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Possible effects of intensive harvesting on continuous productivity of forest lands

S.M. Maliondo

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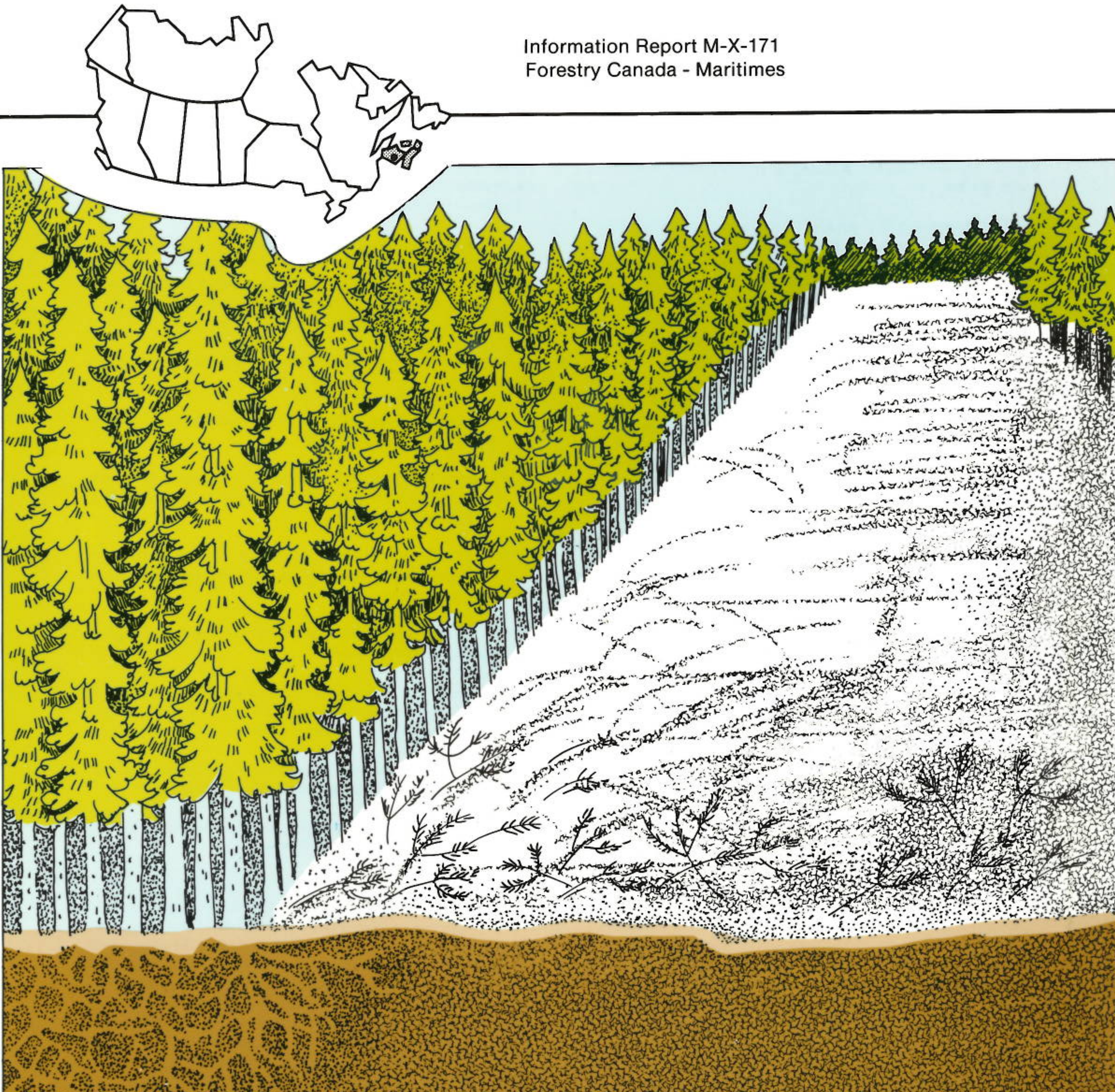
Forestry Canada - Maritimes



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POSSIBLE EFFECTS OF INTENSIVE HARVESTING ON CONTINUOUS PRODUCTIVITY OF FOREST LANDS

by

S.M. Maliondo

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ABSTRACT

Intensive (whole-tree) harvesting of natural forest stands is widespread in the Maritime provinces. In some cases, the goal of whole-tree harvesting is to increase usable biomass, but often foliage and branch components are discarded at the landing site. This report examines the possible effects of whole-tree harvesting on long-term site productivity, particularly on soil fertility. Such effects might include large losses of nutrients in harvested components, long-term decrease in soil organic matter, loss of soil nutrients, including base cations, and the potential for increased soil acidification.

The first part of this report evaluates published data collected from different parts of the world concerning potential decline in soil fertility resulting from the loss of organic matter and base cations caused by different harvesting methods. Biomass and the amount of base cations that would be removed both by conventional and whole-tree harvesting are calculated. Some published data from different stands in New Brunswick and Nova Scotia were used in the second part of this report to examine the effect of species and site quality on base cation losses and the potential increase in soil acidification which would result from whole-tree harvesting. Practising whole-tree harvesting would result in an additional gain in biomass of 55-103% and 29-74% for site classes and species comparisons, respectively. The corresponding increase in base cation losses would vary from 209-283% and 82-283% for site classes and species comparisons. The consequences of high base cation losses, especially from the infertile acid soils of this region, on long-term site productivity are discussed. The role of foliage and branch components in nutrient cycling processes in natural forest stands is stressed. It is concluded that the effects of whole-tree harvesting on site productivity will vary with species and site quality, but that long-term site studies, including nutrient cycling studies, will be needed to quantify such effects.

RÉSUMÉ

La récolte intensive (par arbres entiers) des peuplements forestiers naturels est très répandue dans les provinces Maritimes. Dans certains cas, on y a recours pour augmenter la biomasse utilisable, mais souvent le feuillage et les branches sont jetés au premier dépôt transitoire. L'auteur examine les effets possibles de cette méthode de récolte sur la productivité à long terme des sites, notamment sur la fertilité du sol. Les effets possibles comprennent une perte importante de substances nutritives par les composantes récoltées des arbres, une diminution à long terme des matières organiques du sol, une perte de substances nutritives du sol, y compris des cations de base, et la possibilité d'une acidification accrue du sol.

La première partie du rapport est consacrée à l'évaluation des données publiées dans différentes parties du monde sur la réduction potentielle de la fertilité des sols à cause de la perte de matières organiques et de cations de base résultant de différentes méthodes de récolte. La biomasse et la quantité de cations de base prélevées par la méthode classique et la méthode par arbres entiers de récolte sont calculées. Dans la deuxième partie du rapport l'auteur examine, à partir de données publiées pour différents peuplements du Nouveau-Brunswick et de la Nouvelle-Écosse, l'influence de l'essence et de la qualité de la station sur les pertes de cations de base et l'augmentation potentielle de l'acidité du sol attri buables à la méthode par arbres entiers. Il est estimé que l'augmentation associée à cette méthode serait pour la biomasse de 55 à 102% et de 29 à 74% pour les classements de stations et les comparaisons d'essences. L'augmentation correspondante des pertes de cations de base serait de 209-283% pour les classements de stations et de 82-283% pour les comparaisons d'essences. Les conséquences des pertes élevées de cations de base, particulièrement quand subies par les sols acidiques et infertiles de cette région, et leur effet sur la productivité à long terme des sites, sont discutés. Le rôle du feuillage et des branches dans les processus du cycle des éléments nutritifs dans les peuplements naturels est souligné. Il est conclu que les effets de la récolte par arbres entiers sur la productivité des sites varient selon les essences et la qualité du site, mais que des études à long terme sur les sites, y inclues les études sur le cycle des éléments nutritifs, seront nécessaires pour déterminer des telles effets.

ENFOR

ENFOR (Energy from the Forest) is a contract research and development (R&D) program managed by Forestry Canada, Government of Canada. It is aimed at generating sufficient knowledge and technology to realize a marked increase in the contribution of forest biomass to Canada's energy supply. The program was initiated in 1978 as part of a federal interdepartmental initiative to develop renewable energy sources.

The ENFOR program deals with biomass supply matters such as inventory, growth, harvesting, processing, transportation, environmental impacts, and socio-economic impacts and constraints. A technical committee oversees the program, developing priorities, assessing proposals, and making recommendations. Approved projects are generally carried out under contract.

General information on the operation of the ENFOR program, including the preparation and submission of R&D proposals, is available upon request from:

The ENFOR Secretariat
Forestry Canada
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19th Floor, Place Vincent Massey
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INTRODUCTION

Canada and many other countries have been examining the possibility of using forest biomass to supplement fossil fuel in meeting the nation's energy requirements. The ENergy from FORest (ENFOR) program was initiated to conduct research and develop techniques aimed at increasing the contribution of forest biomass in the effort to supplement nonrenewable energy resources.

One way of increasing forest yields is to adopt silvicultural techniques aimed at reducing growth constraints of an environmental (nutrients, moisture, light, temperature, air) and biological (competition) nature. However, in areas where old stands predominate, it may not be economically feasible to apply intensive silvicultural techniques on a scale that would substantially boost yields. This seems particularly relevant in the Maritime Provinces of Canada, where a large proportion of existing old forests comprise poor stands which were naturally regenerated. Under such conditions, it might be more worthwhile to increase the amount of crop recovered through intensive harvesting. The main objective of whole-tree harvesting is to increase yield from forest stands by increasing recovery of most of the above-ground tree components. In this report, intensive harvesting and whole-tree harvesting will be used interchangeably.

Two approaches to intensive harvesting are popular in North America. In the first approach, all above-ground biomass of woody plants of a given range of diameter at breast height (dbh) is harvested from the logging area and transported to the mill for further processing. This may include processing for biomass energy production (Hornbeck and Kropelin 1982).

In the second approach, all above-ground portions are harvested and then transported to a landing where stems are delimbed and those having more than a prescribed minimum top-diameter are either processed directly, or transported for further processing at the mill. The unused crown components are discarded at the landing as residue (Smith 1985). In both cases, the net result is more biomass removal from the logging area than would have been the case in conventional harvesting, where only the merchantable bole would be removed.

