INTENSIVE HARVESTING IMPACTS ON SOIL TEMPERATURE AND SOLUTION CHEMISTRY IN THE MARITIMES REGION OF CANADA

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ABSTRACT

Starting in 1989, a series of lysimeter studies was initiated to evaluate the potential impacts of different harvesting and site preparation methods on site quality. Experiments were laid out in the field on soil types representative of the land base supporting the growth of all the major commercially important tree species in the Maritimes region. Although different treatments applicable to local situations were implemented on each site, three treatments included on all sites were: control (no harvest), conventional stem harvest (boles only) with slash left on site, and whole-tree harvest (all biomass above the stump removed from the site.

On all study sites, soil temperature was monitored hourly (1) immediately below the organic horizons, (2) mid-way between the surface and the bottom of the rooting zone, and (3) below the rooting zone.

Hourly mean temperatures in the top (immediately below the organic) horizon clearly exhibited effects of harvesting methods. In the whole-tree harvest plots, during June-August, the hourly mean temperature was 6–8°C warmer than that in the conventional harvest plots. Also, temperature peaked about 2 h later in the whole-tree harvest plots than in the conventional-harvest plots. Similar trends were consistently recognisable at lower depths as well, indicating that whole-tree harvesting has the potential to enhance weathering in the subsoil. The treatment effects were equally distinguishable in the values for daily mean temperature, except in the early spring and later summer (late August) when the daily mean temperature was higher in the conventional-harvest plots than in the whole-tree harvest areas owing to the insulating effect of slash. The accumulated heat units (cumulative number of hours times the soil temperature above 5°C) were greatest in the whole-tree harvest areas, followed by the conventional-harvest and then the control plots.

Keywords: whole-tree harvesting; biomass harvesting; lysimeter; soil solution; temperature; organic matter.

INTRODUCTION

Potential impacts of intensive harvesting on site have been of concern to forest soil scientists since the late nineteenth century (Ebermayer 1876—*see* Tamm 1979 and Smith *et al.* 1986). However, it was not until the second half of the twentieth century that interest in this subject was rekindled after evidence was discovered in Sweden and Germany of decreasing forest productivity due to repeated annual litter raking (*see* Rennie 1955). The reduced productivity was attributed to loss of nutrient reserves in the forests subjected to intensive harvesting, and this loss of nutrients was due to increased removal of biomass rich in nutrients and to leaching loss of reserves in the soil. Lately, many reviews have been written on the topic (Foster & Morrison 1982; Freedman 1981; Kimmins *et al.* 1985; Smith *et al.* 1986). In New Brunswick and Nova Scotia, preliminary work has been done to evaluate the comparability of local results with those published elsewhere (Mahendrappa *et al.* 1988, 1989; Maliondo 1989).

The results of biomass and nutrient inventories of New Brunswick forests (Maliondo *et al.* 1990) indicated that a high proportion of the nutrients is removed from forests in whole-tree harvesting, compared to conventional (stem only) harvesting. As a result of whole-tree harvesting, the soil lacks protection from solar radiation and hydrologic factors that cause soil erosion. Increased incidence of solar radiation results in faster biochemical reactions that ultimately lead to potential site degradation, characterised by nutrient depletion and site acidification. The reactions responsible for such degradation include faster decomposition of reserve organic matter, nitrification of mineralised ammoniacal nitrogen, and leaching of base cations in association with nitrate. Nitrification, being an acidifying reaction, produces hydrogen ions and thus increases the solubility and mobility of acid cations such as aluminium, iron, manganese, zinc (Maliondo 1989; Maliondo *et al.* 1990). These results have been reported in Sweden (Lundkvist 1988), North America (Smith *et al.* 1986; Anderson 1990; Hornbeck 1990; Smith 1990; McCormack 1990), and New Zealand (Dyck & Skinner 1990).

The objective of this paper is to report the observed soil temperature at three soil depths in forests subjected to three harvesting treatments. The observed temperature data are evaluated in detail to explore the extent of the differences in soil temperatures as affected by the degree of slash removal from the harvested sites. The data included here represent the observations made at all the study sites. Studies were conducted in New Brunswick and Nova Scotia to evaluate the potential loss of nutrients from the forests due to intensive harvesting. Although the term "intensive harvesting" is generally used to represent various degrees of biomass removal from forests, in this report it is used to represent whole-tree harvesting. In the Maritimes, almost all the above-ground biomass of merchantable trees only is used in whole-tree harvesting operations; thus, it is assumed that the nutrients in non-merchantable trees are left on site.

