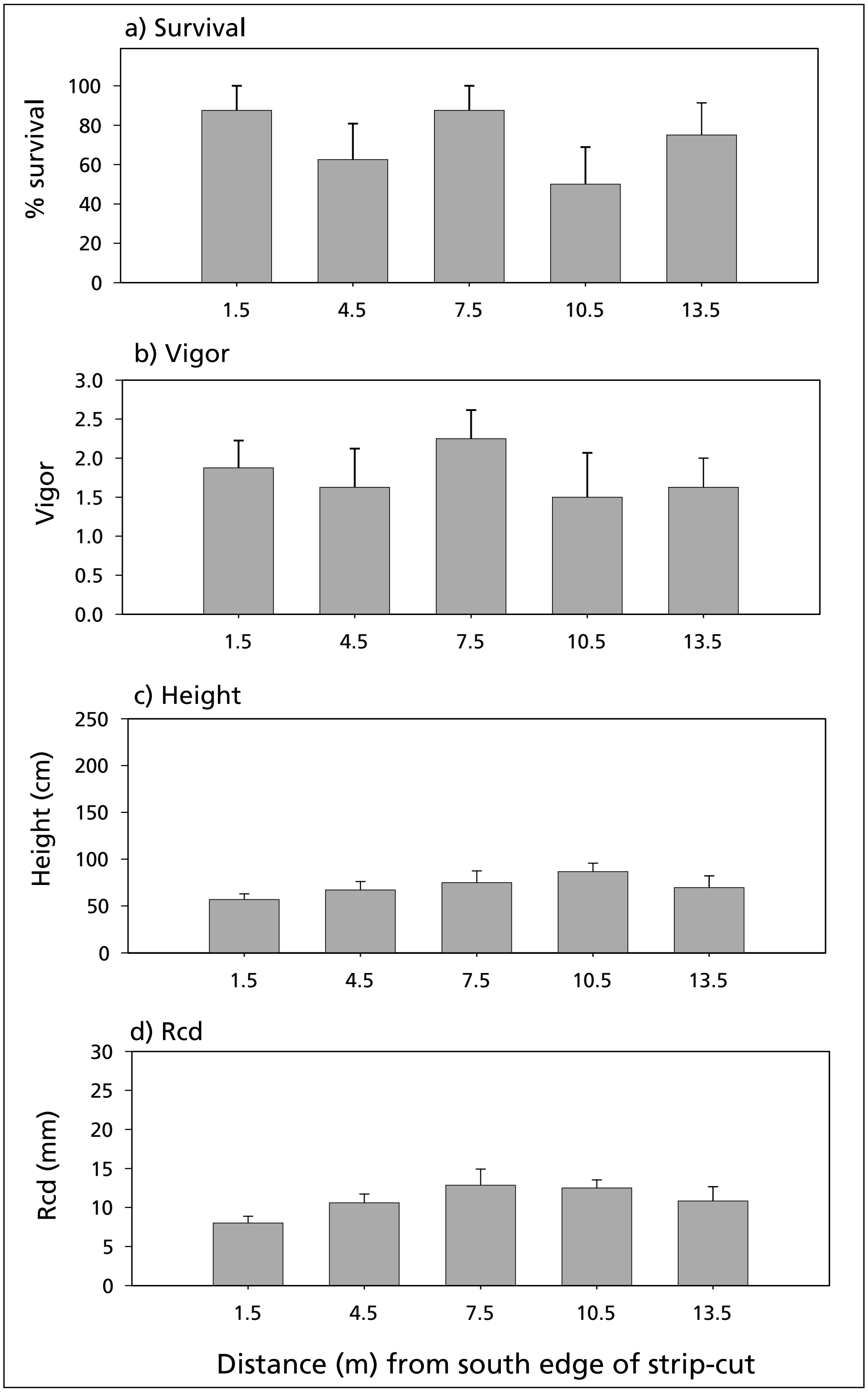


Figure 25. Black spruce seedling response across the strip-cut area, for all plots combined, in the fifth year after harvest (2002). (a) Survival. (b) Vigor. (c) Height. (d) Root collar diameter (rcd). Data are based on seedlings located in the vegetation plots. Vigor is based on the following numeric assignments: 0 = dead, 1 = low, 2 = medium, 3 = high. Mean and standard error of the mean are shown.