Although intensive harvesting provides additional biomass that would not be recovered in conventional harvesting, concerns have been expressed that this practice might result in site degradation (Weetman and Webber 1972; Wells and Jorgensen 1979). Three areas of potential decline in site productivity resulting from intensive harvesting include decreases in soil organic matter (Anderson 1986; Edwards and Ross-Todd 1983), increased removal of base cations and other nutrients in harvested crown components (Boyle *et al.* 1973), and soil acidification (Ulrich 1983). Other potential detrimental effects of whole-tree harvesting include: increased nutrient leaching, soil compaction by logging machinery, exposure of mineral soil and erosion (Martin 1986), and a shift in decomposer microbial populations (Entry *et al.* 1986).

This report has two objectives. The first is to review published information on possible effects of intensive harvesting, with regard to decline in soil fertility as a result of loss of organic matter and base cations and, also, with regard to possible acidification effects. The second objective is to use data from the Maritimes Region to examine base cation losses and potential acidification of soils caused by intensive harvesting of natural stands.

EFFECTS OF INTENSIVE HARVESTING ON SOIL FERTILITY

Loss of organic matter

The consequences on soil fertility of the loss of organic matter resulting from whole-tree harvesting must be viewed within the context of stand development. In temperate and northern forests, the process of forest floor development with increasing stand age is fairly well known (Switzer *et al.* 1966; Miller 1981). Briefly, forest floor accumulation increases rapidly in young stands within the period between canopy closure and maximum foliage accumulation and then slows down to an "apparent" steady state. At this steady state, the rate at which the forest floor passes into different cohorts, i.e., L, F, and H soil organic matter, is fairly constant for each step. Thus, the rate of litter input is assumed to balance the rate of forest floor decomposition, which in turn is assumed to be in balance with the rate of soil organic matter build-up. Any major disruption of the stand canopy, such as thinning or clear-cutting, disturbs this balance.

Changes in the forest floor and soil organic matter resulting from stand harvesting are mainly the result of increased solar radiation and moisture reaching the forest floor after canopy removal, which has the effect of accelerating the decomposition processes. In conventional harvesting, the crown components left on the logging site act as a mulch protecting the forest floor and soil organic matter from the drastic impact of canopy opening. In contrast, on intensively harvested sites, the crown components are removed, exposing the forest floor to increased water and heat input. The net effect is a higher decomposition rate of the forest floor and soil organic matter. The magnitude of this increase also depends on other factors such as litter quality, including nutrient and lignin content, pH, and the predominant decomposers.

Aside from increasing the rate of forest floor breakdown, the high biomass removal as a result of intensive harvesting also affects the organic matter status of the site by reducing the amount of logging slash added to the forest floor. Johnson *et al.* (1985) reported that 28 months after whole-tree harvesting, the hardwood forest floor amounted to 15.4 T/ha in an adjacent uncut forest site, compared to 10.4 T/ha in the clear-cut area. In Scotland, Anderson (1986) observed that, within 18 months, 15 cm of forest floor was lost under an intensively harvested plot. This was twice the amount of forest floor lost under a conventionally harvested plot.

The increased forest floor decomposition under intensively harvested stands will, in the long run, reduce the amount of soil organic matter build-up since soil organic matter decomposition will also be increased. Because organic matter, in turn, influences water and cation retention properties for a given area, both of which are important attributes of site productivity, the reduction of soil organic matter may lead to lower forest site productivity[1].

On the other hand, in certain stands, accumulation of thick forest floor has been associated with low site productivity, mainly due to slow nutrient mineralization (Chapin *et al.* 1986; Van Cleve and Harrison 1985). This is caused by the slow breakdown of the recalcitrant forest floor resulting from poor litter quality, poor drainage, or both. If logging slash is left on the logging area, as is the case in conventional harvesting, decomposition of the remaining forest floor may be accelerated. This acceleration takes place partly because fresh logging residue is rich in readily available carbon and nutrients needed by microorganisms to decompose the litter. By removing the logging residue during intensive harvesting, the period before the litter starts to breakdown may be prolonged and this may affect the rate at which the area is revegetated. Thus, in each of the above cases, the advantages to long-term site productivity of leaving the crown components on the logging area, as is done in conventional harvesting, are apparent.

Increased losses of base cations

Concurrent with organic matter changes, intensive harvesting removes more base cations from the logging site than does conventional harvesting. The crown components left on the site in conventional harvesting, upon decomposition, add bases to the site capital, thereby maintaining site productivity. In contrast, intensive harvesting deprives the site of this potential source of base cations. The magnitude of increased removal of base cations depends on stand age, species composition, and site quality as reflected by soil fertility status.

The age at which a stand is harvested affects the amount of base cations removed in two ways. First, young stands, in comparison to older stands, contain higher concentrations of base cations. Thus, with any given harvesting practice, more base cations relative to biomass will be removed from young stands than old. Second, since the crown portion in young stands comprises a larger portion of the stand biomass and base cations than in old ones, intensive harvesting will remove proportionally more base cations from young stands. Thus, for comparable sites, an adverse impact on site productivity, due to increased base losses resulting from intensive harvesting, may be expected to be more serious in young stands.

Differences between species with respect to nutrient accumulation are well known in forestry (Morrison 1974). In general, hardwood species have higher nutrient concentrations in their tissues (especially in the foliage) than do conifers and, thus, for elements like K, Ca, and Mg, higher losses from

[1]Site productivity is defined as the capacity of the land to produce primary biological products expressed as dry weight or carbon per hectare per year (Buringh 1987). In forestry, it is expressed as site quality, often measured as site index.

intensive harvesting should be expected from hardwoods than from softwoods if logging is done in summer. Exceptions to this generalization do, however, exist. For example, Perala and Alban (1982) reported above-ground Ca contents in white spruce to be much higher than in adjacent hardwood stands and almost as high as in aspen.

The effects of site quality (productivity) on increased losses due to intensive harvesting are more difficult to generalize. In simple terms, mature stands with closed canopies are presumed to meet most of their nutrient requirements from the forest floor and internal recycling (Miller 1981). Immediately after clear-cutting and before stand canopy closure, the main source of nutrients is the mineral soil and the residual forest floor from previous stands. On good sites with fertile soils, the removal of base cations with the crown components may not adversely affect potential site productivity in the short run. However, on poor sites, where the crown components may represent a large proportion of the total site nutrient capital, intensive harvesting may be more detrimental to long-term site productivity.

Other losses which are increased after intensive harvesting include base cations transported in runoff. Although erosion may also increase after conventional harvesting, the large amount of logging slash left behind reduces such losses. Intensive harvesting, by removing a large amount of logging slash, exposes the soil to higher losses of cations both in solution and in sediments from increased surface run-off. However, the extent of base cation losses from erosion depends on several factors including slope, topography, soil texture, and soil organic matter.

Potential acidification

It is essential to realize that internal soil acidification occurs in forest stands (Nilsson *et al.* 1982; Ulrich 1983; Krug and Frink 1983) in addition to that resulting from external causes such as atmospheric input. In closed forest stands, atmospheric acid input is partly neutralized by the stand canopy. Both conventional and intensive harvesting result in the opening of the canopy, allowing more acid to reach the forest floor. However, the base-rich crown components left on the site in conventional harvesting help to buffer the soil from the effects of atmospheric acid input. Intensively harvested sites lack this protection and may accordingly be more acidified. Also, the base-rich crown components left on the site during conventional harvesting add more base cations to soil capital upon decomposition. This source of base cations is reduced in intensively harvested areas. Both the reduced buffering against atmospheric acid inputs and base depletion as a result of the removal of crown components in intensive harvesting may lead to lower future site productivity.

The increased decomposition of the forest floor and soil organic matter due to intensive harvesting leads to increased production of acids. In particular, organic matter decomposition is followed by microbial oxidation of S and N compounds producing organic and inorganic acids. Soil acidification is also increased through the leaching of cations in association with NO3 and SO4 anions. Increased microbial activity by itself can cause increased acidity by the production of organic acids. High acidity will also increase the amount of labile Al and H in the plant root zone (Ulrich 1983; Fuller *et al.* 1987).

Acidification arising from stand growth (Nilsson *et al.* 1982) and atmospheric inputs is likely to be higher under conifers than under broadleaved species. Thus, evaluation of additional acidification resulting from intensive harvesting of mature stands should incorporate the differential species influences.

Increased acidity from intensive harvesting has several implications for soil fertility and, hence, for long-term site productive capacity. These implications include increased displacement of cations such as Ca, Mg, K, and NH4 from the exchange sites by H and Al cations (Nykvist and Rosen 1985). Such displaced cations will then be susceptible to leaching by percolating water. In the context of intensive harvesting, Nykvist and Rosen (1985) showed that soil base saturation was reduced by 80% on sites where slash was removed compared to those where it was left. Also, to ensure the charge neutrality requirement, the increased cations in the soil solution must be balanced by complementary anions such as sulfate, nitrate, bicarbonate, and organic anions. Thus, both cations and anions are increased in the soil solution and are more labile. The increased lability and the reduced amount of growing vegetation that would otherwise intercept the flux means that, unless the mineral soils in question have a high capacity to retain this influx (Snyder and Harter 1985), these nutrients will be lost through leaching. Increased leaching of labile and mobile nutrients such as nitrate-N and Ca beyond the rooting zone have been reported by Bormann *et al.* (1968) and Silkworth and Grigal (1982). Moreover, the increased activities of Al and H ions in the rooting zone, in addition to the low base status, may affect the regeneration and survival of some commercially important tree species (Ulrich 1983).

Methods of evaluating nutrient losses due to biomass harvesting

The subject of nutrient losses due to different harvesting methods in Canada has been addressed by many research workers (Weetman and Webber 1972; Kimmins 1977; Freedman, 1981). Recently, Kimmins *et al.* (1985) compiled an exhaustive bibliography of papers on this subject and other related topics. The general conclusions drawn from most of the cited papers are that sites differ in their susceptibility to nutrient depletion, that absolute impact can be assessed only through long-term studies, and that potential impact is site-specific as dictated by the variety of vegetation, soils, and climate considered (Silkworth and Grigal 1982).

In evaluating the impact of different harvesting methods on nutrient losses, three basic approaches as discussed by Smith *et al.* (1986) are used. The first involves static comparisons of site nutrient capital with nutrients removed through different harvesting regimes. The amount of nutrients contained in the vegetation and the amount that may be lost in a given harvesting scheme are calculated and compared with those in the forest floor and mineral soil. Estimates of the amount of nutrients held in the vegetation are obtained as a product of the biomass of components and their respective element concentrations. Tree biomass is often estimated using component biomass equations (Ker and van Raalte 1981; Ker 1984). The quantity of elements either as total or 'available' (extractable or exchangeable) may be used in estimating the forest floor and mineral soil nutrient capital (Boyle *et al.* 1973; Weetman and Webber 1972; Boyle 1976).