MATERIAL AND METHODS

The studies were initiated at six locations, representing hardwood, softwood, and mixed stands growing on different soil types in the Maritimes region (Fig. 1). Some mensurational characteristics of stands on each study site are listed in Table 1. Three treatments common to each of the six study sites include control (Cont), conventional harvest (boles only) (CH), and whole-tree harvest (WT). Additional treatments were included in the experiments to match the silvicultural practices used by collaborating agencies. These included selection cutting, in which a certain proportion of the trees were harvested; flail operation, in which the residue from the chippers was spread back on the soil; and spreading of ash from co-generation stations. In addition, at one site, lysimeters were installed in the skidder rows where the organic horizons had been disturbed by trees being dragged to the roadsides.

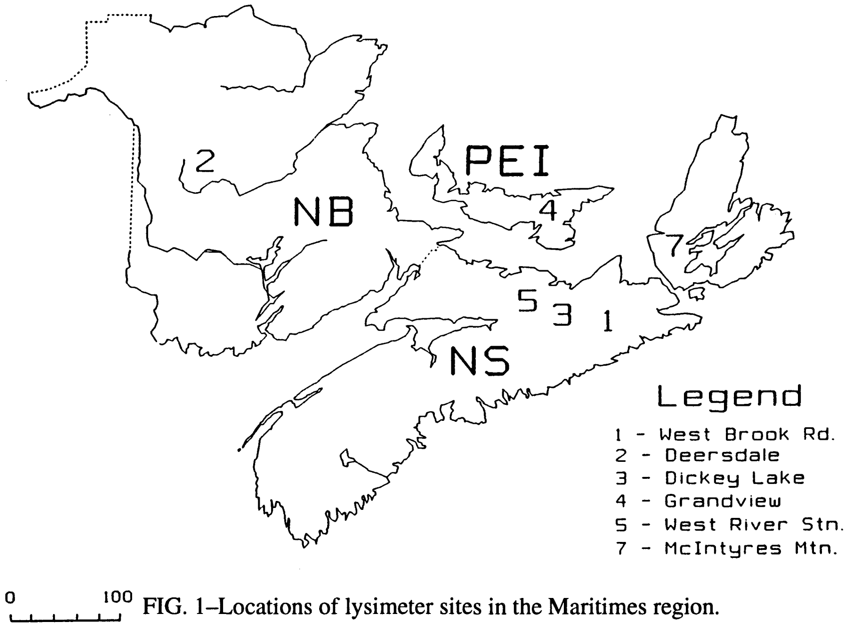

FIG. 1–Locations of lysimeter sites in the Maritimes region.

TABLE 1–Forest mensurational characteristics at the study sites in the Maritimes region.

Site	Biomass (t/ha)		Volume (m^3/ha)		Basal area (m^3/ha)	Elevation (m)
	Total	Merch.*	Total	Merch.		
Deersdale	144	140	216	192	30	600
West Brook Road	209	204	359	336	42	180
Dickey Lake	143	137	182	158	24	190
West River Station	133	128	195	174	30	210
McIntyres Mountain	165	159	230	202	0	230

* Boles with a diameter of 7 cm.

On each site, the treatments were duplicated on 100 × 200-m blocks. In each block, two duplicate lysimeter systems for collecting soil solution samples were installed at three different depths. Temperature sensor probes (thermistors) were located at the same positions. The lysimeters and thermistors were located immediately below the organic horizon, at the bottom of the rooting zone, and at the midpoint between the two. The locations of the lysimeters were horizontally staggered, such that the collection of leachates from the upper lysimeters did not influence the collection of leachates from the lysimeters located at a greater depth.