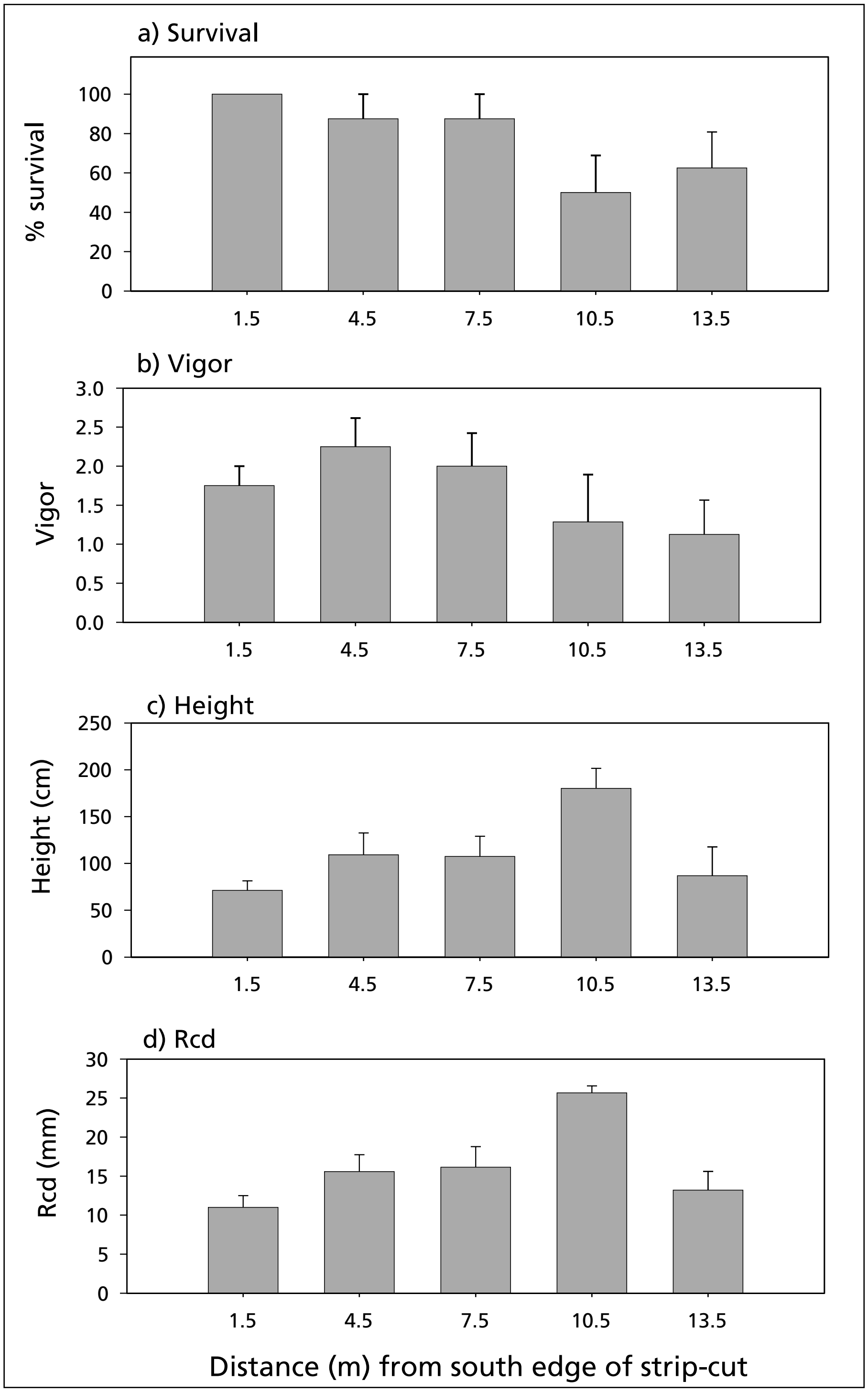


Figure 26. Larch seedling response across the strip-cut area, for all plots combined, in the fifth year after harvest (2002). (a) Survival. (b) Vigor. (c) Height. (d) Root collar diameter (rcd). Data are based on seedlings located in the vegetation plots. Vigor is based on the following numeric assignments: 0 = dead, 1 = low, 2 = medium, 3 = high. Mean and standard error of the mean are shown. There is no error bar for survival at 1.5 m, as the standard error was 0 (i.e., no dispersion from the mean) at that distance.

Wind Interaction

Tree sway in the uncut stand indicated similar motion on the north–south and east–west axes of the clinometers at low wind speeds (associated with tree sway less than 0.1 degrees), which suggested a rotating motion in response to wind, regardless of direction (Fig. 27). At greater sway (i.e., higher wind speed), visible separation of the traces indicated a shift to a directional mode of response. Replotting sway against drag measured from the top of the main tower (Fig. 28) showed a linear relation. Being aware of this correlation was important because it allowed comparison of individual trees in the uncut stand and residual strips of the strip-cut, where representative drag could not be measured.

For trees of different sizes within the same treatments there were small differences in measured sway (Fig. 29), probably because proportionately smaller crown profiles were presented to the wind by slimmer trees, which have a higher slenderness coefficient (i.e., larger height–diameter ratio).

Maximum sway for trees in the residual strips of the strip-cut was 60% greater than for their counterparts in the uncut area, which suggested more wind penetration from the top and edges of the canopy as a result of the cut. The understory wind in the residual strips was at least 3 times greater than in the uncut area, far more than can be accounted for by the sway data. For this reason, understory wind was not a good indicator of susceptibility to wind damage.

The greater sway in the residual strips was consistent with greater drag on trees on the face of the cut (the strip edge) (Fig. 30). The implications of this lateral drag are mixed. The residual canopy must dissipate more energy, which could lead to increased windthrow during extreme events. However, lateral drag provides a limiting mechanism that prevents a buildup of speed along long strips, which would otherwise lead to more damage to trees at the downwind end of a cut strip.

Ancillary measurements taken to directly test for the presence of lateral drag on the vertical face at the edge of the residual strips showed drag of similar magnitude but opposite direction on opposite edges of the cut strips (Figs. 30, 31). The time series provided strong evidence that lateral dissipation does occur when the wind blows parallel to the face of the stand. The south edge was perhaps less rough (i.e., fewer individual branches extending into the cut-strip), as indicated by the lesser magnitude of the measured drag, compared with the opposing point on the north edge, but the timing is convincing.

Table 14 summarizes the midstrip wind studies. Mean speeds indicate that the wind had already stabilized by the time it had traveled to the 90-m mast, whether approaching from the west or the east. That is, the aerodynamic boundary layer stabilized between 60 and 90 m after the uncut–cut interface and became disrupted somewhere near the 60-m distance for winds approaching the interface. The off-axis winds (perpendicular to the strip) showed good agreement at all three points, as would be expected if there was no instrument bias. The results in this table relate to the risk of windthrow based on the length of the cut strips.

