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A BRIEF REVIEW OF THE ISSUES SURROUNDING FULL TREE HARVESTING

Alan Wiensczyk

INTRODUCTION

Full tree harvesting has increased in prominence in northwestern Ontario as timber harvesting operations have converted to more mechanized, less labour intensive harvesting equipment (Timmer *et al*. 1983, Olford 1988). In Ontario, 65 percent of the annual harvest is by the full tree method (Greenwood 1988). Full tree harvesting is a technique in which the entire above-ground portion of the tree, including branches and foliage, is removed to roadside. In most full tree harvesting systems, only the bole is taken to the mill; branches and foliage are removed from the trees and left at roadside. If a chipper is used, the branches may be chipped along with the stem and then hauled to the mill. In some cases the post-chipping branch, bark and foliage debris may be returned to the site. Full tree harvesting has also been referred to in the literature as intensive harvesting, biomass harvesting and whole tree harvesting. In Ontario, whole tree harvesting refers to the harvesting of root systems and stumps in addition to the tree's above-ground components, but it is not in operational use (Greenwood 1988).

The purpose of this report is to summarize our knowledge on the potential effects of full tree harvesting on site fertility and long term site productivity.

POTENTIAL EFFECTS OF FULL TREE HARVESTING

Full tree harvesting has several operational advantages over other conventional harvest methods including a reduction in logging costs, provision of extra biomass for fibre (Maliondo *et al*. 1990), and a reduction in on-site slash. Less slash reduces site preparation costs, improves accessibility for planting (Standish *et al.* 1988) and may improve aesthetics (Wells and Jorgensen 1979). Full tree harvesting may also result in increased soil temperature and moisture availability. In northern ecosystems this may promote more rapid and greater seed germination and increased microorganism activity resulting in greater nutrient availability (D. Morris, pers. comm. 1991).

However, full tree harvesting removes substantially more nutrients from the site than tree length harvest methods due to the high concentration of nutrients in the branches and foliage (Maliondo *et al*. 1990). The possible effects of this nutrient removal include a decline in soil fertility (Wells and Jorgensen 1979, Perala and Alban 1982, Silkworth and Grigal 1982), loss of organic matter and a potential increase in site acidification (Maliondo *et al*. 1990).

The quantity and proportion of nutrients removed from the site varies with species composition, stand age and history, the inherent fertility of the site, the degree of harvest utilization, and the season of harvest (Weetman and Webber 1972, Boyle *et al*. 1973, White 1974, Freedman 1981, Silkworth and Grigal 1982).

There is little quantitative information regarding the effects of full tree harvesting on long-term site productivity (Maliondo *et al*. 1990) and the potential effects are currently subject to debate in the environmental assessment hearings in Ontario (Greenwood 1988). Kimmins (1977) listed six questions that should be considered when evaluating the consequences of timber harvesting on future site productivity.

1) What proportion of the site nutrient capital is removed in harvested materials, considering both available and total soil nutrient levels?
2) How rapidly does the remaining site nutrient capital cycle? How ‘available’ is it to plants?
3) How rapidly are the losses from either total or available soil capital replenished and by what mechanisms? Are these mechanisms affected by the harvesting treatment?
4) What is the nutrient requirement of the subsequent crop? How does nutrient demand on the soil vary during the life of the crop?
5) What is the magnitude of other harvest induced losses of nutrients?
6) How frequently will harvest induced nutrient losses occur? What is the rotation length?

These points should be kept in mind when reading through the remainder of this report.

Effect on Nutrient Levels and Nutrient Cycle

Full tree harvesting removes more nutrients from the site than does tree length harvesting. Timmer *et al*. (1983) suggest that this increase is in the range of 59 - 238 percent while Alban *et al*. (1978) propose that full tree logging puts a 2 to 11 times greater nutrient drain on the site, depending on species and nutrient. In New Brunswick, full tree harvesting increased biomass removals by 8-133 percent depending on species, removals of nitrogen (N) by 90-542 percent, phosphorus (P) by 121-830 percent, potassium (K) by 72-381 percent, calcium (Ca) by 53-307 percent and magnesium (Mg) by 51-297 percent over conventional tree length harvesting (Maliondo *et al*. 1990).