The second approach adds to the first one by coupling input-output estimates with the static pools. Element inputs include those in precipitation water collected both in the open and within the stand. The latter includes throughfall, stemflow, and canopy leaching. Further refinements include partitioning into dry and wet deposition, solution and solid inputs (Mahendrappa and Ogden 1973; Mahendrappa 1974). Other inputs include litterfall and fertilizer inputs. Nutrient inputs through lateral water flow from higher slopes, which may be important in certain situations, are not usually considered. However, in the long run the most important input for most nutrients apart from N is from rock and soil mineral weathering, releasing soluble nutrients into the soil. Input of N through biological fixation, both symbiotic and non-symbiotic, may also be important.

The extent to which minerals in the geologic substrate are weathered and release nutrients to counteract losses caused by harvesting, or acid deposition, is not known for many sites in North America (Johnson *et al.* 1988). Efforts to acquire or estimate weathering input data are thus warranted. Since the chemical composition of minerals in the parent material and in the mineral soil largely affects the extent to which weathering can supply base cations to replace losses (Li *et al.* 1988), there is a need to characterize the mineral composition of the geologic substrate for different sites. It is known, for example, that for primary rock minerals, the ease of weathering follows this order: Olvines > pyroxenes > amphiboles > biotites > K-feldspars > Muscovite > Quartz; and Ca - plagioclase > Na - plagioclase > K-feldspar. For secondary formed minerals, clay minerals (chlorites, vermiculites, vermiculite-chlorites, smectites and kaolinites) are richer in base cations than sesquoxides (Al and Fe oxides), zircon, garnet, tourmaline, ilmenite, and quartz. The mineral composition data of the geologic materials of each site can then be combined with hydrological data and chemical speciation models (Li *et al.* 1988) to estimate the extent of weathering inputs. Other factors affecting the rate of nutrient release by weathering include: temperature, leaching and internal soil drainage, soil pH, redox potential, biotic effects, particle size and specific surface effects, and influences of chemical kinetics, topography, and anthropogenic effects (NCASI 1988).

With respect to nutrient output, leaching and erosion losses (both in water and wind) are also considered important. The most important loss, however, appears to be through harvesting. In most stands, leaching losses may be replaced by nutrients from the atmospheric inputs and rock weathering, but this may no longer be the case following whole-tree harvesting (Hornbeck and Kropelin 1982; Mann *et al.* 1988). For example, Mann *et al.* (1988) reported that in some spruce-fir stands of Maine, hydrologic losses of Ca and K exceeded gain. Both stem-only harvesting and whole-tree harvesting increased hydrologic losses of N, P, K and Ca immediately and up to three years after harvesting. Base cation losses by leaching exceeded whole-tree harvesting exports (Johnson *et al.* 1988).

The third approach uses information synthesized from the two approaches mentioned above to develop simulation models (Aber *et al.* 1982; Kimmins and Scouller 1979, 1986) which facilitate examination of different scenarios, including various harvesting levels, to predict possible changes in site productivity. This approach is being continually refined as more empirical data becomes available. For example, FORCYTE-11 (Kimmins and Scouller 1986) may include several species and up to five nutrient elements per run.

The above schemes do not explicitly address the total effect of intensive harvesting on base losses - the kind of information needed to evaluate potential acidification effects. Ulrich (1983), Nilsson *et al.* (1982), and Richter (1986) attempted to quantify this effect by calculating cation balance obtained by subtracting total anions from total cations in tree components. A further modification was suggested by Mahendrappa (1986b), who pointed out that since N in most forest ecosystem cycles occurs mostly as NH_4+, it has to be included in calculations involving base removals due to harvesting.

Examples from literature on base cation losses due to intensive harvesting

Literature on nutrient cycling studies in forestry (Cole and Rapp 1981) is replete with information that can be used to compile the amounts of base cations that may be lost through different harvesting intensities. Table 1 was compiled from such data and contains a summary of information on gains in biomass and losses of base cations resulting from adopting intensive rather than conventional harvesting techniques. The calculated base contents include NH_4+ (Mahendrappa 1986b). The amounts of base cations that may be removed in conventional (CH) or intensive (WH) harvesting were determined, and the difference expressed as the percentage of bases removed in conventional harvesting, i.e.,

% Increase in bases (or biomass) = ([WH -CH]/CH)*100 .... (1)

The percentage increase in base cations removed can be considered an index of the effect in terms of base cation losses involved in adopting intensive rather than conventional harvesting techniques.

As expected, species exhibit large differences with respect to base cation losses as a result of intensive harvesting. There is a clear distinction between hardwoods, which have a lower range (19-217%), and conifers, which have a higher range (57-585%).

The data given in Table 1 are not sufficient to show clear trends concerning the effect of site quality on base cation losses from intensive harvesting. However, using the study of Fornes *et al.* (1970) involving stands either treated or untreated with K, a rough indication is possible. It is assumed in that case that the addition of K increased the site quality. The results are different and opposite for the two species considered. The percentage loss is lower and slightly decreased by K addition in the *Pinus resinosa* Ait. stand (155-148%) compared with 406-585% in *Picea abies* (L) Karst. Although this comparison is restricted to two species only, it indicates a possible interaction between site quality and species. Data from a wider range of site classes and more species (>2) are needed to explore this trend further.

Since increased removal of base cations due to intensive harvesting is related to increased acidification, the above data can also be viewed as a crude measure of this potential. However, there is a need for a better index of potential acidification resulting from intensive harvesting. The index should combine the increased amount of base losses in harvested trees and some other attributes of the site that are related to site acidification. A proposed index is discussed in the next section and illustrated with data from the Maritimes Region.

THE SITUATION IN THE MARITIMES REGION

Whole-tree logging is practised on large tracts of forest land in the Maritime Provinces.Interest in intensive harvesting of natural stands in this region arises from the increased demand for energy and fiber requirements from trees, and also from the cost savings attributable to increased mechanization of harvesting operations. Moreover, the poor quality of residual stands, caused by high-grading practised in the past and salvage removal of budworm-affected stands, means that logging costs can be rationalized by more intensive harvesting.

Table 1. Effect of intensive harvesting on base cation losses - a summary from literature.

Species	Location	Age yrs	Site class	Harv. meth.	Biomass T/ha	Incr. %	Bases Keq/ha	Incr. %	References	Remarks
Northern hardwoods	N. Hampshire	60		CH	42.2	43	22.64	138	Whittiker, Likens	Calc. from Cole & Rapp.
				WH	60.4		53.77			
Betula papyrifera-Acer rubrum	Maine	29		CH	70.6	13	27.77	32	Ribe, 1974	"
				WH	79.8	13	36.71			
Fagus grandifolia-Acer saccharum-Tsuga canadiensis	N. Hampshire	4		CH	4.5	20	2.07	73	Safford and Filip, 1974	"
				WH	5.4		3.57			
P. tremuloides-B. papyrifera	Wisconsin	45-50		CH	120.3	39	24.11	78	Boyle and Ek, 1974	"
				WH	166.9		42.97			
Acer rubrum	Maine	18		CH	27.8	34	13.95	85	Ribe, 1974	"
				WH	37.2		25.74			
Acer rubrum	Maine	30		CH	49.5	16	24.89	35		"
				WH	57.4		33.64			
B. papyrifera	"	39		CH	121.7	8	37.98	19		"
"				WH	131.4		45.19			
B. veruccosa	E. England	22		CH	43.1	41	11.43	217	Ovington, 1962	
"				WH	60.8		36.25			
"	C. England	24		CH	48.0	30	13.58	114	Ovington and Madgwick, 1959	
				WH	62.2		29.0			
"	C. England	55		CH	134.5	22	27.96	116		
				WH	164.0		60.41			
Fagus sylvatica	W. England	39		CH	97.9	36	17.74	102	Ovington, 1962	
				WH	133.4		35.86			
"	Germany Solling	80		CH	129.6	23	30.85	67	Cole and Rapp, 1981	
				WH	158.8		51.31			

Table 1. (Continued)

Fagus sylvatica	S. Sweden	90		CH WH	245.0 314.0	28	61.14 110.24	80	Nihligard and Lindgren, 1977	
"	"	90		CH WH	221.0 324.0	47	40.44 115.76	186	Lindgren, and Nihligard, 1972	
"	"	100		CH WH	166.0 225.0	36	35.32 77.78	120	Nihligard and Lindgren, 1977	
Plantanus occidentalis	Kentucky	3		CH WH	5.9 9.2	56	3.15 7.90	151	Wood et al., 1977	
"	"	3		CH WH	9.1 13.7	51	5.11 12.38	142	"	
Populus tremuloides	Mississippi	1	M	CH WH	0.8 2.4	200	2.42 5.42	124	Baker and Blackmon, 1977	
Populus tremuloides P. grandidentata	Minnesota "	40	M	CH WH	147.0 167.0	14	52.73 80.66	53	Perala and Alban, 1982	plot on a very fine sandy soil
Populus tremuloides	"	40	M	CH WH	124.1 153.0	23	49.7 82.92	67	"	plot on a loamy fine sandy soil
P. tremuloides	Maine	45		CH WH	52.5 58.0	10	27.36 34.92	28	Ribe, 1974	
Quercus robur- Pinus excelsor	France	115-160		CH WH	210.0 284.0	35	77.00 157.26	104	Duvigneaud, Denayer-de Smet, 1967	
Quercus petrea	S.E. England	21		CH WH	28.3 42.4	50	9.83 31.10	216	Ovington, 1962	
Q. robur	W. England	47		CH WH	106.6 138.3	30	29.09 47.66	64	"	
Eucalyptus obliqua	Australia "	70-80		CH WH	376.7 401.0	6	30.31 47.79	58	Baker and Attiwill, 1985	Plot on a clay loam soil
"	"	80-90		CH WH	218.8 255.1	7	22.76 44.92	97	"	Plot on a clay soil
Larix decidua	W. England	46		CH WH	145.8 189.4	30	13.8 42.25	206	Ovington, 1962	

Table 1. (Continued)