The summary of maximum wind events (calculated on the basis of hourly wind averages) covers the May to October period, when the soil is thawed enough for windthrow (Table 15). The years 2000 and 2002 had a slightly greater number of days with maximum hourly wind speed over 4 $m \times s^{-1}$ than other years (data not shown). However, on the basis of wind data from the top of the uncut canopy, the year-to-year variation in mean and maximum wind speeds was not great (Table 16).

Table 14. Wind statistics in the strip-cut, at three distances east of the west end of the strip-cut, for summer 1998[a]

	On-axis west winds			On-axis east winds[b]			Off-axis winds		
Variable	120 m	90 m	60 m	120 m	90 m	60 m	120 m	90 m	60 m
Wind speed ($m \cdot s^{-1}$)									
Mean	0.52	0.53	0.35	0.24	0.25	0.20	0.37	0.35	0.37
Variance	0.22	0.20	0.12	0.04	0.03	0.03	0.06	0.05	0.08
No. of observations	201	201	201	19	19	19	51	51	51
Significant difference from 60-m distance[c]	Yes	Yes	–[d]	Yes	Yes	–	No	No	–
Regression statistics									
R^2	0.79	0.81		0.74	0.65		0.87	0.80	
$y = mx + b$[e]	$y = 1.351x$	$y = 1.345x$		$y = 1.10x$	$y = 1.05x$		$y = 0.935x$	$y = 0.876x$	

[a] Wind data take f-axis winds blow across (perpendicular to) the strip-cut.

[b] Relatively few east wind events were available, because the prevailing winds were from the west.

[c] A paired two-sample t-test was used to compare mean wind speed at 60 m with that at 90 m and 120 m.

[d] Dashes indicate not applicable.

[e] No intercept (line goes through origin).

Table 15. Frequency of maximum daily wind speeds for May to October at the main tower in the uncut area[a]

Maximum daily wind speed (m•s^{-1})[b]	No. of days 1997	1998	1999	2000	2001	2002
0.0	0	0	0	0	0	0
0.5	1	8	5	0	0	0
1.0	4	6	4	0	0	0
1.5	13	13	9	3	4	4
2.0	35	24	28	25	19	18
2.5	39	24	39	47	37	42
3.0	39	24	43	37	55	40
3.5	16	17	21	26	28	38
4.0	17	5	23	28	20	23
4.5	5	4	6	14	11	14
5.0	1	3	3	3	9	3
5.5	1	1	3	2	1	2
6.0	0	0	1	0	0	1
6.5	1	0	0	0	1	0
Total events[c]	172	129	185	185	185	185
Windthrow[d]	25	12	11	5	5	5

[a] Maximum daily wind speeds based on hourly averages.

[b] To convert to kilometers per hour, multiply by 3.6.

[c] Number of days on which observations were recorded (1997 and 1998 had fewer observations because of equipment failure).

[d] Number of trees uprooted (root failure) or snapped off (stem failure) for that year.

Table 16. Hourly wind speed (km·h^{-1}) at top of canopy (23 m) in the uncut area

Year	Annual Mean	Maximum	Growing season (1 May to 30 September) Mean	Maximum
1997	NA	NA	9.0	22.0
1998	NA	NA	NA	NA
1999	NA	NA	9.0	20.2
2000	9.7	22.3	10.1	18.4
2001	10.1	22.7	10.8	22.7
2002	10.1	23.8	10.8	20.2

Note: NA = complete yearly record not available.

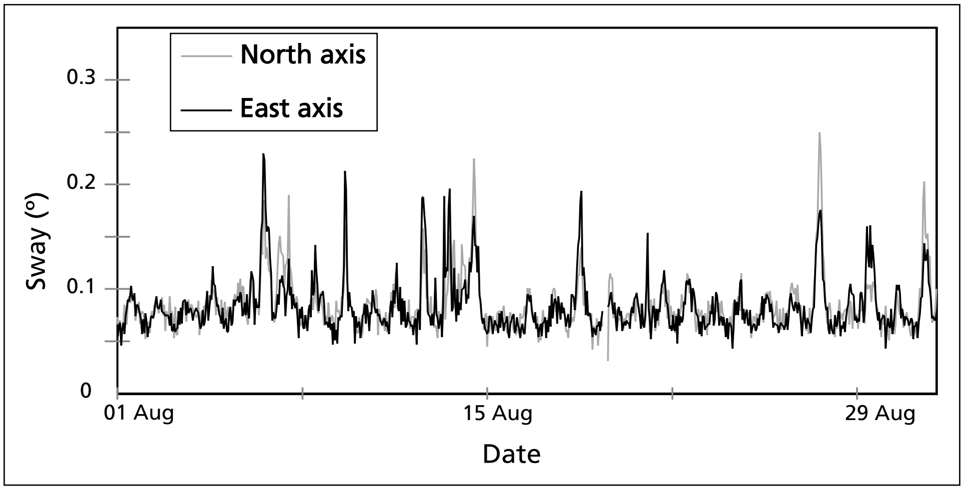


Figure 27. Tree sway over time in the uncut area. Data are based on a biaxial clinometer time series from 1 to 31 August, 1998. Sway is the standard deviation of stem angle (measured in degrees).