Differences in nutrient removal as compared to biomass removal are due to the elevated nutrient content of the foliage relative to the bole (Timmer *et al*. 1983). Most boreal species exhibit a large accumulation of N, P, and K in the foliage and branches, as compared to large accumulations of Ca and Mg in the bole and bark (Maliondo *et al*. 1990). Generally, the foliage contains the greatest concentration of elements followed by fine roots and twigs, branches and larger roots, and the stem (Kimmins 1977). Also, the bark generally has higher nutrient concentrations than the wood (Kimmins 1977).

The effect of the increased nutrient removals resulting from full tree harvesting on site productivity is unclear. Several authors have concluded that the removal of nutrients contained in the present crop of trees is unlikely to result in a decline in tree productivity in the next rotation. Foster and Morrison (1976) reached this conclusion for a jack pine (*Pinus banksiana* Lamb.) stand that they studied. A similar conclusion was reached by Weetman and Webber (1972) who studied two black spruce (*Picea mariana* Mill. B.S.P.) stands with average fertility. However, they did suggest that Ca may be a limiting nutrient in the next crop.

In contrast, Timmer *et al*. (1983) suggest that full tree harvesting may cause deficiencies in P, K or Ca in the next rotation on several sites in the Lake Nipigon area. However, they did not account for the input of nutrients into the system from outside sources such as precipitation and dry matter deposition. Alban *et al*. (1978) also noted that full tree harvesting drains the site of nutrients, especially Ca. Weetman and Algar (1983) reported that full tree harvesting in a dry jack pine site would result in a severe loss of potentially mineralizable N and a potential Ca deficiency. Calcium is an important nutrient as it indirectly stimulates the mineralization of N in the humus layer (Dahl *et al*. 1967). However, since most of the Ca is contained in the stems, the drain on this element may occur regardless of the harvesting method used (Morrison 1973). Morrison (1973) added that Ca deficiencies are extremely unusual in conifers.

Nitrogen deficiencies, on the other hand, often limit the productivity of many forest ecosystems (Weetman and Webber 1972, Weetman and Algar 1983, Bormann and Gordon 1989). The forest floor is a particularly important source of N and P (Weetman and Webber 1972, Gaskin et al. 1989). The availability of N is associated with the rate and type of humus decomposition (Weetman and Webber 1972). Gordon (1983) reported a long residence time (30-83 years) for N on some forested sites, and residual mineral soil N may become available at a rate of only 3-4 percent annually (Jorgensen *et al*. 1975). Canopy removal greatly accelerates the decomposition process and results in increased levels of available N and other nutrients (Weetman and Webber 1972, Gordon 1983). However, available forms of nutrients, such as nitrate ions (NO_3^-), are often more soluble in water and therefore may be more easily lost from the site through leaching (Gordon 1983).

The decomposition of logging slash is an important source of N for the next tree crop, especially on nutrient poor sites (Weetman and Webber 1972). With full tree harvesting there is often very little remaining debris (Gordon 1983), and this may lead to a N deficiency. However, the extent of any deficiency would depend on the amount of N reserves in the mineral soil. On some sites the presence of nutrient rich slash and litter left after conventional harvesting may actually reduce N availability due to the stimulation of denitrification by bacteria (Foster and Morrison 1987).

Acidification

The loss of nutrients associated with full tree harvesting may also result in site acidification (Maliondo *et al.* 1990). However, there is little experimental data to show the long-term impact of harvest practices on soil pH. One Swedish study (Nykvist and Rosen 1985) found that 1-10 year post-harvest soil pH was lower when slash was removed from the site than when slash was left on the site, even though there was an overall increase in soil pH for both sites following harvest. The long-term effect of this difference on soil pH has not been documented.

Theoretically, site acidification is thought to result from the removal of positive ions or cations (K, Ca, Mg and sodium (Na)) normally present in the branches and foliage of trees (Foster and Morrison 1987, Maliondo 1988). These cations normally buffer acid inputs from precipitation and from the decomposition of organic matter (Maliondo 1988). Organic matter decomposition releases organic and inorganic acids as well as cations and may be accelerated after full tree harvesting due to increased soil temperature and moisture availability (Maliondo 1988).

Increased site acidity can result in further displacement of K, Ca, Mg and Na ions by hydrogen and aluminum ions. The displaced cations are easily leached from the site (Maliondo 1988) resulting in a decrease in site fertility. The process of nitrification is extremely sensitive to oxygen and pH levels. Low pH reduces the rate of nitrification (D. Morris, pers comm. 1991).