Installation of Lysimeters and Thermistors

For the installation of the lysimeters and thermistors, soil pits measuring approximately 1.3 × 1.3 m were excavated and small holes were dug with trowels in two walls of the soil pit. These holes were extended as far as the arm could reach (50–60 cm). The lysimeters and thermistors were placed at the end of these holes such that the soil above them was not disturbed. After they were installed, a fibreglass tub measuring 1.3 × 1.3 × 1 m was lowered into the soil pit and the space between the tub and the pit was carefully back-filled, making sure that the tygon tubing and wires attached to the lysimeters and thermistors were not damaged. The thermistors were connected to Omnidata data loggers and the tygon tubing from the lysimeters was connected to the sample bottles (Fig. 2). The lysimeters consisted of a glass housing, 6 cm in diameter, fitted with a fritted glass disc fused in place 5 mm below the rim of the funnel. The fine pores in the fritted discs, measuring 2–5 microns, are very effective in filtering out the particulates in the leachates. Collection of soil solution (leachates) was facilitated by connecting the sample bottle to the vacuum system created by siphoning water from one bottle to another located at a height differential of 100 cm (Reikerk & Morris 1983). A one-way flow valve was placed between the sample bottle and the upper vacuum bottle to avoid contamination of the sample with the liquid used in the vacuum system. Another one-way flow valve was placed at the lower end of the siphon tube to prevent reverse flow of the liquid from the lower bottle.

Collection and Processing of Temperature Data

Seven thermistors were connected to each data logger—six in the soil profile and the other to record air temperature about 0.5 m above the soil surface. The data logger was programmed to measure soil and air temperatures at half-hour intervals and to record an average of two measurements each hour. The temperature measurements were carried out from May to Oct/Nov (until frost occurred both day and night). Datapacks (DSP) were changed when they were more than 90% full. The information from the datapacks was downloaded directly on to a computer using an Omnidata reader.

Statistical Evaluations

The temperature data were statistically evaluated using SAS (SAS 1989). A 15% spline function was used to smooth the average daily temperatures for graphing purposes only. The

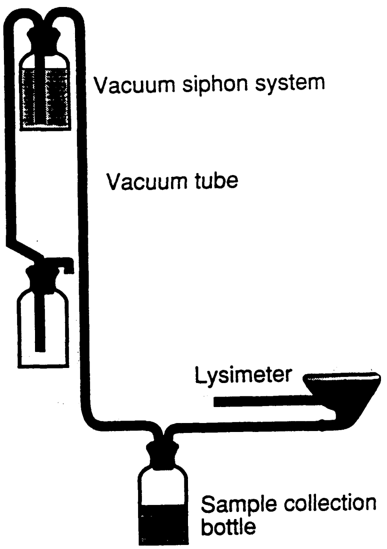

FIG. 2–Schematic representation of lysimeter system.

Scheffe test (SAS Institute) was used to evaluate the statistical differences in the temperature and heat units affected by the treatments. These tests were also used to establish differences in the soil solution chemistry as affected by the treatments. Simple and multiple regression equations were used to test the relationships among the concentrations of different nutrients in the soil solutions.

RESULTS AND DISCUSSION

General Observations Regarding the Lysimeters

The first lysimeter study was started in 1989 in Deersdale, New Brunswick. Over a period of 4 years after their installation, 97% of the lysimeters functioned very well, yielding leachates consistently. Therefore, these small (6 cm across) lysimeters appear well suited to long-term monitoring of soil solution chemistry without disturbing the soil above. The very small (3%) failure rate was caused by mice chewing on the tygon tubing connected to the lysimeters (the mice shelter in and around the fibreglass tubs). It should, however, be pointed out that, at times, where the soil above the lysimeters had dried out, the vacuum system appeared to fail. However, the problem corrected itself after rainfall. This was particularly true for lysimeters at the interface of the organic and mineral horizons.

Soil Temperature

The impacts of harvesting methods on the soil temperature are expressed in terms of hourly means within a day, and daily mean temperatures during the growing season.

Hourly mean temperature

The average hourly temperatures for 1991 and 1992 at the McIntyres Mountain study site (location number 7 in Fig. 1) are presented in Fig. 3. The McIntyres Mountain study site was harvested in mid-July 1991 and the temperature probes and the lysimeters were installed immediately after harvesting was completed. These values indicate the temperatures observed during the year of implementing the treatments and the first year after treatment application and installation of thermistors. The patterns shown in Fig. 3 are similar to those observed during 1992 in Deersdale where thermistors were installed 3 years earlier. In Fig. 3, Chart a represents the hourly mean temperature observed at the interface between the organic and mineral horizons; Charts b and c, respectively, represent the observed hourly mean temperature at the midpoint and bottom of the rooting zone. The charts in Fig. 3 are representative of the data showing the treatment effects at all the lysimeter study sites in the region.