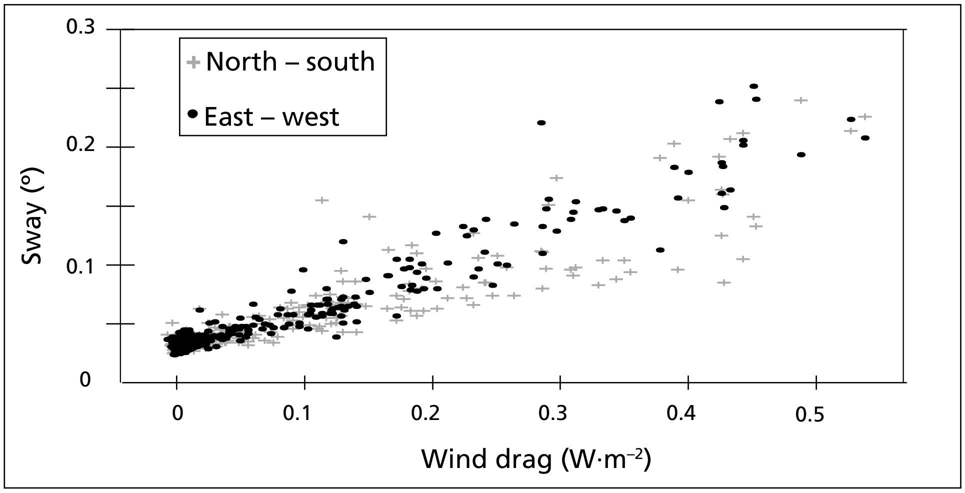


Figure 28. Tree sway in the uncut area as a function of wind drag. Sway is the standard deviation of stem angle (measured in degrees).

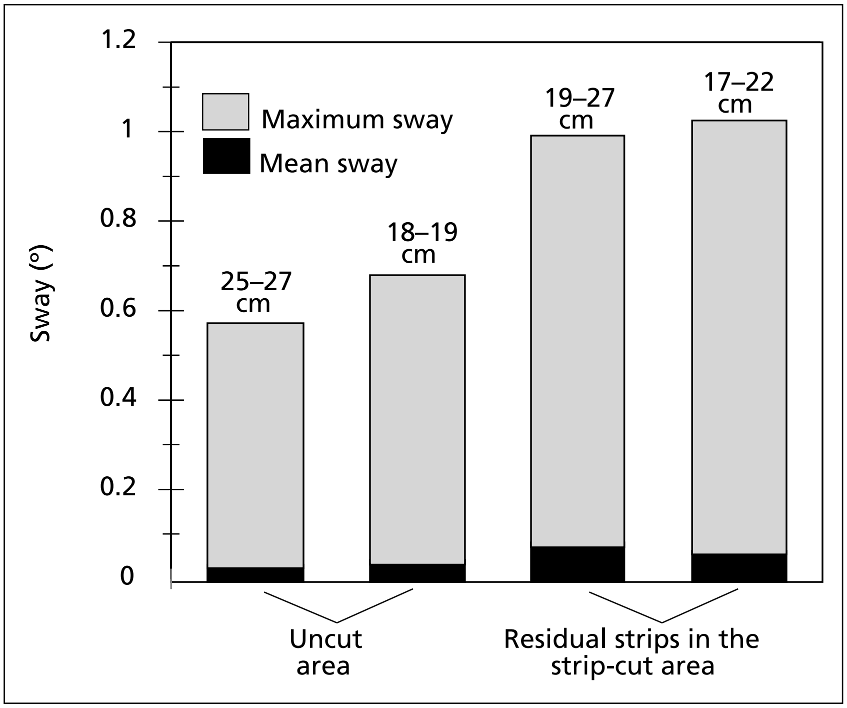


Figure 29. Tree sway for representative-diameter trees in the uncut area and in residual strips of the strip-cut during October 1998. Data are based on 3 smaller and 3 larger trees in each of the two areas. Diameter at breast height size range is shown above the histogram bars. Sway is the standard deviation of stem angle (measured in degrees).

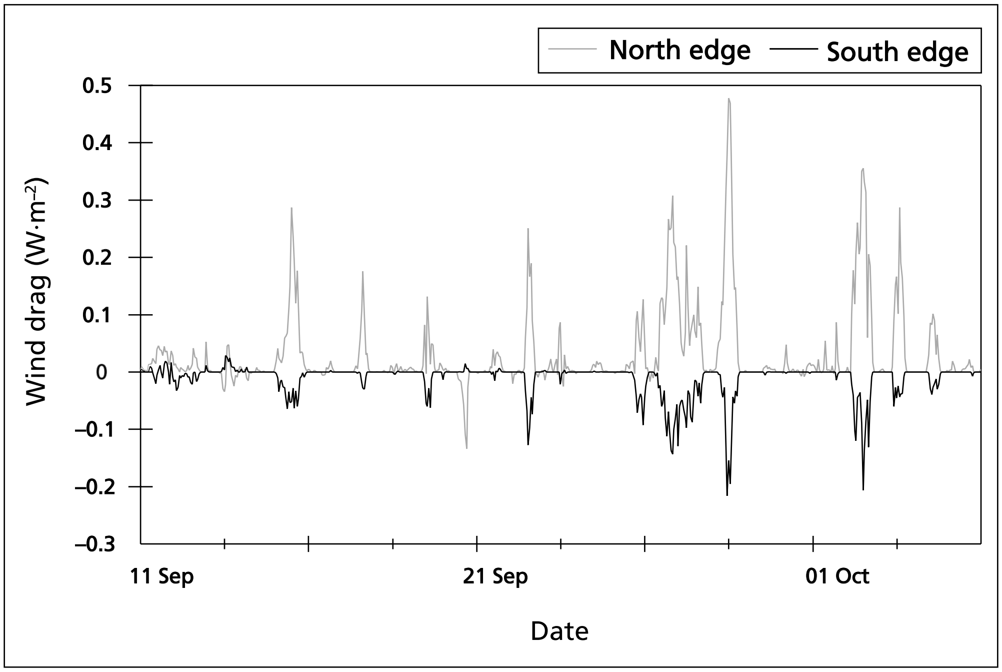


Figure 30. Wind behavior at the edge of residual strips in the strip-cut area in 1998. Measurements were taken in cut strip 4, 90 m east of the uncut area (see Fig. 2). Sign of data indicates direction of deflection, where positive drag is northward deflection from the harvested strip into the residual crown and negative drag is southward deflection from the harvested strip into the residual crown.