Picea abies	S. England	20		CH	157.2	39	40.50	139		
				WH	218.3		96.98			
"	New York	33		CH	21.7	99	5.22	406	Fornes et al., 1970	Control plot in K fertilization exper.
				WH	43.1		26.41			
"	"	33		CH	29.9	105	7.30	585	"	110 kg/ha added to a 19-yr-old stand
				WH	61.4		49.99			
Picea abies	Minnesota	40	M	CH	101.1	41	24.20	219	Perala and Alban, 1982	On a loamy fine sand soil
				WH	143.0		77.31			
"	"	40	M	CH	102.2	52	22.90	228	"	On a very fine sandy loam soil
				WH	155.0		75.13			
"	W. England	47		CH	182.4	44	23.67	273	Ovington, 1962	
				WH	262.7		88.31			
"	"	47		CH	107.9	30	15.50	166		
				WH	139.8		41.16			
"	Sweden	52		CH	105.8	25	16.30	138	Tamm and Carbonier, 1961	
				WH	132.2		38.73			
"	S.Sweden	55		CH	262.0	19	40.90	132	Nihligard, 1972	
				WH	311.0		94.70			
"	Germany Solling	87		CH	198.4	23	36.95	137	Cole and Rapp, 1981	
				WH	244.4		87.66			
"	"	115		CH	195.7	16	43.45	84	"	
"	"			WH	228.0		79.91			
Picea glauca-Abies lascorpa	B.C.	<350		CH	176.0	25	35.53	62	Kimmins and Kurmlik, 1976	
				WH	220.0		57.46			
Picea mariana	Alaska	57		CH	14.0	66	6.62	114	Van Cleve et al., 1981	On a North slope, permafrost-free site
				WH	23.2		14.17			
"	"	62		CH	8.0	91	2.48	201	"	On a Muskeg, permafrost present
				WH	15.3		7.47			
Picea mariana	Quebec	65		CH	53.9	99	9.25	225	Weetman and Webber, 1972	
				WH	107.2		30.09			
"	Alaska	51		CH	8.6	93	2.47	123	Cole and Rapp, 1981	
				WH	16.6		5.51			

Table 1. (Continued)

"	"	130		CH WH	86.1 113.2	32	30.44 53.54	76	Cole and Rapp, 1981	
Picea mariana	Quebec	200	low (III)	CH WH	60.9 89.40	47	6.57 23.05	251	Weetman and Algar, 1983	
Picea rubens-Abies balsamea	"	All aged		CH WH	82.3 132.0	60	15.12 55.25	265	Weetman and Webber, 1972	
"	Maine	Mature		CH WH	164.0 311.0	90	14.59 52.90	263	Norton and Young, 1976	
Pinus banksiana	Minnesota	40		CH WH	121.7 141.0	16	18.37 34.59	88	Perala and Alban, 1982	On a very fine sandy soil
"	"	40		CH WH	111.2 242.0	117	16.10 27.58	71	Alban, 1982	On a loamy fine sandy soil
Pinus banksiana	Ontario	48		CH WH	90.5 112.6	24	12.50 25.03	100	Foster and Morrison, 1982	
"	"	65		CH WH	90.2 113.7	26	12.48 23.03	85	Morrison, 1980	
"		53	M (II)	CH WH	33.2 57.0	72	13.60 22.70	67	Weetman and Algar, 1983	
Pinus resinosa	New York	32		CH WH	40.5 61.4	52	10.06 25.67	155	Fornes et al., 1970	Control plot in K fertilization experiment
"	"	32		CH WH	91.2 142.8	57	16.59 41.07	148	"	90 kg/ha of K applied to 20-yr-old stand
"	Wisconsin	34		CH WH	72.0 95.0	32	13.19 31.88	142	Bockheim et al ., 1983	
"	Minnesota	40		CH WH	167.0 207.1	24	26.45 50.10	89	Perala and Alban, 1982	On a very fine sandy loam
"	"	40		CH WH	141.0 167.0	18	24.30 42.38	74	"	On a loamy fine sand soil
Pinus nigra	Culbin, Scotland	18	I	CH WH	16.1 25.8	60	4.11 11.84	188	Wright and Will, 1958	

Table 1. (Continued)

"	"	28	I	CH	52.7	3	7.40	132	"
				WH	54.3		17.15		
"	"	45	I	CH	102.0	7	12.01	93	Miller et
				WH	109.0		23.19		al, 1980
"	"	48		CH	95.3	2	14.47	90	Wright and
				WH	97.0		27.53		Will, 1958
Pinus radiata	S. Australia	20		CH	211.8	24	23.18	159	Baker and
				WH	262.0		60.14		Attiwill, 1983
"	"	24		CH	234.4	19	22.02	134	"
				WH	278.0		51.47		
Pinus sylvestris	Culbin, Scotland	18		CH	35.6	54	7.19	165	Wright and
				WH	54.9		19.08		Will, 1958
"	Culbin, Scotland	28		CH	75.4	25	12.4	114	"
				WH	94.1		26.5		
"	S. Scotland	33	II	CH	118.8	26	16.75	116	"
				WH	149.8		36.11		
"	N.E. Scotland	64		CH	97.4	22	17.55	76	"
				WH	118.8		30.88		
Pinus taeda	E. Texas	16		CH	124.8	25	18.45	93	Pehl et al., 1984
				WH	156.0		35.66		
"	N. Carolina	20		CH	69.2	23	9.27	87	Tew et al., 1986
				WH	84.8		17.34		
"	E. Texas	25		CH	147.5	15	20.71	57	Pehl et al., 1984
				WH	169.3		32.48		
"	S. Carolina	64		CH	49.8	20	5.02	66	Phillips and
				WH	59.3		8.35		Van Lear, 1984
Pseudotsuga menziesii	S. Vancouver Island	15-20		CH	42.9	51	8.53	223	Webber, 1977
				WH	64.8		27.52		
"	Oregon	450		CH	472.6	12	30.85	93	Cole and
				WH	530.0		59.56		Rapp, 1981

Although whole-tree logging is widespread, the consequences of this practice on sustained productivity of forest lands are less well known. For example, little quantitative information on the effect of intensive harvesting on nutrient losses is available for the Maritime Provinces. Past research has been directed at developing biomass equations for the major forest species of the Region (Ker 1980a, b, 1984, Ker and van Raalte, 1981) to be used in biomass inventory work. This is an important exercise as it precedes and may actually simplify the nutrient inventory, especially regarding the tree components. However, there is lack of reliable nutrient concentration data to estimate nutrient contents of different stands. Such data is needed to estimate the nutrient cost incurred by adopting different harvesting techniques.

Earlier local studies, modelled according to the Hubbard Brook watershed study (Bormann *et al.* 1969), mainly considered the effect of conventional clear-cutting on stream water chemistry. The Nashwaak Watershed clear-cut experiment included nutrient cycling studies, a summary of which was given by Krause (1982).

A study specifically designed to collect data for evaluating the effects of different harvesting techniques on forest nutrient budgets in Nova Scotia was started in 1978. Based on information gathered from literature (Freedman 1981) and data from field work, Freedman *et al.* (1984) assessed the potential impact of whole-tree harvesting versus conventional harvesting on nutrient losses. Both the static and input-output approaches were used. The main conclusion was that most sites examined in that study were capable of sustaining several > 50-yr whole-tree harvesting rotations without significant losses in site productivity due to nutrient losses, apart from Ca losses which were deemed serious. Even though N, and to a lesser extent P, are known to limit forest productivity in the unmanaged stands of this region (Mahendrappa and Ogden 1973; Krause *et al.* 1978, 1982), the study concluded that, even with whole-tree harvesting, loss of these two elements would not seriously affect long-term site productivity. To resolve this apparent contradiction, further studies are warranted. Also, because the impact of harvesting on site productivity is usually site-specific, studies involving a broader range of sites differing in quality and species composition are needed.

In the last 13 years, considerable biomass and nutrient data have been gathered by Forestry Canada - Maritimes as part of a broad range of nutrient cycling studies (MacLean and Wein 1978; Mahendrappa and Kingston 1980; Mahendrappa and Salonius 1982). This information is being processed with the aim of assessing the impact on site productivity and increased potential acidification of sites due to air pollution and management practices (Mahendrappa and Kingston 1982).

In view of concern that intensive harvesting, especially on poorly buffered soils, may lead to potential acidification, there is a need to summarize available information within this framework. The summarized information can then be interpreted accordingly to guide management decision-making processes.

Scope of study

The danger of potential acidification of sites as a result of intensive harvesting is illustrated using two studies. The first study took place in New Brunswick and the other in central Nova Scotia. Both involved natural stands and are part of the ENFOR (ENergy from FORest) program aimed at assessing the impact of intensive harvesting on site productivity in the Maritimes. The effects of site quality and species on potential acidification of sites due to intensive harvesting will be examined.

MATERIAL AND METHODS

The data set from New Brunswick is part of a larger study involving a province-wide inventory of 25 forest stands of eight commercially important tree species, each species growing on three different site classes (Fig. 1). In this study, seven stands were used (Table 2), including three black spruce stands growing on good, medium, and poor site quality classes. The site classes were based on site index at age 50. These are used to assess the site quality effect on potential acidification. At the time of writing, a complete data set for the remaining four species was available only for the good sites. Together with data from the black spruce stand growing on the good site, this data set is used to assess the effect of species on potential acidification.

Data from Nova Scotia is taken from Freedman *et al.* (1984) and the characteristics of the stands are given in Table 3. Site classes were based on CLI system. In that system, SC 3, 4, 5, and 6 correspond to 8.1, 6.4, 4.5, and 2.4 m^3/ha/y, respectively. This data set is used to broaden interpretation of the species effect on potential acidification.

Table 2. Selected stand characteristics for the New Brunswick study.

Species	Site Class	Basal Area m^2/ha	Volume m^3/ha Total	Merch.	Biomass Total T/ha	Major species %
Picea mariana	Good	35	215	178	146	81
Picea mariana	Medium	40	204	126	154	99
Picea mariana	Poor	14	47	18	41	98
Pinus banksiana	Good	39	294	250	175	87
Abies balsamea	Good	38	258	227	152	76
Populus tremuloides	Good	48	398	357	230	94
Betula papyrifera	Good	23	133	85	107	70

Table 3. Selected stand characteristics for Nova Scotia stands.