The temperature at the interface of the organic and mineral horizons showed distinct patterns in diurnal temperature variations. The observed patterns (Fig. 3a) also reflected the normal diurnal air temperature variations. However, the hour of day when maximum temperatures were recorded appeared to be affected by the harvesting methods used in the various treatments. In the control area, the diurnal pattern resembled that of air temperature. The temperatures in the whole-tree harvested plots were higher, reaching a maximum later in the day than those in control and CH plots. The peak temperature values observed in the WT plots were more than 5°C greater than those observed in the CH plots with slash on the ground. This is a statistically ($p = 0.05$) significant difference. Thus, the soil temperature in

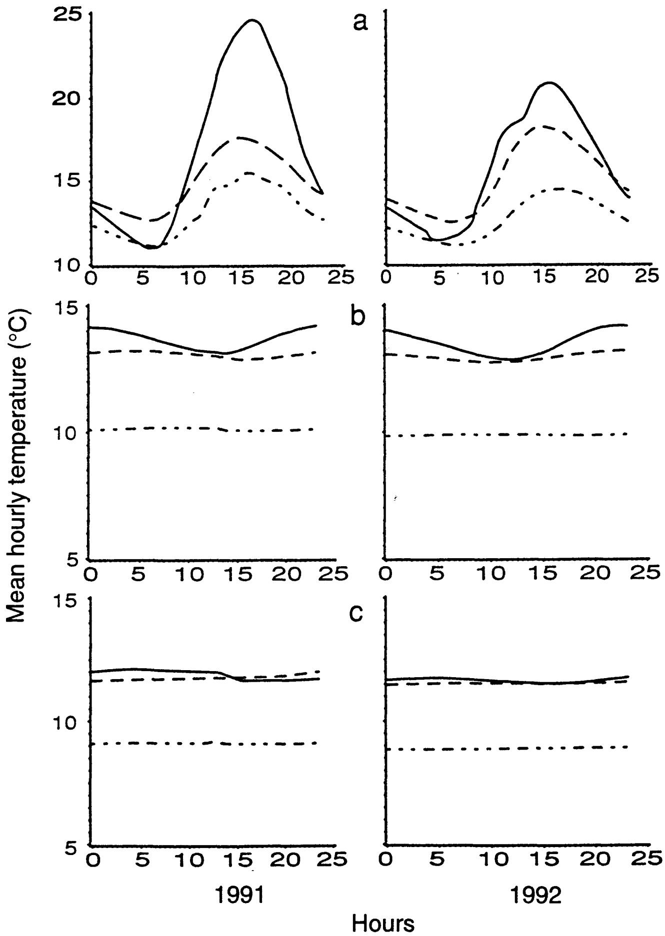

FIG. 3–Effects of harvesting methods on the hourly mean temperature recorded at Depths 1 (a), 2 (b), and 3 (c) in control (· - - -), CH (-----), and WT (——) plots in McIntyres Mountain harvested during mid-July 1991.

the WT plots stayed warmer for longer periods of time than in CH plots. During the early morning hours of May and part of June, the temperature in the WT plot appeared to be lower than that in the CH plots. During August-September, however, the soil temperature in the CH plots was warmer than in WT plots. This was due to the insulating effect of slash on the ground in the CH plots.

The normal Q_{10} value of 2 for all the biochemical reactions means that for each 10°C rise in temperature, the rate of reactions will double. The observed 5°C difference between the peak temperatures in the WT plots and CH plots suggests that the rate of organic matter decomposition in the WT plots would be 100% higher than that in the CH plots. Thus, based on a Q_{10} value of 2 for microbial processes, greater temperatures will cause greater loss of organic carbon from the soil surface. Drying of the surface layer of the organic horizon, however, can have a moderating effect on the process.

The patterns observed at the interface of organic and mineral horizons were also evident in the soil temperature measured at the midpoint and bottom of the rooting zone. The differences between the peak temperature observed in the WT and CH plots, however, are not statistically significant. Nonetheless, it is important to note that the treatment effects were discernible at the bottom of the rooting zone (about 50–60 cm below the soil surface). These differences persisted until the middle of September or until frost persisted day and night.