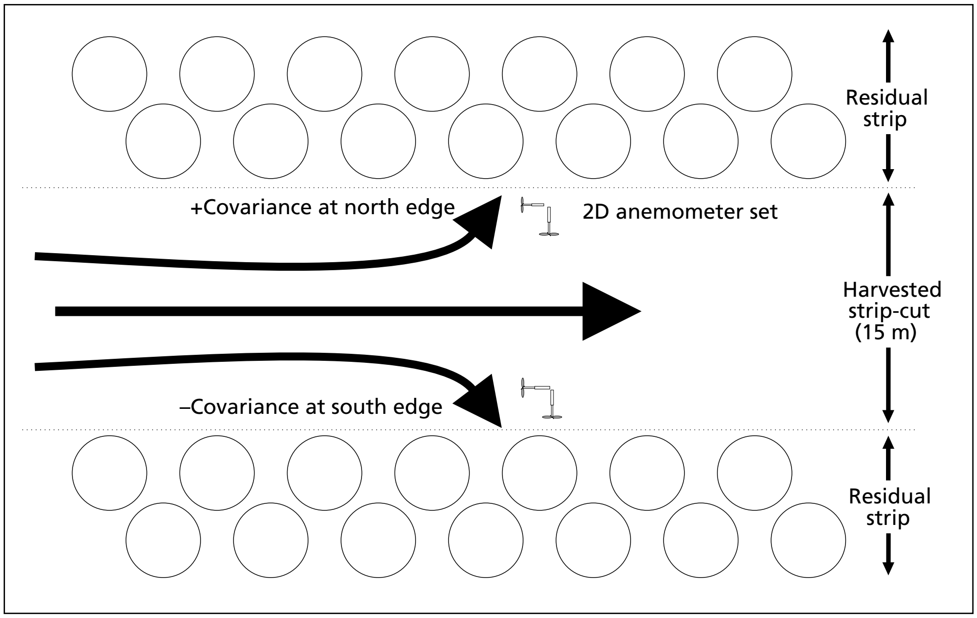


Figure 31. Schematic representation of redirection of wind blowing down a cut strip. Winds near the strip edge are deflected, because of drag from the tree edge, toward the north (along the south facing edge) and toward the south (along the north facing edge) (see Fig. 33). Circles represent tree crowns in the residual strips. Graphic elements are not drawn exactly to scale.

Windthrow Response

This site was deemed to be at high risk of windthrow after harvest, because of the high endemic windthrow on the site, as well as the high water tables associated with this phenomenon (Schaetzl et al. 1989). However, 5 years after harvest, the cumulative windthrow was very low in the 0.83-ha area covered by the 15-m-wide residual strips of the strip-cut area. Only 5.2% of the white and black spruce had blown down (50 white spruce trees and 10 black spruce, as well as 1 balsam fir and 2 larch), based on the preharvest density of trees over 5 m tall (about 1 300 stems per hectare). This lower-than-expected windthrow may have been due in part to several years of drier weather after harvest in 1998 and 2002, which lowered the water table (Table 3). This would allow development of a greater abundance of fine roots in the aerated zone, thus enhancing tree stability.

Most of the windthrown trees had been uprooted (root failure) to expose the soil–root plate (55 trees); a few were snapped off (stem failure) 3–4 m above the base (8 trees). The morphology of windthrown white spruce trees was not significantly different from those in the canopy as a whole (average height 19.4 m for windthrown white spruce and 20.5 m in the preharvest canopy; average dbh 23.3 cm for windthrown white spruce and 27.9 cm in the preharvest canopy).

The spatial pattern of the windthrown trees is shown in Figure 32. While there appears to be a greater incidence of windthrow on the east end of the cut strips, further from the protection of the uncut area (e.g., strip 8, Fig. 32), the correlation between density of windthrow and distance from the uncut area on the west side of the strip-cut was not significant at an á value of 0.05 (Spearman's correlation, $P = 0.5332$). This correlates with the wind analysis presented earlier. The average distance of windthrown trees was 158 m from the west edge of the strip-cut area (the strip length varied from 121 m for strip 1 to 344 m for strip 8 [Fig. 2]). Direction of windthrow was usually toward the southeast. Other orientations may have occurred because of tree rotation during strong wind events.

Analysis of tree–wind interaction shows that, on this site, the occurrence of windthrow was not related to tree size, even though larger trees have larger and deeper crowns that drag on the wind. The architecture of the cut strips appears to have been able to reduce the wind speeds significantly relative to open areas. Average wind speed at a height of 6 m within the strip-cut area was less than half that above the canopy in the uncut area. (Fig. 33).

In terms of windthrow, the stands appear to have stabilized soon after harvest, and yearly windthrow rates did not vary with the strength of the wind. After an initial pulse of blowdown immediately after harvest, the windthrow was more uniform over subsequent 5 years (and was entirely uniform over the last 3 years of the study) (Table 15).