Increased acidity also may increase the availability of aluminum ions (Nykvist and Rosen 1985) which, at high concentrations, are known to be phytotoxic to some plants (Brady 1984). The impact of cation removal on site acidification varies with site and species and may be greater for black and white spruce (*Picea glauca* Moench. Voss.) and balsam fir (*Abies balsamea* L.) than for other species (Maliondo *et al.* 1990).

Although full tree harvesting may potentially contribute to site acidification, Maliondo (1988) concluded that it was unlikely that the effects of acidification on site productivity would be manifested after only one rotation. Further research on the long-term effects of slash removal on soil pH is necessary to verify this conclusion.

Effect on Organic Matter

Full tree harvesting reduces the amount of logging slash and hence organic matter left on the site. This may result in decreased levels of available N (Weetman and Webber 1972), reduced supplies of carbon (C) and other nutrients needed by most microorganisms (White and Harvey 1979, Maliondo 1988), increased daily temperature fluctuations (Lundkvist 1988) and excessive drying (Foster and Morrison 1987).

The bulk of the available N for the early growth of the next tree crop probably comes from logging slash (Weetman and Webber 1972). The potential lack of slash resulting from full tree harvesting may be of critical importance on sites with low levels of available N (Weetman and Webber 1972), such as dry upland boreal sites with little organic matter, and on the generally acid soils of the Canadian Shield (Gordon 1983). The nutrients contained in coarse woody slash (eg. branches and unmerchantable stems) are generally immobilized during the early stages of decomposition (Maliondo *et al.* 1990). Microorganisms contained in logging slash and organic debris may aid in the decomposition process but may also assimilate and retain some of the nutrients released from the readily decomposable slash (Graham and Cromack 1982) reducing the potential loss of these nutrients through leaching (Maliondo *et al.* 1990).

Logging slash and soil organic matter provide the nutrients required by most microorganisms (White and Harvey 1979, Maliondo 1988). Rotting wood on the forest floor is an important microsite for N fixation (White and Harvey 1979, Freedman 1981) and is especially important in forests having relatively acidic forest floors (Freedman 1981). Full tree harvesting may result in a lack of the microsites necessary for N fixation (Freedman 1981).

Logging slash may also help to reduce the magnitude of daily temperature fluctuations on the site (Lundkvist 1988) and prevent excessive drying (Foster and Morrison 1987). The shade provided may reduce the rate of photo-oxidation (decomposition) of organic material. Logging slash acts as a mulch which may reduce the impact of canopy removal on the forest floor and soil organic matter (Maliondo 1988). Soil organic matter helps to protect the mineral soil from the impact of rainfall, reducing surface runoff and erosion (Foster and Morrison 1987).

Physical Effects

Complete canopy removal by any method of harvesting may result in increased soil temperatures, soil compaction, surface and ground water flow, and decreased forest floor biomass. However, these effects may be further increased as a result of full tree harvesting (Wells and Jorgensen 1979). Increased surface water flow increases the risk of soil erosion.

Soil temperature and moisture availability may be enhanced by full tree harvesting due to greater amounts of solar radiation and moisture reaching the forest floor (Maliondo 1988, Standish *et al.* 1988). Soil temperature and moisture influence biological activity in the soil and therefore affect nutrient release (Lundkvist 1988). Increased temperature and moisture will increase the rate of organic matter decomposition (Foster and Morrison 1976). However, the magnitude of the change depends on litter quality, including nutrient and lignin content, pH and predominant decomposers (Maliondo 1988). The decomposition of conifer litter is slow even when exposed to increased temperature and moisture (Wells and Jorgensen 1979). Denitrification may also be stimulated by increases in soil temperature and moisture (Wells and Jorgensen 1979).