Species	Age	Site class	Density stems/ha	Basal Area m^2/ha	Major species %
Picea rubens- Abies balsamea	Mature	5	2903	27.1	49.4
Picea rubens - Abies balsamea	Pole	5	2560	37.6	86.4
Picea rubens - Abies balsamea	Pole	5	2214	26.3	63.5
Picea rubens - Abies balsamea	Mature	4	1840	42.8	67.5
Picea abies - Abies balsamea	Pole	5	3900	36.3	53.4
Picea mariana	Pole	5	1710	28.4	82.7
Picea glauca	Mature	3	1535	34.8	67.5
Picea rubens - Abies balsamea	Mature	5	1865	45.4	81.1
A. saccharum	Pole	5	5180	27.4	89.9
Betula papyrifera - A. saccharum	Pole	6	3770	23.2	62.1
Populus grandidentata - P. tremuloides	Mature	6	3810	18.1	59.7
P. grandidentata - P. tremuloides	Mature	4	3655	59.7	23.8
Acer saccharum - B. papyrifera	Mature	4	2135	32.4	41.4
A. saccharum - Fagus grandifolia	Mature	3	3645	30.8	33.8
A. saccharum - A. rubrum	Pole	3	2940	31.8	45.3
A. saccharum - A. rubrum - B. lutea	Mature	4	2645	32.9	11.6

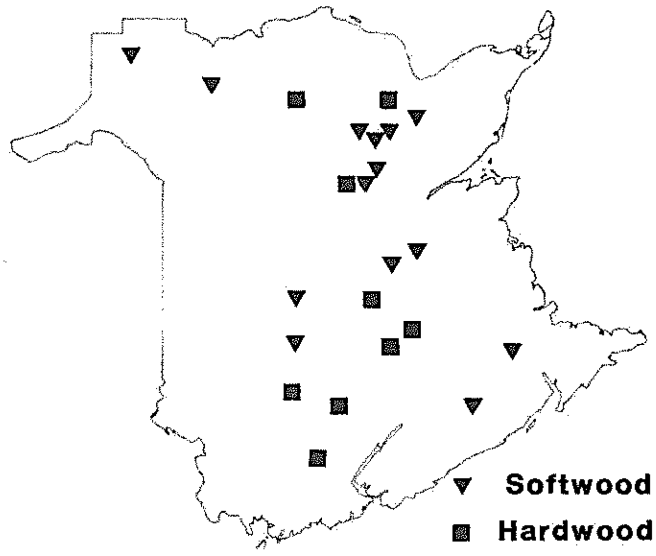

Fig. 1. Sampling Locations - New Brunswick.

In both studies, biomass and nutrient data were used to calculate the additional amounts of base cations (K, Ca, Mg, and NH_4) that can be removed through intensive harvesting compared with conventional harvesting. The amounts of bases expressed as equivalents were taken as indices of the potential to neutralize acidity generated on site or added from external sources (e.g., acid rain and dry deposition). The method of calculation is the same as that used for Table 1.

Since information on forest floor base contents was available for all the stands, the additional bases removed through whole-tree harvesting were compared with the amounts contained in the forest floor (FF). This was used as another index of potential acidification (P.A.). The ratio was calculated as follows:

P.A. = FF(B) / [WH(B)- CH(B)] .... (2)

where, FF(B), WH(B) and CH(B) are amounts of bases in the forest floor, in harvestable whole tree, and conventionally harvestable portions, respectively. The magnitude of this ratio was assumed to indicate the extent of potential acidification resulting from intensive harvesting (Mahendrappa 1986a). This ratio is considered a more suitable index than that based only on the removal of bases alone, since it incorporates the amounts of base cations held in the forest floor which are considered important in buffering against acidification.

RESULTS

Effect of site class on stand organic matter

Stand organic matter in the context of this report includes only above-ground tree biomass and the forest floor and thus excludes the stump, roots, and organic matter in the mineral soil horizons.

The distribution of stand organic matter in three black spruce stands growing on different site classes in New Brunswick varied with site quality (Fig. 2). As

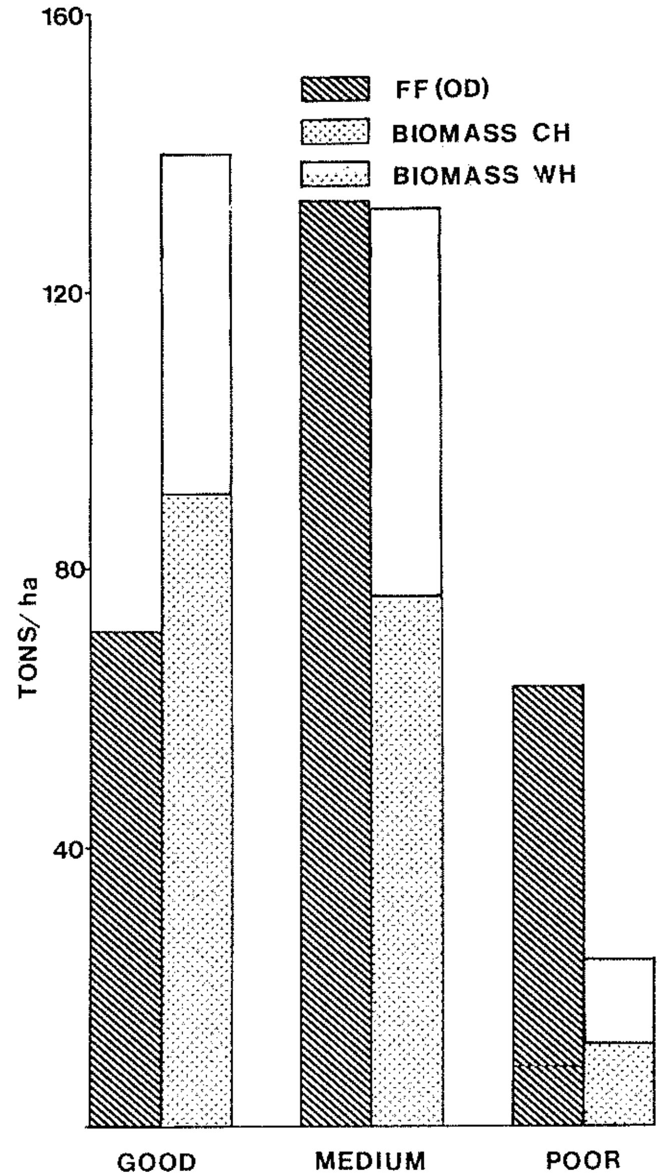

Fig. 2. Effect of site quality on FF and above-ground biomass distribution.

expected, above-ground biomass increased with site quality, but the proportional gain in biomass from intensive harvesting decreased with increasing site quality (Table 4).

The weight of the forest floor relative to above-ground tree biomass differed with site quality. On the medium site, organic matter was equally distributed between the forest floor and above-ground tree portions. The above-ground biomass was twice the weight of the forest floor on the good site, but on the poor site the forest floor weighed three times as much as the above-ground biomass. This is partly a result of poor litter decomposition on the poor site.

Effect of species on stand organic matter

Examination of the New Brunswick data shows that mature stands growing on good sites exhibited large species differences in terms of above-ground biomass (Table 4). Aspen had the highest amount of biomass and white birch the lowest. For all forest stands, the forest floor weighed less than above-ground biomass.

The proportional increase in biomass that could be removed via whole-tree harvesting was highest for white birch and lowest for jack pine (Table 4). It is interesting to note that, except for jack pine and, to a lesser extent, white birch, the absolute gains in biomass resulting from whole-tree harvesting were very similar for all other species.

For the Nova Scotia study, species comparisons were restricted first to the pole-size stands on site class 5 and second to the mature stands on site class 4. From the first comparison, species differences were marginal both in terms of above-ground biomass, forest floor weights, and gains in biomass due to intensive harvesting. In the second comparison, above-ground biomass and forest floor weights differed between species, but there were no species differences in terms of biomass increase caused by intensive harvesting.

The two studies thus indicate that the above-ground biomass was, in most cases, three times higher than the forest floor and that the gain in biomass from intensive harvesting was in most cases less than 50%.

Effect of site class on potential soil acidification

As suggested previously, increased loss of base cations due to intensive harvesting may result in a decrease in the acid neutralizing potential of a given site. The New Brunswick study shows that the amount of bases contained in the above-ground tree components was about the same for the good and medium site classes (Fig. 3). In contrast, the above-ground biomass in the poor site contained only 18% of that held in the better sites.

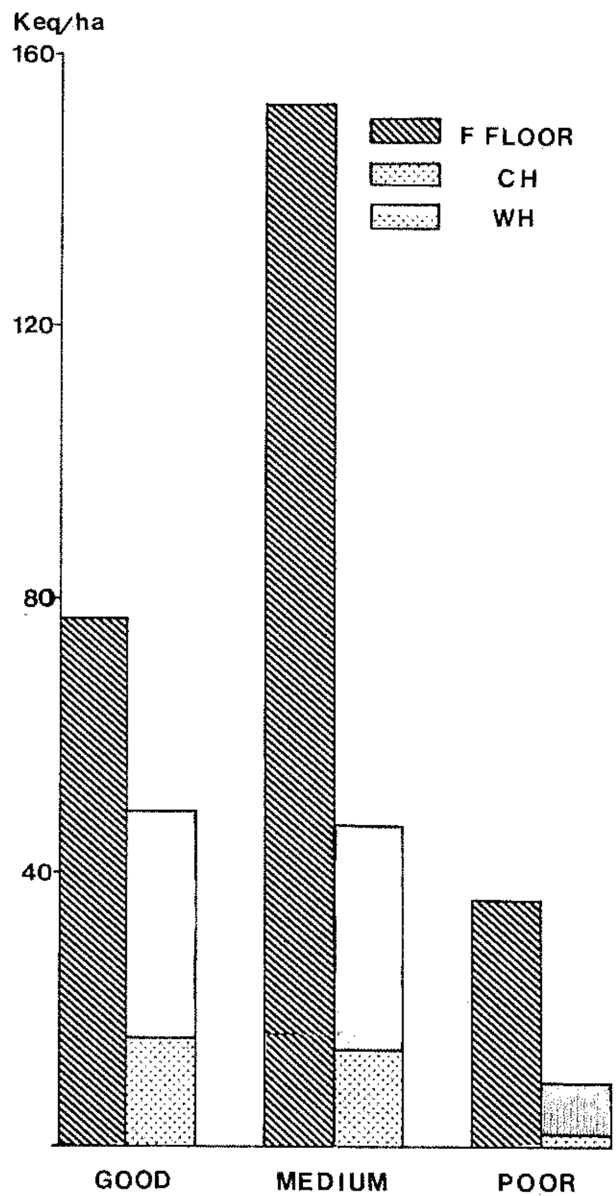

Fig. 3. Effect of site quality on FF and above-ground base contents.

Table 4. Potential acidification due to intensive harvesting - Maritimes data.