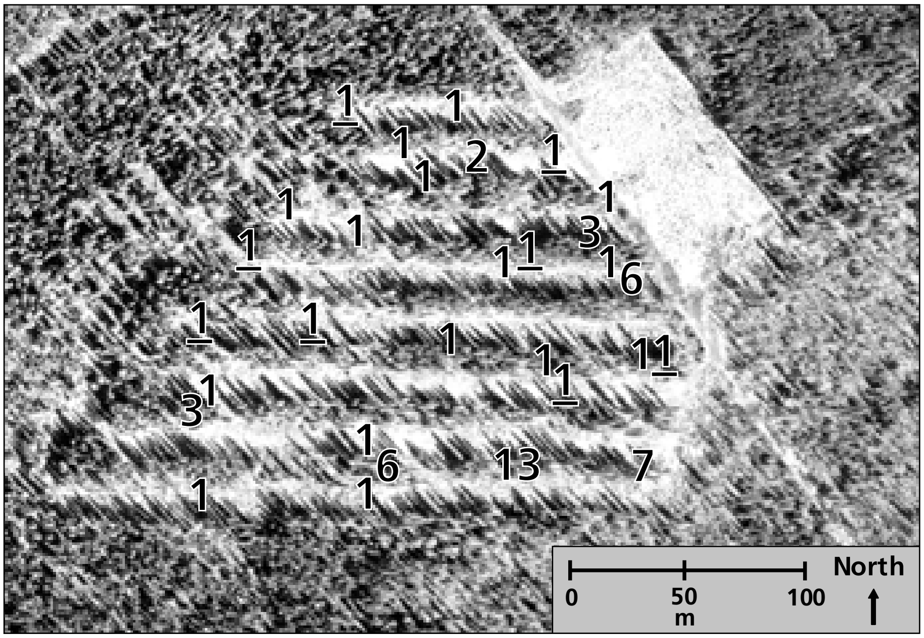


Figure 32. Number and spatial distribution of windthrown trees 5 years after harvest (August 2002). Numbers without underline = trees with root failure, numbers with underline = trees with stem failure.

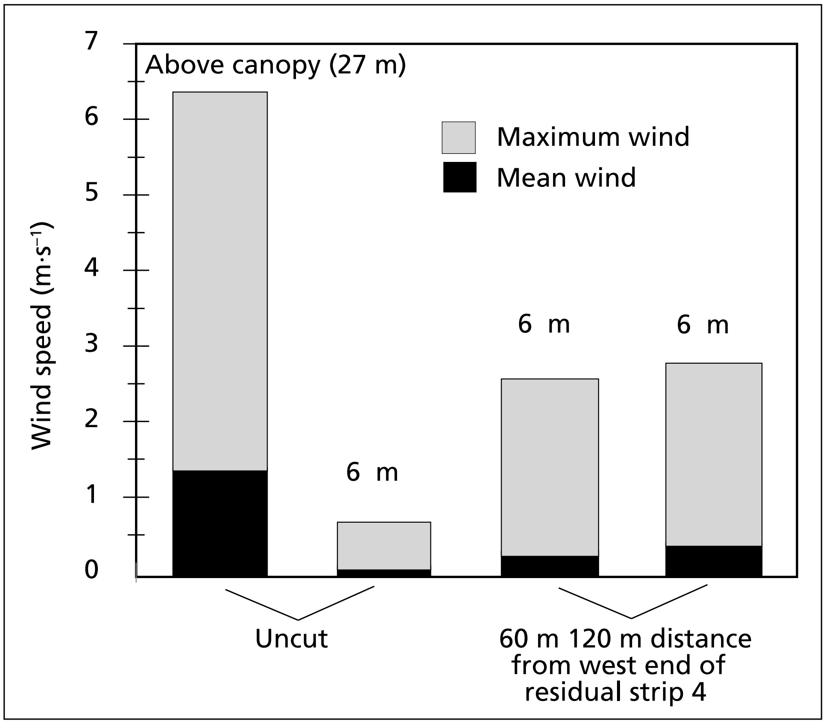


Figure 33. Mean wind speed below the canopy in the uncut area and in residual strips of the strip-cut area during October 1998. The above-canopy wind speed is included as a reference point. Below-canopy winds were recorded at 6 m and above-canopy winds were recorded 3 m above the tree crowns (27 m above ground level).

Management Implications

Although the site was deemed to be at risk of high windthrow rates after harvest, windthrow was, in fact, light and mostly occurred soon after harvest. Given the conclusion that cut strips longer than 90 m may not be associated with greater windthrow, this treatment might be successfully applied on blocks larger than those used for this experiment.

Neither strip-cutting nor patch-cutting resulted in wetting-up, and on the strip-cut there was no evidence of a sustained rise in the water table under the cut strips relative to the residual strips. Although wetting-up has not been a problem so far, mounds did help seedling performance. Best survival and growth on mounds was found on the strip-cut area. Retention of structure in the residual strips met multiple silvicultural objectives, including less windthrow than along edges of similar sites logged with clear-cut systems.

The microclimatic findings indicate the potential to create conditions more conducive to successful seedling establishment and growth under the generally extreme weather conditions associated with northern wetland sites such as this one. This study also shows that regeneration by seeding is a risky strategy, with poor chance of success.

This research demonstrated a successful approach to harvesting and regenerating mineral wetland sites, to ensure prompt reforestation. This approach requires prompt postharvest site preparation and planting with vigorous stock to avoid the problems of vegetation competition and partial retention of the overstory to ameliorate ground-level microclimate conditions following harvest. Amelioration of microclimate and development of a suitable microsite were key to successful regeneration. While these results are applicable to mineral wetlands, the regeneration of treed peatlands dominated by black spruce would require other management considerations.