For statistical evaluation of treatment effects on the hourly mean temperatures, the 24-hour period was divided into four equal parts of 6 hours, such that the high and low temperature values were matched respectively. The results of the Scheffe test indicate that, for a period of 3 months starting from May, the soil temperature in the WT plots was significantly higher than in CH plots. Starting from the end of August, the differences were small and in September the peak temperature values in CH plots were warmer than those in WT plots. These patterns were more noticeable at Depth 1 (below the organic horizons) than at Depths 2 and 3.

The treatment effects on the diurnal patterns of soil temperature at each depth were noticeable four growing seasons after the harvesting treatments were implemented. It is anticipated that the temperature differences due to treatments will be detectable for another 8–12 years (until crown closure). Thus, soil temperature monitoring will be continued at each of the sites.

Daily mean temperature

Representative daily mean temperatures observed over a 3-year period at the Deersdale study site (location 2 in Fig. 1) are included in Fig. 4. As with hourly mean temperature, Fig. 4a represents the temperature recorded at the organic and mineral horizon interface. The values in Fig. 4b and 4c, respectively, represent the temperatures recorded in the middle and bottom of the rooting zone. The solid lines in each graph represent the temperature in the soils of WT plots and the broken lines and dotted lines represent the soil temperature in the CH and control plots, respectively. Discontinuity in the graphs indicates the period when the data logger failed to record the temperatures. For plotting these graphs, the temperature data were processed with 15% spline function (SAS 1989) to smooth the lines.

In general, soil temperature was higher in the WT plots than in the CH or control plots. This was true for each depth. For statistical comparison of the treatment effects, the Scheffe test was used for the data divided into 15-day intervals. For example, effect of treatments on soil temperatures in the Deersdale study site during 1990–92 for 15-day intervals starting from 15 to 30 May were compared. At the beginning of spring, the temperatures in the CH plots were significantly higher than those in either the WT or control plots. The temperatures in the WT plots were generally higher than those in the control plots. From the end of June, the temperatures in the WT plots were significantly higher than in CH plots. From the middle of August, however, soil temperature in the CH plots was higher than in WT plots. During the early spring and fall, slash left on the ground in the CH plots had an insulating effect. The biggest treatment effects, however, were observed during the period from mid-June to mid-August (day periods of 5–9) when soil temperatures in the WT plots were higher than in the CH plots. These patterns were observed at all depths, although differences due to treatment effects were smaller in the middle and bottom of the rooting zone than at the organic and mineral soil interface.