MAJOR SPECIES	SITE	AGE	SC	METH. HARV.	BIOM.	% INCR.	BASE CAT.	% INCR.	P. ACID. RATIO	SOURCE	COMMENTS
NOVA SCOTIA DATA											
Acer saccharum	C. Nova Scotia	Pole 50 yr	5	CH WH FF	87.0 138.0 31.9	59	20.09 52.60 55.6	162	1.7	Freedman et al., 1986	
Betula papyrifera - A. rubrum	"	"	6	CH WH FF	55.6 91.7 22.5	65	15.37 37.32 31.8	143	1.5		
Populus grandidentata - P. tremuloides	"	Mature 75 yr	6	CH WH FF	41.6 64.2 20.3	54	12.73 30.04 28.6	136	1.7	"	
Populus grandidentata - P. tremuloides	"	Mature	4	CH WH FF	64.9 92.4 23.0	42	19.32 40.99 41.36	112	1.9	Freedman et al., 1984a	
Acer saccharum-Acer rubrum	"	Pole	3	CH WH FF	126.0 174.0 33.0	38	28.20 59.43 Data not given	111	-	"	
Acer saccharum - Betula papyrifera	"	Mature	4	CH WH FF	120.7 165.3 49.0	37	30.24 59.71 85.52	98	2.9		
A. saccharum - Fagus grandifolia	"	Mature	3	CH WH FF	157.6 204.8 21.0	30	38.56 70.22 Data not available	82	-	"	
A. saccharum - A. rubrum - B. lutea	"	Mature 100 yr	4	CH WH FF	113.0 154.6 18.7	37	28.84 56.13 28.5	95	1.0	Freedman et al., 1986	
Picea rubens - Abies balsamea	"	Pole 50 yr	5	CH WH FF	106.7 154.6 45.2	45	20.82 50.13 48.3	141	1.7	"	
P. rubens - A. balsamea	"	Pole	5	CH WH FF	67.9 100.8 74.0	48	14.00 33.20 88.45	137	4.6	Freedman et al., 1984a	

Table 4. (Continued)

P. rubens - A. balsamea	"	Mature	5	CH WH FF	79.8 119.3 45.2	49	15.59 39.74 48.36	155	2.0	"	
P. rubens - A. balsamea	"	Mature	4	CH WH FF	189.0 243.4 83.0	29	35.21 70.66 Data not given	101	-	"	
P. rubens - A. balsamea	"	Mature	5	CH WH FF	93.1 144.1 58.0	55	19.12 49.96 Data not given	161	-	"	
Picea mariana	"	Pole 75 yr	5	CH WH FF	73.4 112.7 60.1	54	17.17 38.33 61.3	123	2.9	Freedman et al., 1986	
Picea glauca	"	Mature 50 yr	3	CH WH FF	104.1 143.0 31.6	37	18.44 42.00 42.9	128	1.8	"	
Picea rubens - Abies balsamea	"	Mature 100 yr	5	CH WH FF	167.1 223.7 93.9	34	32.21 69.76 75.7	117	2.0	"	
Picea rubens - A. balsamea	"	All-aged plot	5	CH WH FF	105.2 152.5 -	45	19.77 40.26 76.6	104	3.7	"	Whole-tree harvested plot
NEW BRUNSWICK DATA											
Picea mariana	N.B.	Mature	Good	CH WH FF	90.8 140.4 71.0	55	15.95 49.26	209	2.3	Mahendrappa et al., 1987	
"	"	"	Med.	CH WH FF	76.3 132.9 134.0	74	14.15 46.49	229	4.7	"	
"	"	"	Poor	CH WH FF	12.0 24.3 63.0	103	2.23 8.54	283	5.7	"	
Pinus banksiana	"	"	Good	CH WH FF	130.0 169.0 49.0	30	10.82 31.16	188	1.7	"	

Table 4. (Continued)

Abies balsamea	"	"	Good	CH	95.5	55	19.39	230	1.8	"
				WH	148.1		63.93			
				FF	61.0					
Populus tremuloides	"	"	Good	CH	167.0	33	49.80	121	1.2	"
				WH	222.0		110.00			
				FF	35.0					
Betula papyrifera	"	"	Good	CH	49.0	74	9.57	203	2.0	"
				WH	85.0		29.00			
				FF	37.0					

In all site classes, the forest floor had a larger amount of bases than that contained in above-ground biomass. The magnitude of this ratio increased with a decrease in site quality. A comparison of the sites with respect to the amount of bases contained in the forest floor shows that the medium site had twice the amount of bases as that in the good site, which in turn had twice as much as that in the poor site.

Figure 3 also shows that the additional loss of bases which would result from whole-tree harvesting, compared to conventional harvesting, was similar for the good and medium site classes. The poor site, which was very impoverished in base cations, had the highest potential loss of base cations that would be removed via whole-tree harvesting. The same conclusion was reached by examining the proportional increases in base cations removed by intensive harvesting compared to conventional harvesting (Table 4).

Species effects on potential acidification

Both the New Brunswick and Nova Scotia studies show that, unlike stand organic matter, the forest floor contains more bases than the above-ground biomass components (Table 4). The proportional increase in base cation losses resulting from intensive harvesting ranged from 82-283%, the lower figure being much higher than that obtained in the general literature survey (9%). There is a striking similarity between the clear-cut red spruce-balsam fir stand from Nova Scotia and the mature balsam fir stand from New Brunswick, especially in terms of stand base cation distribution and the increased base cation losses from intensive harvesting.

Results from the New Brunswick study are further summarized in Figure 3b which shows large differences between species with respect to the amount of bases contained in the above-ground tree components. The amount of bases contained in the forest floor also showed species effects.

Forest floor base content as an indicator of potential acidity

The ratios of bases in the forest floor to the additional bases removed by whole-tree harvesting over conventional harvesting are shown in Table 4. The ratios indicate that potential acidification would decrease with increasing site class for black spruce.

Based on the data of a mature red spruce-balsam fir stand from Nova Scotia, it seems that this ratio remains virtually constant for a given species growing on the same site quality, even if base distribution between the forest floor and above-ground biomass differ.

Further examination of Table 4 shows that, in general, this ratio tended to be higher for conifers than for hardwoods. The mature sugar maple stand on site class 4 (Nova Scotia) had the lowest ratio and red spruce stands, on average, had the highest ratios.

Thus, the extent of potential acidification resulting from intensive harvesting appeared to be species-dependent.

DISCUSSION

The proportional gain in biomass from intensive harvesting ranged from 55-102% and 29-74% for site classes and species comparisons, respectively. The corresponding loss in bases varied from 209-283% and 82-283% for site classes and species, respectively. Thus, for the gain in biomass recovery, a high price is paid in base losses from the site. The study by Nykvist and Rosen (1985), among others, shows the immediate danger to site fertility of practising intensive harvesting.

Most of the stands considered in this study were growing on acidic podzols. Other soil limitations which might be encountered at different sites in the region may include poor to imperfect drainage, thick organic horizons over shallow mineral soils, thin dry soils, and coarse textured dry soils. It seems likely, based on the characteristics of the soils on which these stands are located, that the soils fall within the Al buffer range (Ulrich 1986; Meiwes *et al.* 1986). Under such conditions, these stands are assumed to be mostly acidifying with a tendency to accumulate more cations than anions.

In conditions approaching steady state, part of this acidity is neutralized as a result of base leaching from the canopy, returned litter, and decomposing forest floor. Also cation exchange mechanisms within the forest floor and the top soil, and dissolution of inorganic Al compounds, contribute to acid neutralization. Since most of the bases in above-ground biomass are in tree crowns, conventional harvesting also returns most of these bases to the forest floor, thus neutralizing the acidity. Intensive harvesting removes base-rich crown components and can be considered to represent an irreversible proton addition to the soil (Ulrich 1983). This may prove serious, especially on poor acidic soils with a thick recalcitrant forest floor. On such soils, the addition of base-rich logging slash could accelerate the decomposition of recalcitrant forest floor and hence release the immobilized cations for the next crop.

As expected, this study has shown that stand base capital is higher on good sites than on poor ones. However, on the poor site, most of the site bases were in the forest floor. Based on the potential acidification ratio, site acidification resulting from intensive harvesting was higher on the poor site than on the good one. Furthermore, the potential acidification ratio tended to be higher for conifers than for hardwood stands. These results seem to suggest that potential acidification arising from intensive harvesting of the natural stands is species-dependent and, for a given species, the effect decreases with increasing site class.

Intensive harvesting, by accelerating forest floor decomposition, actually lowers the buffering capacity of the stand. Although some bases are released during the increased mineralization (Snyder and Harter 1985), more protons and organic and inorganic anions are also released, leading to further leaching and acidification. Snyder and Harter (1985) also noted that both base cations and organic matter were translocated to the mineral horizon following clear-cutting.

James and Riha (1986) reported that the organic horizons from some forest stands retained a constant proportion of H^+ (67-96%). The organic horizon had high buffer capacities which were an order of magnitude higher than those of the mineral soil horizons. These results further emphasize the importance of the organic horizons relative to the mineral soils regarding buffering against acid stresses.

Krug and Isaacson (1984) have reported that, in acid soils similar to the ones supporting the stands reported here, neutralization of excess protons occurred through replacement of bases from exchange sites and through the dissolution of organic matter and Al compounds. These processes lead to the leaching of bases and increased levels of labile Al. If these results are applied to this study, they seem to indicate that intensive harvesting of forest stands on fragile sites with poor soils (Krause *et al.* 1978) will lead to decreased acid neutralizing capacity.

It has been observed in this region that conifer and hardwood stands neutralize 20-40% and up to 80%, respectively, of the H^+ input from the atmosphere (Mahendrappa 1983). Moreover, in a recent study it was shown that the ability of the forest floor to neutralize external acid input was species-dependent (Mahendrappa 1986b) and presumably site-specific. Thus, enhanced potential acidification due to removal of bases resulting from intensive harvesting of forest stands must be viewed in the broader context of increased H^+ input from the atmosphere and other sources.

The results of this study and those of Weetman and Webber (1972), Morrison (1980) and Foster and Morrison (1982), seem to indicate that the indiscriminate practice of intensive harvesting of natural stands on poor soils could lead to site degradation resulting from increased soil acidification. The increased removal of base cations and Al mobilization may adversely affect the long-term stability and productivity of these sites. This effect will likely be particularly aggravated by increased acid input from the atmosphere.

In the present study, potential acidification effects were based on harvesting after a single rotation. It is very unlikely that in most sites, large acidification effects from intensive harvesting will be manifested after only one rotation. The effect of varying rotation lengths has also not been addressed. Furthermore, acidification resulting from intensive harvesting has to be viewed in the context of total site acidification from different sources (Van Breeman *et al.* 1984; Ulrich 1986). In order to examine single and cumulative effects of several factors and possible interactions on potential acidification, computer simulation models can play an important role (Kimmins 1985). For this reason, and as a way of synthesizing available information, we are currently compiling data to enable implementation of FORCYTE 11. However, in order to incorporate the potential acidification effects caused by intensive harvesting, a soil compartment model similar or associated with those developed to simulate the effect of atmospheric acid input (Arp 1983; Bloom and Grigal 1985; Kauppi *et al.* 1986) must be developed and incorporated into the ecosystem models.