SUMMARY AND CONCLUSIONS

Data on the level of the groundwater table collected for 8 years (1995–2002) on the study site showed that neither strip-cutting nor patch-cutting caused groundwater to intersect the ground surface. Furthermore, there was no evidence of groundwater mounding under the 15-m-wide cut strips. Surface water occurred naturally as a small, groundwater-fed stream in a topographic low (alder swamp) in the strip-cut area before and after treatment. Groundwater levels during the growing season were controlled primarily by the frequency, duration, and amount of rainfall. Drainage was controlled by local topography and slope. Response to significant rainfall was rapid, but the water table started to decline as soon as the rain ceased. The rate of decline in the water table for the site averaged about 6–8 mm × day^{-1}. During a summer month without rain the water table might drop by 250 mm.

Comparison of the weather record for the period of the experiment with the longer-term records for a nearby fire lookout suggested that the climate since initiation of the study was essentially normal; therefore, the results of the study can be used to predict the outcome of similar treatments of similar forest types.

Temperature measurements taken during three growing seasons (1998–2000) indicated that ground surface temperatures lethal to coniferous seedlings (>46°C) occurred, although rarely, on the patch-cut and strip-cut treatments. In 2002, when additional recording devices and temperature probes were installed near seedlings, temperature gradients were detected at the surface across the cut strips on the strip-cut treatment. Temperatures were higher in the northern half of the cut strips than in the southern half. Data from the new equipment confirmed the occurrence of high surface temperatures on both the strip-cut and the patch-cut treatments.

In general, windthrow was light and occurred right after harvest, with little subsequent windthrow. Windthrow was directed toward the southeast and was concentrated at the east end of each residual strip, farthest from the uncut area. The cutting pattern in the strip-cut area kept the wind below the threshold for large-scale windthrow, and the residual strips buffered wind effects across the alternating strips. Water demand and interception by vegetation were sufficient to limit flooding. The shading pattern in the harvested strips moderated the seedling environment.

The cutting pattern applied to the strip-cut increased canopy roughness enough to increase wind drag by 60%. Auxiliary measurement of wind behavior within the strips showed that wind speed stabilized over a distance of 90 m or less. Turbulence measurements at the vertical face of the canopy explain the mechanism that both limits wind speed in the cut strips and increases wind load experienced by the residual canopy. The size of a tree seemed to make a relatively small contribution to its sensitivity to wind.

The east-to-west orientation of the strip-cut produced measurable microclimate effects. The sunny aspect of the strip-cut was not noticeably different from the patch-cut. The shady aspect was similar to the undisturbed understory, except that greater exposure to open sky made it more prone to radiative frost events than was the case for the patch-cut and the sunny exposure of the strip-cut. The experiment site as a whole was prone to frost and could not be said to have a reliable frost-free period. Exposed microsites were subject to more frequent and intense frosts, compared to the uncut area.

Fifth-year seedling survival for all species was significantly better on the strip-cut area than on the patch-cut area. There was better survival on mounded than non-mounded microsites on both the strip-cut and the patch-cut for all species except black spruce on the patch-cut. Most mortality occurred within the first 3 years after planting. Seedling growth (especially height growth) at 5 years after harvest was better on the strip-cut area than the patch-cut area, for all species. Growth of white spruce was better on mounded than non-mounded microsites, whereas for black spruce and larch, growth was similar on the two types of microsites. These results suggest that, when regenerating wet mineral sites after timber harvesting, the best survival rates of white spruce, black spruce, and larch seedlings can be obtained if the seedlings are planted on mounds created during site preparation after strip-cut harvesting.

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APPENDIX

Analysis of variance for seedling growth response

Total height, fifth year, patch-cut treatment[a, b]

Source	df	Mean square	*F* value	$P^r > F$
Siteprep[c]	1	1 542.9	1.23	0.3481
Rep[c]	3	24 325.5	19.42	0.0181
Siteprep*rep	3	1 252.8	0.07	0.9756
Species	2	373 702.4	20.46	0.0001
Siteprep*species	2	2 473.8	0.14	0.8746
Error	12	18 263.2	–	–

	Least squares means (cm)[d, e]		
	Larch	Black spruce	White spruce
Mounded	92.5a	57.1b	55.9b
Non-mounded	92.6a	57.9b	50.2b

[a] Model r^2 = 0.7912.
[b] Analysis performed with untransformed data.
[c] Tests of hypothesis for siteprep and rep used a type III mean square, with siteprep*rep as the error term.
[d] Mean values are adjusted for all terms in the model.
[e] Means followed by the same letter do not differ significantly ($P \geq 0.05$) in least squares means test.

Total height, fifth year, strip-cut treatment[a, b]

Source	df	Mean square	*F* value	$P^r > F$
Siteprep[c]	1	21 301.5	1.61	0.2943
Rep[c]	3	43 078.7	3.25	0.1794
Siteprep*rep	3	13 429.5	0.59	0.6327
Species	2	570 370.1	25.44	<0.0001
Siteprep*species	2	3 468.6	0.15	0.8584
Error	12	22 424.3	–	–

	Least squares means (cm)[d, e]		
	Larch	Black spruce	White spruce
Mounded	118.8a	75.8b	72.9b
Non-mounded	115.2a	65.0b	69.4b

[a] Model r^2 = 0.8326.
[b] Analysis performed with untransformed data.
[c] Tests of hypothesis for siteprep and rep used a type III mean square, with siteprep*rep as the error term.
[d] Mean values are adjusted for all terms in the model.
[e] Means followed by the same letter do not differ significantly ($P \geq 0.05$) in least squares means test.