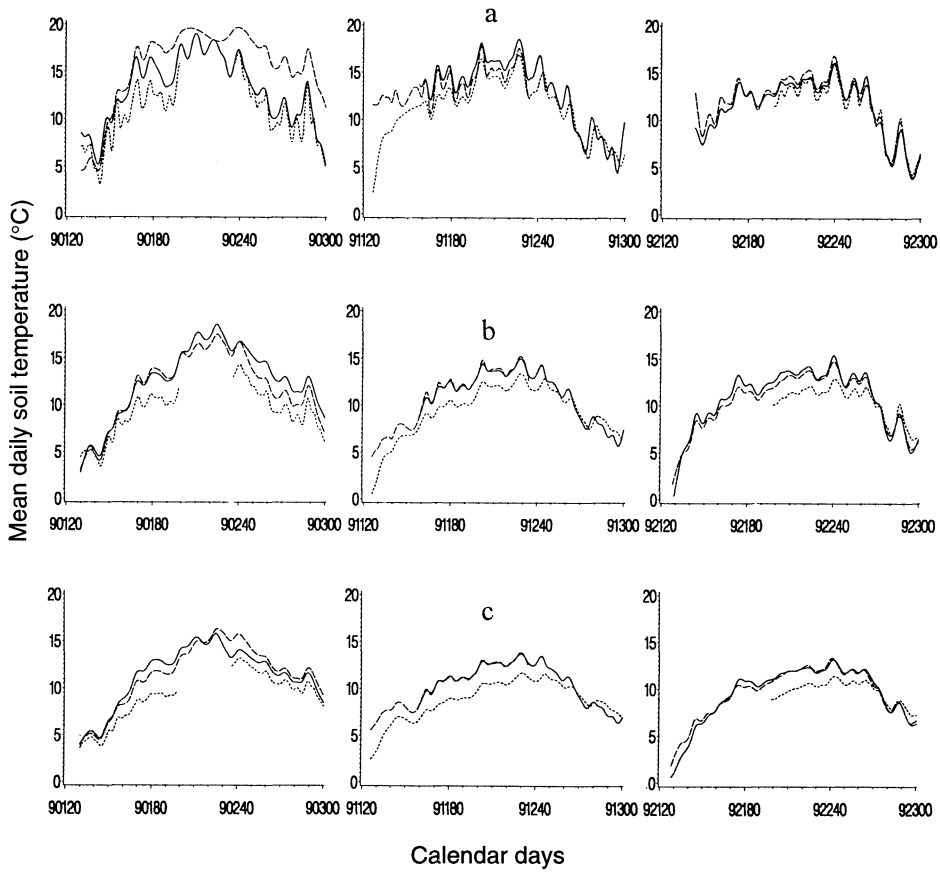

FIG. 4—Effects of harvesting methods on the daily mean temperature recorded at Depths 1 (a), 2 (b), and 3 (c) in control (·····), conventional (------), and whole-tree (——) plots in Deersdale. The first two digits of the x-axis label refer to the year, the next three to the calendar day, i.e., 1 May = 120, 1 July = 182, 1 Nov. = 305.

The daily mean temperature patterns recorded at the Deersdale study site were also observed in all the other study sites, where the stand composition varied from pure hardwood to pure softwood growing on different soil matrices. The differences in the soils or the composition of the stands in terms of dominant tree species did not affect the temperature patterns.

At each depth, the temperature peaks for the WT plots seemed to have decreased during the 3 years after the treatments were implemented. Also the differences among the peaks of WT, CH, and control plots appeared to be reduced greatly in the upper depth. It would be interesting to determine the number of years needed for the temperature in the WT and CH plots to be similar to that of the control plots. At Depths 2 and 3, however, the differences between the temperatures in WT and CH plots and the control plot were considerably less than those observed at Depth 1 (just below the organic horizon).

Heat Units

A single statistical evaluation of the treatment effects on soil temperature was not possible because of crossing over of the lines representing the observed data in the CH and WT plots. Therefore, heat units accumulated in the CH, WT, and control plots were calculated. Heat units were calculated using the formula (T-5) multiplied by the number of hours. Below 5°C, microbial activity is negligible; thus, only values above 5°C were considered treatment responses. For calculating heat units, the discontinuity of data points in the graphs again posed a problem. These heat units are analogous to the conventional degree days.

The results of Scheffe tests showing the statistically significant differences among the mean temperatures during different 15-day periods are indicated in Table 2. Only values followed by different letters are significantly different ($p = 0.05$) from one another. Table 2 contains data showing the calculated cumulative heat units for different 15-day periods. As stated above, no values were plotted for periods with missing temperatures. There was a consistent trend in the data showing larger heat units accumulated in the WT plots than in the CH plots. The heat units accumulated in the control plots were the smallest throughout. It is clear that the patterns of heat units accumulated in the organic-mineral horizon interface were similar to those in the middle and bottom of the rooting zone. This pattern was observed in the majority of the study sites with temperature recorders.

Presented in the last column of Table 2 are the sums of net cumulative heat units accumulated in each study site. There was a statistically significant difference ($p = 0.05$) between heat units accumulated in the WT plots for 1990 to 1992 and those in the CH plots at each site. The data, therefore, strongly support the hypothesis that whole-tree harvesting raises the soil temperature and probably increases the rate of soil organic matter decomposition throughout the solum (rooting zone).

Soil Solution Chemistry

The observed concentrations (mg/ℓ) of aluminium (Al) and nitrate-nitrogen ions in the leachates collected at three different depths in the Deersdale study site are presented in Fig. 5 and 6, respectively. The values represent the data collected 1, 2, and 3 years after the harvest treatments were implemented in 1989. In addition to the data for the three main treatments, data are also presented for selection cut plots (where 40% of the softwoods were removed within the strips) and the skidrows (which represent the areas used by the porters to drag the trees to the roadsides). Along the skidrows, the soil organic horizons were completely displaced and the mineral soil horizon was slightly mixed by dragging trees with branches and foliage. During each trip, the porters usually dragged between 6 and 10 trees from where they were felled to the roadside.