This report has mainly stressed the effects of whole tree-harvesting on productivity at the stand level. It has emphasized changes in soil fertility (nutrients, moisture, biological, air, temperature, and mineral conditions) and the predominant role played by soil organic matter in nutrient conservation. At the regional level, however, other determinant factors of land productivity (Buringh, 1987) such as climate (van Groenewoud 1984), vegetation (Loucks 1962), time or succession (MacLean and Wein 1978), topography, major bedrock formations and lithological-mineral composition of the soil parent materials (van Groenewoud and Ruitenberg 1982), must be taken into account. Thus, decisions regarding whole-tree harvesting at a regional level in New Brunswick must be compatible with the evolving forest site classification system for New Brunswick (van Groenewoud and Ruitenberg 1982).

CONCLUSIONS

The conclusions of this study may be summarized as follows:

1. Potential acidification increases with intensive harvesting of forest biomass.
2. Poor sites are more susceptible to the acidification resulting from intensive biomass harvesting.
3. The degree of estimated acidification of sites is dependent on major tree species in a given stand.
4. There is a need to use computer simulation models to predict future trends in site productivity due to potential acidification of sites including that resulting from intensive harvesting.

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REFERENCES

Aber, J.D., Melilo, J.M., and Federer, C.A. 1982. Predicting the effects of rotation length, harvest intensity and fertilization of fiber yield from northern hardwood forests in New England. For. Sci. 28: 31-45.

Anderson, M. 1986. The impact of whole-tree harvesting in British forests. Quart. J. For. LXXIX: 33-39.

Arp, P.A. 1983. Modeling the effect of acid precipitation on soil leachates: a simple approach. Ecol. Model. 19: 105-117.

Baker, J.B., and Blackmon, B.G. 1977. Biomass and nutrient accumulation in a cottonwood plantation - the first growing season. Soil Sci. Soc. Am. J. 41: 632-636.

Baker, T.G., and Attiwill, P. 1985. Above-ground nutrient distribution and cycling in *Pinus radiata* D. Don and *Eucalyptus obliqua* L'Hariet. forests in Southeastern Australia. For. Ecol. Manage. 13: 41-52.

Bloom, P.R., and Grigal, D.F. 1985. Modeling soil response to acidic deposition in nonsulfate adsorbing soils. J. Environ. Qual. 14:489-495.

Bockheim, J.G., Lee, S.W., and Leide, J.E. 1983. Distribution and cycling of elements in a *Pinus resinosa* ecosystem, Wisconsin. Can. J. For. Res. 13: 609-619.

Bormann, F.H., Likens, G.E., Fisher, D.W., and Pierce, R.S. 1968. Nutrient losses accelerated by clear-cutting a forest ecosystem. Science 159: 882-884.

Boyle, J.R. 1976. A system for evaluating potential impacts of whole-tree harvesting on site quality. Tappi. 59: 79-81.

Boyle, J.R., and Ek, A.R. 1972. An evaluation of some effects of bole and branch pulpwood harvesting on site macronutrients. Can. J. For. Res. 2: 407-412.

Boyle, J.R., Phillips, J.J., and Ek, A.R. 1973. "Whole-tree harvesting": Nutrient budget evaluation. J. For. 71: 760-762.

Buringh, P. 1987. Bioproductivity and land potential. Pp. 27-46 *In* D.O. Hall, and R.P. Overend (eds.) Biomass: Regenerable Energy, John Wiley & Sons.

Chappin F.S. III, Vitousek, P.M., and Van Cleve, K. 1986. The nature of nutrient limitation in plant communities. Am. Nat. 127: 48-58.

Cole, D.W., and Rapp, M. 1981. Elemental cycling in forest ecosystems. Pp. 341-409 *In* D.E. Reichle (ed.) Dynamic properties of forest ecosystems. Cambridge University Press.

Duvigneaud, P., and Denaeyer-de Smet, S. 1967. Biomass, productivity, and mineral cycling in deciduous forests in Belgium. *In* Symp. on Primary Productivity and Mineral Cycling in Natural Ecosystems, E.D. Young, editor, Univ. of Maine, Orono pp. 167-186.

Edwards, N.T., and Ross-Todd, B.M. 1983. Soil carbon dynamics in a mixed deciduous forest following clearcutting with and without residual removal. Soil Sci. Soc. Am. J. 47: 1014-1021.

Entry, J.A., Stark, N.M., and Lowenstein, H. 1986. Effect of timber harvesting on microbial biomass fluxes in Northen Rocky Mountain forest. Can. J. For Res. 16: 1076-1081.

Fornes, R.H., Berglund, J.V., and Leaf, A.L. 1970. A comparison of the growth and nutrition of *Picea abies* (L) Karst. and *Pinus resinosa* Ait. on a K-deficient site subjected to K fertilization. Plant Soil 33: 345-360.

Foster, N.W., and Morrison, I.K. 1982. Nutrient cycling with respect to whole-tree harvesting in natural stands. Pp. 60-65 *In* FPRS (ed.) The sixth international FPRS industrial wood energy forum '82.

Freedman, B. 1981. Intensive forest harvest: a review of nutrient budget considerations. Can. For. Serv., Marit. For. Res. Cent., Inf. Rep. M-X-121.

Freedman, B., Prager, U., Duinker, P., Morash, R., Hanson, A.J., and Ogden, J.D. 1984. Effects of harvesting biomass for energy on nutrient status and long-term productivity of selected forest sites in Nova Scotia. Report submitted to Maritimes For. Res. Center under Contract No. OSC79-00086, ENFOR Program.

Freedman, B., Duinker, P.N., and Morash, R. 1986. Biomass and nutrients in Nova Scotian forests, and implications of intensive harvesting for future site productivity. For. Ecol. Manage. 15: 103-127.

Fuller, R.D., Driscoll, C.T., Lawrence, G.B., and Nodvin, S.C. 1987. Processes regulating sulphate flux after whole-tree harvesting. Nature 325: 707-710.

Hornbeck, J.W., and Kropelin, W. 1982. Nutrient removal and leaching from a whole-tree harvest of northern hardwoods. J. Environ. Qual. 11:309-316.

James, B.R., and Riha, S.J. 1986. pH buffering in forest soil organic horizons: Relevance to acid precipitation. J. Environ. Qual. 15: 229-234.

Johnson, J.E., Smith, D. Wm., and Burger, J. 1985. Effects on the forest floor of whole-tree harvesting in an Appalachian oak forest. Amer. Midl. Nat. 114: 51-61.

Johnson, D.W, Kelly, J.M., Swank, W.T., Cole, D.W., Van Miegroet, H., Hornbeck, J.W., Pierce, R.S., and Van Lear, D.H. 1988. The effects of leaching and whole-tree harvesting on cation budgets of several forests. J. Environ. Qual. 17: 418-424.

Kauppi, P., Kamari, J., Posch, M., Kauppi, L., and Matzner, E. 1986. Acidification of forest soils: model development and application for analyzing impacts of acid deposition in Europe. Ecol. Modell. 33: 231-253.

Ker, M.F. 1980a. Tree biomass equations for ten major species in Cumberland County, Nova Scotia. Can. For. Serv., Marit. For. Res. Cent. Inf. Rep. M-X-108.

Ker, M. F. 1980b. Tree biomass equations for seven species in southwestern New Brunswick. Can. For. Serv., Marit. For. Res. Cent., Inf. Rep. M-X-114.

Ker, M.F. 1984. Biomass equations for seven major Maritimes tree species. Can. For. Serv., Marit. For. Res. Cent., Inf. Rep. M-X-148.

Ker, M.F., and van Raalte, G.D. 1981. Tree biomass equations for *Abies balsamea* and *Picea glauca* in northwestern New Brunswick. Can. J. For. Res. 11: 13-17.

Kimmins, J.P. 1977. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. For. Ecol. Mgmt. 1: 169-183.

Kimmins, J.P. 1985. Future shock in forest yield forecasting: implications for forest management. For. Chron. 50: 27-31.

Kimmins, J.P., and Scouller, K.A. 1979. FORCYTE: a computer simulation approach to evaluating the effect of whole-tree harvesting on nutrient budget in northwest forests. Pp. 266-273 *In* Proceedings of the Forest Fertilization Conference. Union, Washington.

Kimmins, J.P., and Scouller, K.A. 1986. FORCYTE-11. A user's manual. Volume 1: introduction to the input files, programs, output files, and use of FORCYTE-11. (Second approximation.) Contract Report to Canadian Forestry Service, Ottawa.

Kimmins, J.P., Binkley, D., Chatarpaul, L., and de Cantanzaro, J. 1985. Biogeochemistry of temperate forest ecosystems: literature on inventories and dynamics of biomass and nutrients. Can. For. Serv. Inf. Rep. P1-X-47 E/F.

Krause, H.H. 1982. Effect of forest management practices on water quality - A review of Canadian studies. Pp. 15-29 *In* Associate Committee on Hydrology (ed.) Proc. Can. Hydrol. Symp. 14-15 June 1982, Fredericton, N.B.

Krause, H.H., Weetman, G.F., and Arp, P.A. 1978. Nutrient cycling in the Boreal forest ecosystem. Pp. .287-319 *In* C.T. Youngberg (ed.) Forest Soils and Land Use. Proc. Fifth North Am. For. Soils Conf., Colorado State Univ., Ft. Collins, Colorado, Aug. 1978.

Krause, H.H., Weetman, G.F. Koller, E., and Veilleux, J.M. 1982. Interprovincial forest fertilization program. Results of five-year growth measurements. Dep. Environ., Can. For. Serv., Ottawa, Ont., Inf. Rep. DCP-X12.

Krug, E.C., and Frink, C.F. 1983. Acid rain on acid soils. A new perspective. Science 221: 520-525.

Krug, E.C., and Isaacson, P.J. 1984. Comparison of water and and dilute acid treatment on organic and inorganic chemistry of leachate from organic-rich horizons of an acid forest soil. Soil Sci. 137: 370-378.

Leaf, A.L. 1979. Impact of intensive harvesting on forest nutrient cycling. Proceedings of a symposium held at the SUNY, Coll. Environ. Sci. For., Syracuse, New York.