The slightly elevated rates of organic matter decomposition and nitrification coupled with the increased surface and ground water flow following full tree harvesting may result in greater losses of nutrients due to leaching (Gordon 1983) and erosion (Maliondo 1988). However, the difference between full tree harvesting and tree length harvesting on these losses may be negligible when compared to the increases related to full canopy removal (R. Greenwood, pers. comm. 1991). The losses of nutrients via leaching and erosion are influenced by a number of factors such as slope, topography, soil texture and soil organic matter (Maliondo 1988). Leaching losses are generally greater on well to moderately-well drained soils but are negligible on wetter soils (Smith *et al.* 1988). Leaching and erosion losses are often greater on steep slopes than on level sites (Boyle *et al.* 1973). Losses of nutrients to leaching and erosion can be expected to be minimal on sites where revegetation is rapid (Boyle *et al.* 1973, Foster and Morrison 1976).

The potential for increased soil compaction as a result of full tree harvesting can also be expected where it requires more passes over a site than are required for conventional harvesting (Standish *et al.* 1988). The increase in soil bulk density from full tree skidding can be about twice the increase incurred from tree length skidding (Mace 1970). However, any increases in soil compaction would be dependent upon the season of harvest, the equipment type used, and the susceptibility of the soil to compaction.

Other Potential Effects

The removal of cones from the site is an additional impact of full tree harvesting. This may reduce the potential for natural regeneration. However, a study conducted in northwestern Ontario to compare the supply of jack pine cones after tree length and full tree harvesting produced variable results. On some sites full tree harvesting left more cones on-site than tree length harvesting, while on others the opposite was true. Other factors such as stand age, season of harvest, and the application of site preparation had a significant impact on the distribution of cones following harvesting (Bowling and Niznowski 1991).

FACTORS INFLUENCING THE IMPACTS OF FULL TREE HARVESTING

Nutrient losses from the site as a result of full tree harvesting and the impact of those losses on site fertility and long-term productivity are dependent on a variety of factors including site, species harvested, length of rotation, age of the stand, and season of harvest.

Site Differences

The effects of full tree harvesting on site fertility and long-term productivity depend on the difference between nutrient income and removal, quantities of available nutrients and the rate of nutrient turnover (Weetman and Webber 1972).

Nutrient inputs via precipitation and dry matter deposition will depend on the location of sites relative to industrial centres and other sources of nutrients, such as the ocean (Wells and Jorgensen 1979). Parent material of the soil will strongly influence nutrient inputs (Wells and Jorgensen 1979).

Site quality affects the relative distribution of biomass and nutrients in trees (Wells and Jorgensen 1979) and therefore affects the quantities of nutrients removed by harvesting. Black and white spruce, larch (*Larix laricina* (DuRoi) K. Koch.), trembling aspen (*Populus tremuloides* Michx.) and maple (*Acer* spp.) stands growing on good and medium sites had higher N contents than stands growing on poor sites (Maliondo *et al*. 1990). A similar relationship between tree nutrient content and site quality was also found for P, K, Ca and Mg. These relationships, however, were species-dependant. The potential for site acidification of black spruce stands could also be expected to decrease as site quality increases because of the increased buffering capacity of base-rich (Ca, Mg, P, K) mineral soils (Maliondo 1988).

Forests on deeper soils are generally less susceptible to nutrient depletion from full tree harvesting than stands on shallow soils (Timmer *et al*. 1983). This is, in part, related to the absolute soil volume differences between the two soil depths and the associated differences in aeration, water retention and movement. The nutrient loss from sites as a percentage of soil nutrient reserves for four sites in the Nipigon area are shown for both conventional tree length and full tree logging methods (Table 1). Percentages greater than 100 indicate that insufficient nutrient reserves remain on the site to support a second crop of equal size grown on similar rotation ages. However, nutrient inputs from external sources such as precipitation, dry matter deposition and weathering of parent material which might potentially offset the losses were not included in this study.

Full tree harvesting of a jack pine site in northern Ontario should not result in significant impoverishment of the site when nutrient inputs are taken into account (Foster and Morrison 1976). A similar conclusion was reached for an upland boreal spruce stand (Foster and Morrison 1987). There appeared to be sufficient reserves and replenishment following full tree harvesting to sustain the next rotation of spruce through the early growth period.

Table 1. Nutrient loss from sites as a percentage of soil nutrient reserves associated with tree length (TL) and full tree (FT) harvesting operations (adapted from Timmer *et al*. 1983).