The concentrations of both aluminium and nitrate ions in the samples collected with lysimeters immediately below the organic horizon did not show any trend with respect to the treatment effects. This was true for each of the 3 years after the treatments. However, in the solution collected with the lysimeters located at Depths 2 and 3 of skidrows, the concentrations of both aluminium and nitrate were significantly ($p = 0.05$) higher than in other treatment blocks. The main difference between skidrows and the rest of the treatments was the absence of organic horizons and slight scarification of the mineral horizons. Thus it seems logical to hypothesise that, in the absence of protection by the organic horizon, the native organic

TABLE 2–Net cumulative heat units ((T–5) × h) as affected by harvesting methods.

Year	Treatment	Depth	Day period										Total
			3	4	5	6	7	8	9	10	11	12	
1990	CH	1	3882b	4546c	2386c		193c	5395b	4113c	3677c	3594	1062c	24 760c
	WT	1	3431b	3616b	1753b		167b	3628a	2344b	1995b	1965	88a	18 897b
	CON	1	2409a	2678a	1400a		131a	3395a	1981a	1595a	1581	40a	15 213a
	CH	2	2327b	303Bb	1472b		123b	3755b	2481b	1996b	1890	263b	17 350b
	WT	2	2265b	2882a	1445b		128b	4042b	3135c	2521c	2331	541c	19 290c
	CON	2	1602a	2009a	971a		94a	2960a	1902a	1439a	1351	124a	12 456a
	CH	3	1712b	2358b	1200b		119a	3694b	2806b	2323b	2240	680b	17 137b
	WT	3	2056b	2783c	1364b		97a	3172a	2605b	2168a	2034	555a	16 838b
	CON	3	1057a	1516a	760a		88b	2832a	2230a	1880a	1719	486a	12 572a
1991	CH	1	2562b	2834b	3390b	3917b	3891a	246a					16 843a
	WT	1	2839c	3094b	3713c	4275c	4276b	270b					18 469b
	CON	1	2059a	2429a	3061a	3616a	3655a	225a					15 048a
	CH	2	1794b	2371b	2706b	3433b	3315b	279b					13 900b
	WT	2	1730b	2333b	2679b	3369b	3272b	270b					13 667b
	CON	2	1198a	1691a	2018a	2737a	2707a	241a					10 595a
	CH	3	1409b	1989b	2299b	2995b	2917b	277b					11 884b
	WT	3	1401b	2009b	2314b	2987b	2901b	277b					11 891b
	CON	3	780a	1245a	1529a	2150c	2182a	220a					8 109a
1992	CH	1	2408a	2921a	2639a	3201b	3611b	3594b	3168a	2417a	842a	147a	24 951b
	WT	1	2280a	2917a	2705a	3126b	3547b	3538b	3122a	2268a	729a	127a	24 365b
	CON	1				2750a	3226a	3251a	2917a	2317a	812a	155a	15 431a
	CH	2	1684	2298a	2249a	2719b	3181b	3093b	2901b	2333b	1021a	307a	21 789b
	WT	2	1937	2647b	2477a	2932b	3326b	3227c	3012b	2419b	956a	261a	23 199c
	CON	2				2032a	2562a	2484a	2478a	2100a	1104a	639b	13 411a
	CH	3	1167	1803a	1891a	2269b	2779b	2714b	2661b	2202b	1193a	595a	19 283b
	WT	3	1143	1967a	2040a	2308b	2746b	2647b	2715b	2276b	1191a	557a	19 611c
	CON	3				1540a	2068a	2052a	2227a	1967a	1285a	896a	12 153a

