Effects of Logging Residue Removal on Forest Sites

A Literature Review

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1. INTRODUCTION

In recent years, there has been growing interest in the use of biomass resources as substitute feedstocks in industrial processes and for energy production from both agriculture and forest management. Promotion of biomass for energy production has been prompted by international policy initiatives intended to reduce reliance on fossil fuels and, in this country, to address Western U.S. fire problems caused by widespread fuel build-ups.

Three factors have limited the use of forest residues for energy production in North America: burning technologies; collection inefficiencies; and lack of knowledge of site impacts. The majority of commercial and industrial energy production technologies rely on consistent fuel characteristics. Fossil fuels are refined to produce consistent energy feedstocks for use with existing technologies. Biomass feedstocks are by their nature inconsistent and can impact combustion within energy plants. Technology has continued to advance to accommodate such feedstocks and is now at the point that biomass can be used solely or co-fired with fossil fuels to produce energy. While such technology has been available for some time for large industrial facilities, the most recent advances have been in technology for medium and, to a lesser extent, small production facilities which can be constructed at lower capital cost and closer to available residues. This impacts the economics of residue collection and use.

The inability to efficiently collect forest residues has been a consistent barrier to their use as biomass energy resources. Logging residue is often spread across harvest sites and the price of competing energy fuels has often made their collection uneconomical. Rising prices for petroleum, natural gas, and coal have fueled investigation into biomass resources; and like solar energy or wind power, the costs of energy generation using these alternative methods has narrowed compared to energy generated from traditional fossil fuels. In the case of forest residues, a significant advance towards resolving collection difficulties recently occurred with the development of a machine to collect and bundle such residues on-site for transport to energy production facilities. This machine was developed by Timberjack to complement their existing harvesting technology. While use of this machine is still in its infancy, the technology has the potential to revolutionize forest residue collection and use.

The amount of residue that might be readily collectable will vary by site. One wood products company in Minnesota sampled a number of sites on a variety of ownerships and found over four cords per acre of live residual material and nearly seven cords per acre of dead material that could potentially be harvested for energy production.

Assuming such recovery is economically viable, site impacts on productivity become more important. The impact of forest residue removal on site productivity and other site attributes has been a subject of research for some time. In general, this research has been conducted in response to perceived problems or opportunities.

The most extensive research on this topic has been carried out in Canada, the Nordic countries and in the Western United States. In the case of Canada, the research seems to have been prompted by that country's long-standing strength in all areas of forest research and the predominance of relatively poor soils, especially in the north, that could be most impacted by residue removal.

Research in the Nordic countries has primarily been driven by that regions relative lack of fossil fuels for energy generation. Harvest of logging residues for biomass energy production, as part of existing intensive harvest regimes, is viewed as an alternative to production from scarce fossil fuels.

In the Western United States, the vast majority of research conducted on this topic has revolved around residue reduction as a means of influencing subsequent fire regimes and forest fire risks following harvest. In the Midwest and Northeastern United States, such research seems to have been concentrated on the effects of whole-tree chipping when that harvesting method began to be widely adopted.

From this research, it is clear that there are no absolutes regarding the impact of logging residue removals on forest sites. Impacts are highly site specific and dependant on site soils, moisture regimes, forest type, season of harvest, and other factors. Typically in the Lake States, forest residues are either left on-site or burned depending on the management objective for the next stand. Exploring possible impacts of wood residue removal for energy production, as an alternative to retention or burning, is the focus of this literature review. Despite differing site characteristics throughout the region, the review is focused on ascertaining some general principles and conclusions derived from existing research which forest managers can utilize in evaluating this alternative as part of harvest prescriptions.

2. METHODS

The purpose of this study was to assess the current state of knowledge regarding the effects of logging residue removal on forest site productivity, nutrient balances, and other site characteristics following harvest. Particular focus was initially to be on forests characteristic of the Lake States region.

Initial discussions with forest ecologists and researchers, suggested a focused concentration on the Lakes States region would prove difficult since it was their belief that little research had been done in the region regarding this topic. A literature search was done which confirmed these opinions to some extent, at least regarding recent research. Given this fact, the scope of the literature search was broadened to include regions of North America and Europe with similar climates, forest types, and soils with the intent of interpreting this data in the context of Lake States forests to the degree possible.

The literature search was done via the internet and by utilizing the resources at the University of Minnesota. The resources at the University of Minnesota proved to be much more useful than those available over the internet primarily because of their more academic nature and because obtaining hard copies of the research papers was possible at minimal cost. The only inconvenience with this approach was that the person doing the literature search had to be physically present on campus due to the terms of the Universities licensing agreements with the various information resource providers.

Numerous indexes and other university sponsored databases were searched utilizing several keywords and keyword combinations. The most useful information was obtained from the following combinations: whole & tree & chipping; harvesting & wood & residue; logging & slash; and slash & removal. Identification of abstracts largely resulted from these searches with subsequent retrieval of the full articles from the universities hard copy resources. The literature cited within these articles provided another avenue for expanding the search for relevant information.

Initial searches revealed that extensive research has been done in the United States and tropical countries regarding the effects of burning logging residues on site characteristics. This, however, was not the focus of this project since it is clear that burning slash on-site would have vastly different impacts compared to completely removing the slash, particularly on nutrient levels. Consequently, much of the literature on the impacts of burning slash was ignored except where the study compared a range of residue treatments which included burning and removal.