	Balsam Fir		Hardwood		Black Spruce 'Deep'		Black Spruce 'Shallow'	
Nutrient	TL	FT	TL	FT	TL	FT	TL	FT
			- percent -					
Nitrogen	3	11	4	9	10	24	9	23
Phosphorus	1	3	49	165	31	75	22	54
Potassium	19	102	30	87	21	84	19	73
Calcium	14	50	3	6	34	68	85	359
Magnesium	8	25	4	7	7	16	17	43

The concept of recovery or replacement time is another approach to determining the impact of full tree harvesting on site nutrient status. Recovery or replacement time is defined as the number of years required for the stand to return to its pre-harvest nutrient status. This concept takes into account nutrient reserves and inputs of nutrients from various external sources (eg. precipitation, dry matter deposition, weathering of parent material) as well as other nutrient losses (eg. leaching). Gordon (1983) determined recovery times for several nutrients in a variety of stands in northwestern and central Ontario (Table 2). He concedes that these recovery times may be somewhat liberal since they were calculated at steady state input with maximum internal cycling and minimal losses (Gordon 1983).

Table 2. An estimate of the number of years required to replace, through input, nutrients lost in a single crop removal (left) and a single crop removal plus two years of leaching (right) (Gordon 1983).

	Single crop removal Total					Crop removal plus leaching Total	
	N	P	K	Ca	Mg	N	Ca
Red Spruce - fresh till	23	23	45	28	20	31	34
Black Spruce - peat	22	18	31	22	20	28	27
Black Spruce - outwash sand	24	21	42	22	22	31	27
Mixedwood - fresh till	20	16	19	17	14	28	21
Mixedwood - silt, fine sand	19	21	23	20	16	25	23

In these stands the longest recovery time was 45 years for K in a red spruce stand. The recovery time for K in a black spruce stand on an outwash sand was 42 years. A rotation length less than the recovery time could lead to a potential nutrient deficiency in subsequent rotations. For the most part however, rotation lengths in these stands would generally be longer than the recovery time and thus nutrient deficiencies would not be expected. The stands in this table were mostly Site Class 1 spruce (Plonski 1974); recovery times would be longer on lower site classes (Gordon 1983), but so would rotation ages.

Recovery times can be somewhat difficult to compute as they require a broad range of data on nutrient inputs and outputs for each site in question. Available data on nutrient inputs are still meagre (Weetman and Webber 1972). Gordon (1983) also cautioned that there are many limitations in using this method to predict minimum rotation ages.

Sites with thin, coarse-textured soils derived from oligotrophic (nutrient poor) minerals are more prone to nutrient depletion from full tree harvesting (Freedman 1990). The till soils common to the Canadian Shield are characterized by coarse and medium sands derived from granite and gneiss and have a very low base content (Weetman and Webber 1972). Losses of nutrients on these sites, particularly Ca, as a result of full tree harvesting may be more serious, especially for more demanding species such as spruce (Weetman and Webber 1972). However, Foster and Morrison (1987) note the large site-to-site variability in nutrient reserves, especially Ca which ranged from 44 kg ha^{-1} (Weetman and Webber 1972) to 2324 kg ha^{-1} (Timmer *et al.* 1983).

Most till soils, on the other hand, are mineralogically rich enough and have enough cation-exchange capacity (CEC) to support the nutrient loss associated with full-tree harvesting on a 50 year rotation (Weetman and Webber 1972). The exceptions include sites with smaller reserves of organic N in the humus layer available for mineralization such as muskeg sites (Northwestern Ontario Forest Ecosystem (NWO FEC) soil types S11, S12F, S12S & SS9; Sims *et al.* 1989) without nutrient inputs from lateral water movement or dry coarse-textured sandy sites (NWO FEC S1 & SS5) with low cation exchange capacity (Weetman and Webber 1972). Logging slash left on these sites following conventional harvesting probably represents the major source of potentially mineralizable organic N for the next crop of trees.

On poor quality sites, in which a large proportion of the nutrient capital of the site is contained in the crown components, full tree harvesting may be more detrimental to long-term productivity (White and Harvey 1979, Maliondo 1988). According to White and Harvey (1979), timber harvesting should be avoided on sites with very shallow to bedrock soils and marginal fertility. A significant proportion of the nutrients are contained in the above ground biomass and the limited productivity of the site is maintained by the nutrient cycle.