Li, C.S., Bockheim, J.G., Leide, J.E., and Wentz, D.A. 1988. Potential for buffering of acid precipitation by mineral weathering in a forested entisol. Soil. Sci. Soc. Am. J. 52: 1148-1154.

Loucks, O.L. 1962. A forest classification for the Maritime provinces. Proc. Nova Scot. Inst. Sci. 25: 1-169.

MacLean, D.A. and Wein, R.W. 1978. Litter production and forest floor nutrient dynamics in pine and hardwood stands of New Brunswick. Holoarct. Ecol. 1:1-15.

Mahendrappa, M.K. 1974. Chemical composition of stemflow from some eastern Canadian trees. Can. J. For. Res. 4: 1-7.

Mahendrappa, M.K. 1983. Chemical characteristics of precipitation and hydrogen input in throughfall and stemflow under some eastern Canadian forest stands. Can. J. For. Res. 13: 945-948.

Mahendrappa, M.K. 1986a. Abilities of organic horizons under some eastern Canadian forest stands to alter the acidity of rain water. Can. J. For. Res. 16: 18-22.

Mahendrappa, M.K. 1986b. Potential acidification of black spruce (*Picea mariana* (Mill.) B.S.P.) sites due to intensive harvesting. Pp. 165-171 *In* IEA Workshop "Predicting the consequences of Intensive Forest Harvesting on Long-Term Productivity", May, 24-31, 1986, Jadraas, Sweden.

Mahendrappa, M.K., and Kingston, D.G.O. 1980. Nutrient cycling studies at the Acadia Forest Experiment Station: Establishment and soil characteristics. Can. For. Serv., Marit. For. Res. Cent., Inf. Rep. M-X-113.

Mahendrappa. M.K., and Kingston, D.G.O. 1982. Prediction of throughfall quantities under different forest stands. Can. J. For. Res. 12: 474-481.

Mahendrappa, M.K., and Ogden, E.D. 1973. Effects of fertilization of black spruce stands on nitrogen contents of stemflow, throughfall, and litterfall. Can. J. For. Res. 3: 54-60.

Mahendrappa, M.K., and Salonius, P.O. 1982. Nutrient dynamics and growth response in a fertilized black spruce stand. Soil Sci. Soc. Am. J. 46: 127-133.

Mann, L.K., Johnson, D.W., West, D.C., Cole, D.W., Hornbeck, J.W., Martin, C.W., Riekerk, H., Smith, C.T., Swank, W.T., Tritton, L.M, and Van Lear, D.H. 1988. Effects of whole-tree and stem-only clearcutting on postharvest hydrological losses, nutrient capital and regrowth. For. Sci. 34: 412-428.

Martin, C.W. 1986. Biomass harvesting, site disturbance, and regeneration. Pp. 39-42 *In* Proc. 1986 Symp. on the productivity of northern forests following biomass harvesting, Univ. New Hampshire, Durham, NH., C.T. Smith, C.W. Wayne, L.M. Trinton (eds.) USDA For. Serv. NE-GTR-115.

Meiwes, K.J., Khanna, P.K., and Ulrich, B. 1986. Parameters for describing soil acidification and their relevance to the stability of forest ecosystems. For. Ecol. Mgmt. 15: 161-179.

Miller, H.G. 1981. Forest fertilization: some guiding concepts. Forestry 54: 157-167.

Miller, H.G., Miller, J.D, and Cooper, J.M. 1980. Biomass and nutrient accumulation at different growth rates in thinned plantations of Corsican pine. Forestry 53: 23-39.

Morrison, I.K. 1974. Mineral nutrition of conifers with special reference to nutrient status interpretation: a review of literature. Environ. Can., Can. For. Serv. Publication No. 1342.

Morrison, I.K. 1980. Full-tree harvesting: disadvantages from a forester's viewpoint. Pulp and Paper Canada 1980: 1-4.

NCASI. 1988. Rates of nutrient release by mineral weathering. NCASI Technical Bulletin No 52.

Nihligard, B. 1972. Plant biomass, primary production and distribution of chemical elements in a beech and a planted spruce forest in south Sweden. Oikos 23: 69-81.

Nihligard, B., and Lindgren, L. 1977. Plant biomass, primary production, and bioelements of three mature beech forests in South Sweden. Oikos 28: 95-104.

Nilsson, S.I. 1983. Effects on soil chemistry as a consequence of proton input (eds.) Effect of accumulation of air pollutants in forest ecosystems. Reidel Publishing Co.; London.

Nilsson, S.I., Miller, H.G., and Miller, J.D. 1982. Forest growth as a possible cause of soil and water acidification: an examination of the concepts. Oikos 39: 40-49.

Norton, S.A., and Young, H.E. 1976. Forest biomass utilization and nutrient budgets. pp. 56-73 *In* Oslo Biomass Studies. Coll. of Life Sci. and Agric., Univ. of Maine, Orono.

Nykvist, N., and Rosen, K. 1985. Effects of clear-cutting and slash removal on the acidity of northern coniferous soils. For. Ecol. Mgmt. 11:157-170.

Ovington, J.D. 1962. Quantitative ecology and the woodland ecosystem concept. Adv. Ecol. Res. 1: 103-192.

Ovington, J.D., and Madgwick, H.A.I. 1959. Distribution of organic matter and plant nutrient contents in a plantation of Scots pine. For. Sci. 5: 344-355.

Pastor, J., and Post, W.M. 1986. Influence of climate, soil moisture and succession on forest carbon and nitrogen cycles. Biogeochem. 2: 3-27.

Pehl, C.E., Tuttle, C.L., and Houser, J.N. 1984. Total biomass and nutrients of 25-year-old loblolly pines (*Pinus taeda* L.). For. Ecol. Mgmt. 9: 155-160.

Perala, D.A., and Alban, D.H. 1982. Biomass, nutrient distribution and litterfall in *Populus, Pinus* and *Picea* stands on two different soils in Minnesota. Plant Soil 64: 177-192.

Phillips, D.R., and Van Lear, D.H. 1984. Biomass removal and nutrient drain as affected by total-tree harvest in southern pine and hardwood stands. J. For. 82: 547-550.

Ribe, J.H. 1974. A review of short rotation forestry. Misc. Rep. 160. Coll. of Life Sci. and Agric. Experim. Stat. Univ. of Maine, Orono.

Richter, D.D. 1986. Sources of acidity in some forested Udults. Soil Sci. Soc. Am. J. 50: 1584-1589.

Safford, L.O., and Fillip, S.M. 1974. Biomass and nutrient content of a 4-year-old fertilized and unfertilized northern hardwood stand. Can. J. For. Res. 4: 549-554.

Silkworth, D.R., and Grigal, D.F. 1982. Determining and evaluating nutrient losses following whole-tree harvesting of aspen. Soil Sci. Soc. Am. J. 46: 626-631.

Smith, C.T. Jr. 1985. Literature review and approaches to studying the impacts of forest harvesting and residue management practices on forest nutrient cycles. Coll. of For. Resourc. Maine Agric. Exp. Stn. Misc. Rep. 305.

Smith, C.T. Jr., McCormack, M.L., Hornbeck, J.W., and Martin, C.W. 1986. Nutrient and biomass removal from a red spruce - balsam fir whole tree harvest. Can. J. For. Res. 16: 381-388.

Snyder, K.E., and Harter, R.D. 1985. Changes in solum chemistry following clear-cutting of northern hardwood. Soil Sci. Soc. Am. J. 49: 235-238.

Switzer, G.L., Nelson, L.E., and Smith, W.H. 1966. The characterization of dry matter accumulation by loblolly pine (*Pinus taeda* L.). Soil Sci. Soc. Amer. Proc. 30: 114-119.

Tamm, C.O, and Carbonnier, C. 1961. Vaxtnaringen som skolig produktfactor. Skogs, ach Landbruks-akademiens Sammantrade tidskrift. 100: 95-124.

Tew, T.T., Morris, L.A., Allen, H.L., and Wells, C.G. 1986. Estimates of nutrient removals, displacement and loss resulting from harvest and site preparation of *Pinus taeda* plantation in the Piedmont of North Carolina. For. Ecol. Manage. 15: 257-267.

Ulrich, B. 1983. A concept of forest ecosystem stability and of acid deposition as a driving force for destabilization. Pp. 1-29 In B. Ulrich and J. Pankrath (eds.) Effects of accumulation of air pollutants in forest ecosystems. D. Reidel Publishing Co.; London.

Ulrich, B. 1986. Natural and anthropogenic components of soil acidification. Z. Pflanzenernaehr. Bodenk. 149: 702-717.

van Breeman, N., Driscoll, C.T., and Mulder, J. 1984. Acid deposition and internal proton sources. Nature 307: 599-604.

Van Cleve, K., Barney, R., and Schlentner, R. 1981. Evidence of temperature control of production and nutrient cycling in two interior Alaska black spruce ecosystems. Can. J. For. Res. 11: 258-273.

Van Cleve, K., and Harrison, A.F. 1985. Bioassay of forest floor phosphorus supply for plant growth. Can. J. For. Res. 15: 156-162.

van Groenewoud, H. 1984. The climatic regions of New Brunswick: a multivariate analysis of meteorological data. Can. For. Res. 14: 389-394.

van Groenewoud, H., and Ruitenberg, A.A. 1982. A productivity oriented forest site classification for New Brunswick. Can. For. Serv., Marit. For. Res. Cent. Inf. Rep. M-X-136.

Weetman, G.F., and Webber, B. 1972. The influence of wood harvesting on the nutrient status of two spruce stands. Can. J. For Res. 2: 351-369.

Weetman, G.F., and Algar, D. 1983. Low site class black spruce and jack pine nutrient removals after full tree and tree length logging. Can. J. For. Res. 13: 1030-1037.

Wells, C.G., and Jorgensen, J.R. 1979. Effect of intensive harvesting on nutrient supply and sustained productivity. Pp. 212-230 *In* Proc. Impact of intensive harvesting on forest nutrient cycling. SUNY Coll. Environ. Sci. and For., Syracuse, N.Y.

Whittaker, R.H., Likens, G.E., Eaton, J.J., and Siccama, T.G. 1979. The Hubbard Brook ecosystem study. Nutrient cycling and element behaviour. Ecology 60: 203-220.

Wood, B.W., Wittwer, R.F., and Carpenter, S.B. 1977. Nutrient element accumulation and distribution in an intensively cultured American Sycamore plantation. Plant Soil 48: 417-433.

Wright, T.W., and Will, G.M. 1958. The nutrient content of Scots and Corsican pines growing on sand dunes. For. 31: 13-25.