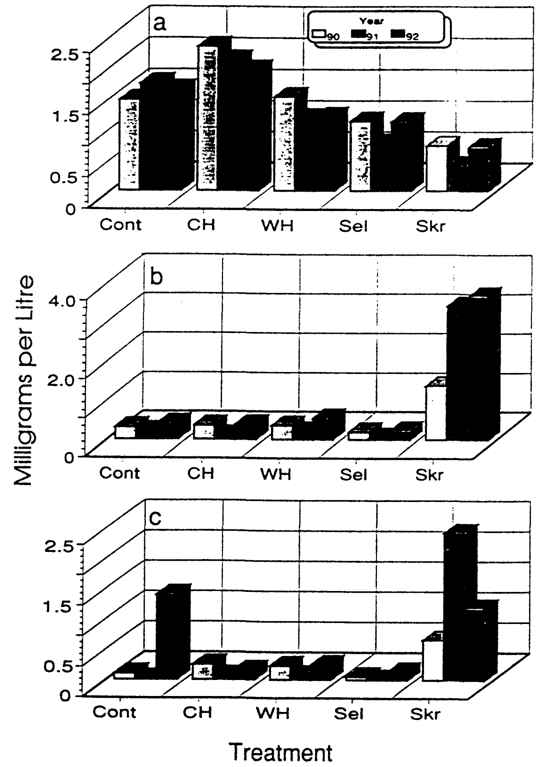

FIG. 5–Observed effects of harvesting methods on the concentrations of aluminium in the soil solutions collected with lysimeters at Depths 1 (a), 2 (b), and 3 (c).

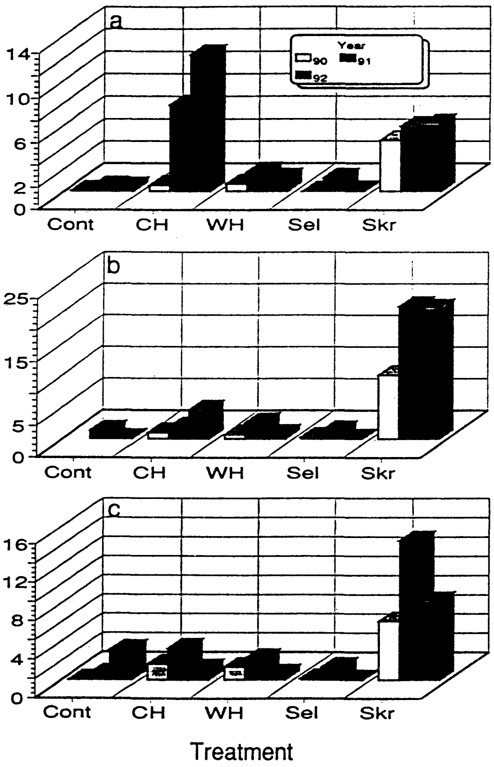

FIG. 6–Observed effects of harvesting methods on the concentrations of nitrate-nitrogen in the soil solutions collected with lysimeters at Depths 1 (a), 2 (b), and 3 (c).

matter undergoes fast decomposition and as a result produces higher nitrate and aluminium concentrations than in areas with organic horizons on the soil surface. Linear regression equations relating hydrogen ions with either nitrate or aluminum ions showed highly significant ($p = 0.001$) coefficients of determinations. The coefficients of determinations (r^2) ranged from 0.4 for the soil solutions collected at Depth 1, to 0.8 for those collected at Depth 3. Lower values of r^2 for the samples collected at Depth 1 were most probably due to the large variations in the degree of dryness reached by the organic horizons during the intervals between sample collections. Once the organic horizon reaches extreme dryness the rainwater flows through the dry organic horizons with a minimum retention time and thus less time is available for the exchange or leaching action to occur. Nonetheless, the highly significant ($p = 0.01$) positive correlation between hydrogen ion concentration and either nitrate or aluminium ions, indicates the potential for acidic leaching to increase with harvesting intensity. The results are not conclusive, however. With the aid of modelling tools, efforts are under way to interpret the observed trends for the long term.

CONCLUSIONS

The effects of different harvesting methods on soil temperature expressed in terms of hourly mean values for the growing season showed significant treatment effects. The daily mean temperatures observed during the growing season also showed treatment effects similar to those exhibited by calculated hourly means. The heat units accumulated in the whole-tree harvest plots were generally higher than in boles only (conventional) harvest plots. However, these trends did not translate into treatment effects on soil solution chemistry. The strength of the relationship (r^2) between hydrogen ions and either nitrate or aluminium levels in the soil solution increased with the depth at which the samples were collected.

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