Species Differences

Tree species vary greatly with respect to growth rate, nutrient content (Freedman 1981), nutrient requirements and the distribution of nutrients among the various tree components. This, in turn, affects the quantities of nutrients removed from the site, the potential for site acidification and the impact of full tree harvesting on site productivity .

Harvest of species with higher foliar concentrations of nutrients, such as spruce and fir, will result in larger nutrient removals than harvest of species with lower foliar nutrient concentrations, such as pines (Kimmins 1977). In addition, hardwood species generally have higher nutrient concentrations in their tissues, especially foliage, than do conifers. Therefore greater losses of nutrients, such as N, K and Ca could be expected from a summer full tree harvest in a hardwood stand than summer logging of a conifer stand (Maliondo 1988). Full tree harvest of jack pine removed the smallest percentage of nutrients while full tree harvest of trembling aspen removed the largest percentage when total nutrients in the upper 36 cm of soil were compared (Alban *et al.* 1978). Losses of nutrients were also high for spruce sites (Alban *et sl,* 1978).

The percent increase in the loss of nutrients when switching from conventional harvest methods to full tree harvesting is less for species which have small crowns and foliage biomass than for species which have large crowns and foliage biomass (Kimmins 1977).

The potential for site acidification is also species dependent and may be greater for black and white spruce and balsam fir than for other species (Maliondo *et al.*. 1990). Jack pine and white birch (*Betula papyrifera* Marsh.) may also be susceptible to acidification due to base losses caused by intensive harvesting (Mahendrappa *et al.* 1986). However, the susceptiblilty is also dependent on the magnitude of the site’s base capital (Mahendrappa *et al.* 1986).

Rotation Length/Age of the Stand

Stand age strongly influences the biomass and nutrient content of forests (Freedman 1981). In general the relative losses of nutrients from full tree harvesting will be greater in young stands than in older stands (Kimmins 1977, Wells and Jorgensen 1979). Similarly, short rotations tend to remove nutrients at a faster rate than long rotations (White and Harvey 1979). Although more nutrients are removed at any one harvest with longer rotations, the loss on an annual basis is actually greater for shorter rotations (Jorgensen *et al.* 1975). For example, more nutrients would be removed on an annual basis in two - 50 year rotations of a stand than in one - 100 year rotation. In addition, longer rotations allow the site a greater recovery time than do shorter rotations.

Season of Harvest

Full tree harvesting of hardwoods after leaf fall will remove less nutrients and in different proportions than harvesting when the trees are in full leaf. Removal of N, P and K would be halved, and most of the Ca and Mg would remain on the site (Freedman 1990) owing to the nutrient resorbtion characteristics of some hardwood species (Ryan and Bormann 1982). Loss of nutrients to leaching is also affected by the season of harvest. Williams and Mace (1974) found that for summer logging of jack pine, nitrate leaching increased by four to five times over unlogged controls whereas winter logging resulted in an increase of only two times in the summer following harvest. This is a result of increased water flow and increased nitrification due to increased disturbance of the organic layer in summer logged areas.

Branch breakage is often more frequent during winter than summer harvesting. Increased branch breakage during a winter harvest would result in more of the nutrient-rich logging debris being left on the site. This may reduce the impact of full tree harvesting on the nutrient status of the site.

IMPACT REDUCTION

The impacts of full tree harvesting could be reduced by redistributing chipped, unmerchantable slash over the site, controlling inter-tree spacing and hence crown size, or by simply restricting full tree harvesting on sensitive sites.

Chipping unmerchantable slash and redistributing it over the site has been suggested as a means of reducing the impacts of full tree harvesting on site nutrient status. However, in one study, the decomposition and nutrient release in jack pine slash chips was found to be relatively slow with less than 10% of the slash chips decomposing after several growing seasons (Tappeiner 1971). On the other hand, a study by Jurgensen *et al.* (1979) found high rates of nonsymbiotic nitrogen fixation near the bottom of 7 year old chip piles on a site in Wyoming. Slash chips, because they create a high C:N ratio, may also induce a N deficiency, especially if they are incorporated into the mineral soil (White and Harvey 1979). Slash chips may also delay soil thawing in the spring and thus delay planting. This may be beneficial in reducing frost damage to buds in the years following planting (White and Harvey 1979). Slash chips may also act as an insulator in the late fall, before heavy snowfalls, to reduce the depth of frost.