Root collar diameter, fifth year, patch-cut treatment[a, b]

Source	df	Mean square	F value	$P^{r} > F$
Siteprep[c]	1	0.6	0.13	0.7380
Rep[c]	3	7.9	1.86	0.3108
Siteprep*rep	3	4.2	0.49	0.6949
Species	2	132.5	15.32	0.0005
Siteprep*species	2	1.2	0.14	0.8702
Error	12	8.6	–	–

	Least squares means (mm)[d, e]		
	Larch	Black spruce	White spruce
Mounded	18.1a	11.7b	11.0b
Non-mounded	18.1a	12.0b	9.9b

[a] Model r^2 = 0.7458.

[b] Analysis performed with untransformed data.

[c] Tests of hypothesis for siteprep and rep used a type III mean square, with siteprep*rep as the error term.

[d] Mean values are adjusted for all terms in the model.

[e] Means followed by the same letter do not differ significantly ($P \geq 0.05$) in least squares means test.

Root collar diameter, fifth year, strip-cut treatment[a, b]

Source	df	Mean square	F value	$P^{r} > F$
Siteprep[c]	1	10.9	2.74	0.1966
Rep[c]	3	11.2	2.81	0.2091
Siteprep*rep	3	4.0	2.44	0.1145
Species	2	99.2	60.77	<0.0001
Siteprep*species	2	0.1	0.04	0.9588
Error	12	1.6	–	–

	Least squares means (mm)[d, e]		
	Larch	Black spruce	White spruce
Mounded	17.8a	11.8b	11.9b
Non-mounded	16.6a	10.4b	10.4b

[a] Model r^2 = 0.9287.

[b] Analysis performed with untransformed data.

[c] Tests of hypothesis for siteprep and rep used a type III mean square, with siteprep*rep as the error term.

[d] Mean values are adjusted for all terms in the model.

[e] Means followed by the same letter do not differ significantly ($P \geq 0.05$) in least squares means test.

Height increment, 5 years, patch-cut treatment[a, b]

Source	df	Mean square	F value	$P^r > F$
Siteprep[c]	1	1 280.7	1.72	0.2807
Rep[c]	3	19 779.3	26.61	0.0116
Siteprep*rep	3	743.3	0.04	0.9876
Species	2	256 003.3	14.79	0.0006
Siteprep*species	2	2 588.3	0.15	0.8627
Error	12	17 311.5	–	–

	Least squares means (cm)[d, e]		
	Larch	Black spruce	White spruce
Mounded	63.0a	34.4b	33.2b
Non-mounded	63.6a	35.0b	27.6b

[a] Model $r^2 = 0.7363$.

[b] Analysis performed with untransformed data.

[c] Tests of hypothesis for siteprep and rep used a type III mean square, with siteprep*rep as the error term.

[d] Mean values are adjusted for all terms in the model.

[e] Means followed by the same letter do not differ significantly ($P \geq 0.05$) in least squares means test.

Height increment, 5 years, strip-cut treatment[a, b]

Source	df	Mean square	F value	$P^r > F$
Siteprep[c]	1	18 432.1	1.39	0.3236
Rep[c]	3	42 368.4	3.19	0.1830
Siteprep*rep	3	13 276.9	0.65	0.5994
Species	2	385 265.1	18.79	0.0002
Siteprep*species	2	1 621.5	0.08	0.9244
Error	12	20 505.5	–	–

	Least squares means (cm)[d, e]		
	Larch	Black spruce	White spruce
Mounded	89.7a	53.2b	53.2b
Non-mounded	86.1a	44.4b	49.0b

[a] Model $r^2 = 0.7958$.

[b] Analysis performed with untransformed data.

[c] Tests of hypothesis for siteprep and rep used a type III mean square, with siteprep*rep as the error term.

[d] Mean values are adjusted for all terms in the model.

[e] Means followed by the same letter do not differ significantly ($P \geq 0.05$) in least squares means test.

Periodic root collar diameter increment, (year 3 to year 5), patch-cut treatment[a, b]

Source	df	Mean square	F value	$P^r > F$
Siteprep[c]	1	0.1	0.06	0.8241
Rep[c]	3	4.4	2.32	0.2536
Siteprep*rep	3	1.9	0.46	0.7139
Species	2	67.9	16.51	0.0004
Siteprep*species	2	0.6	0.15	0.8661
Error	12	4.1	–	–

	Least squares means (mm)[d, e]		
	Larch	Black spruce	White spruce
Mounded	9.3a	5.0b	4.4b
Non-mounded	9.6a	5.0b	3.6b

[a] Model r^2 = 0.7598.

[b] Analysis performed with untransformed data.

[c] Tests of hypothesis for siteprep and rep used a type III mean square, with siteprep*rep as the error term.

[d] Mean values are adjusted for all terms in the model.

[e] Means followed by the same letter do not differ significantly ($P \geq 0.05$) in least squares means test.

Periodic root collar diameter increment, (year 3 to year 5), strip-cut treatment[a, b]

Source	df	Mean square	F value	$P^r > F$
Siteprep[c]	1	3.4	1.14	0.3646
Rep[c]	3	4.7	1.58	0.3586
Siteprep*rep	3	3.0	4.03	0.0340
Species	2	42.0	56.54	<0.0001
Siteprep*species	2	0.1	0.15	0.8606
Error	12	0.7	–	–

	Least squares means (mm)[d, e]		
	Larch	Black spruce	White spruce
Mounded	8.6a	4.7b	4.9b
Non-mounded	8.1a	4.1b	3.8b

[a] Model r^2 = 0.9255.

[b] Analysis performed with untransformed data.

[c] Tests of hypothesis for siteprep and rep used a type III mean square, with siteprep*rep as the error term.

[d] Mean values are adjusted for all terms in the model.

[e] Means followed by the same letter do not differ significantly ($P \geq 0.05$) in least squares means test.