The impacts of full tree harvesting on site fertility may be reduced by controlling inter-tree spacing (Alban *et al.* 1978). Since crown size can be controlled by spacing, it may be possible to reduce nutrient drain without sacrificing yields by the proper adjustment of tree spacing. This has not been confirmed.

The final and most effective means of reducing the impact of full tree harvesting on site fertility and long-term productivity may be simply to minimize the use of this harvesting strategy on sites which may be susceptible to nutrient depletion. For example, Timmer *et al.* (1983) proposed several modifications based on the results of their study in the Lake Nipigon area; namely that:

1) Conventional logging methods exclusively be utilized on fragile, shallow-till sites;

2) Full tree and complete tree chipping operations be restricted to stands supported by relatively deep mineral soils;
3) Marginal sites which are sensitive to full or complete tree logging be harvested in winter with snow present;
4) Hardwood sites be harvested by full tree methods in the dormant (leafless) season;
5) Mechanical flailing or delimbing devices be operated on sites sensitive to intensive harvesting;
6) Rapid regeneration or active regeneration be ensured after whole-tree chipping to accelerate nutrient capture and site recovery processes;
7) Intensive short-rotation forest management be restricted to deeper, more productive sites in Lake Nipigon - Beardmore area.

These recommendations are site specific to the area studied by Timmer *et al.* (1983) (eg. recommendation 4) and the extrapolation of such recommendations to other boreal sites may not be feasible. For example, hardwood stands on deep, fertile soils may not have to be harvested in the leafless season to maintain long-term site productivity in contrast to those occurring on deep fine sand.

Other sites where full tree harvesting should be used with caution include sites with steep slopes, sites with shallow soils, or soils low in biologically essential nutrients (White and Harvey 1979). The identification of potentially susceptible sites may be possible through the use of site classification systems such as the NWO FEC system (Sims *et al.* 1989). However, further study and interpretation are required.

CONCLUSIONS

Full tree harvesting removes greater quantities of nutrients from the site than conventional harvesting systems by virtue of the larger amounts of biomass (foliage, branches and bolewood) being harvested and the high concentration of nutrients in the foliage and branches relative to bolewood. The magnitude of this increase in nutrient removal is dependent upon a combination of factors, such as species being harvested, stand age and history, the inherent fertility of the site, the degree of harvest utilization, and the season of harvest.

Increased nutrient removal may cause a reduction in site fertility and a decrease in long-term site productivity. However, there is little quantitative information linking full tree harvesting to alterations in long-term site productivity. Again, the impact of nutrient removal on site fertility and long-term productivity is very site and species-dependent. Hence the application of results from one study site to another must be done with caution.

Sites sensitive to nutrient depletion as a result of full tree harvesting include those with medium to coarse-textured soils and little humus, and sites with shallow soils. Sites with soils derived from granitic parent material with a low cation exchange capacity, and organic soil sites with no lateral water movement may also be susceptible. The forest manager must consider all available harvesting options and the consequences of those options when planning silvicultural activities for these sensitive areas.

Borderline sites, such as those with fine-textured sand or loamy sand soils or shallow loamy soils, need to also be considerd in the decision framework. The forest manager should consider potential nutrient inputs to and losses from the forest ecosystem when determining the susceptibility of these sites to nutrient depletion. Sources of nutrient input include precipitation, dry matter deposition and weathering of parent material. Other losses include leaching of nutrients beyond the rooting zone and soil erosion.

Site recovery or replacement time is defined as the number of years required for the stand to return to its pre-harvest nutrient status. Recovery time may take from 15-45 years (Site Class 1 black spruce; Gordon 1983) or more. Rotation ages less than the recovery time may indicate that a potential nutrient deficiency may occur in subsequent rotations. However, rotation ages for most stands in northern Ontario (60-80 years) seem to be greater than the recovery times and hence do not appear to present a significant risk of nutrient depletion.

Further research is required in all facets of the nutrient cycling processes in forest stands, including the quantification of inputs and outputs to the system, the effects on site acidification, and the determination of recovery times for a variety of stand types and conditions.

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Northwestern Ontario Forest Technology Development Unit
Ontario Ministry of Natural Resources
R. R. #1, 25th Side Road, Thunder Bay, Ontario, Canada P7C 4T9
Phone: (807) 939-2501 Facsimile: (807) 939-1918