Since whole-tree chipping involves complete removal of biomass, studies on this harvest method are included. Research regarding nutrient content of various parts of trees and individual tree species is included on the theory that management recommendations may vary by species and what parts of the logging residue are harvested for fuel. Also included are several studies that assessed the proportion of biomass and nutrients removed by bole only harvest and complete bole and slash harvest. Additional studies on the impact of slash decomposition on forest sites are also included on the theory that if the slash were removed, the affects described would not occur. Most of the studies which were reviewed, however, dealt strictly with removal of slash.

An estimated 500 or more titles and abstracts were screened for inclusion in the references section of the final report. Approximately 140 were found pertinent to the topic with hard copies of approximately 70 obtained.

3. SOIL NUTRIENTS

A majority of research on removal of logging residues has focused on impacts to site nutrient budgets. All forest management activities and natural disturbance of forest stands have impacts on site nutrient budgets. Natural aging of forest stands also impacts site nutrient budgets and nutrient cycling. Just as there is a hydrologic cycle within the atmosphere, there are nutrient cycles within forests where the concentrations and availability of nutrients vary at different stages of the cycle. Several sources conclude that destruction or removal of living biomass, including residue, will temporarily interrupt nutrient cycling until new vegetation becomes established. Regrowth of vegetation following harvesting is essential to reestablishing nutrient regimes and microclimatic conditions at the soil surface that approach those of undisturbed forest (Smith, 1985).

Mann (1988) summarized the state of research on this question up until that point in time.

> "Increasingly mechanized and intensive timber harvests have increased the potential of reduced future productivity of forest sites. In many forest stands, nutrient depletion by whole-tree harvest is of concern (Weetman and Webber 1971, Boyle and Ek 1972, White 1974, Johnson 1983), but in other stands, whole-tree harvest has little or no effect on total ecosystem nutrients (Miller et. al. 1980, Hornbeck and Kropelin 1982). Evidence of reduced growth after repeated forest rotations is limited to a few studies (Renie 1955, Stone and Will 1965, Keeves 1966, Smith et. al. 1986). The potential for yield reductions in successive crops is greater with short rotations and intensive harvests because of the removal of disproportionately larger amount of nutrients in the relatively nutrient-rich twigs, branches, and foliage (Boyle and Ek 1972, White 1984, Leaf 1979, Johnson et. al. 1982)."

The questions most often addressed in research conducted on this topic are the short-term and long-term impacts on specific nutrients and their availability for subsequent plant growth. Nutrients on forest sites exist in three forms – inorganic, organic, and ionic.

Nutrients in inorganic or mineral components of a site exist in rocks and soil particles. Nutrients in inorganic material are the least available to plants and take the longest to become available through weathering. Nutrient levels in the inorganic component of a site are also the least impacted by forest harvest activities which remove biomass.

Organic materials in forest sites originate from living plants and animals. Nutrients in this material are not readily available to plants until they are subjected to biological processes, such as decay, which converts them to ionic form for subsequent up-take by plants. As such, undecayed wood, forest litter, etc. represent a storehouse of nutrients for future plant growth several years hence.

Nutrients in ionic form support current plant growth and can be lost through leaching and run off following site disturbance. Such losses can have near-term impacts on site regeneration and revegetative success. The vast majority of studies concerning residue removal contain distinct analyzes for impacts on removal of nutrients in organic matter in the longer-term and impacts of such removal on ionic nutrient losses and availability in the shorter-term. It is important that this distinction be recognized since impacts can vary between nutrients contained in these two site components.

As illustration of the differing effects on total vs. available nutrient site capital, Hornbeck and Kropelin (1982) found that a whole-tree harvest of a northern hardwood stand (which removed 96 percent of the above ground biomass) impacted between two and three percent of the soil capital for calcium and nitrogen and approximately one percent of the total soil capital for phosphorus and potassium. In contrast, estimated removals of available nutrient capital were 30 percent for calcium and 85 percent for potassium. Other nutrients in removed material (except in leaves) are in tightly bound form and not part of the available capital. They also found that the available pool increased dramatically soon after harvest.

Freedman et. al. (1981) found high levels of removals of available nutrient capital in whole-tree harvests of balsam fir in Nova Scotia compared to conventional clearcuts. Removals from the available pools of nutrients were 500, 34, 184, 306 and 95 percent for nitrogen, phosphorus, potassium, calcium, and magnesium respectively. In contrast, removals from the total site nutrient capital were under six percent for all five nutrients studied. In a 1990 study by Hornbeck et. al., the authors concluded that only calcium would be limiting in the long-term by whole-tree harvests of northeastern spruce-fir forests. Boyle et. al. reached a similar conclusion in evaluating nutrient removals by whole-tree harvesting of a 40 year old aspen/mixed hardwood forest in Wisconsin; however, they estimated that calcium would not become limiting for 270 years at this site (nine crop rotations).

3.1 Biomass and Nutrient Concentrations in Merchantable Stems and Slash.

A pertinent question in assessing potential impacts of logging residue removal is how much of the existing on-site nutrients exist in various components of the above ground biomass. This is an important question, in management terms, in balancing residue removal with retention of enough residual material to ensure site productivity is not impacted in both the short and long term. Of the living biomass in forest stands, nutrients contained in the boles or stems of trees will take the longest to become available due to the length of time it would take them to decompose. Nutrients in branches would take a relatively shorter time to become available while those in leaves, needles, and herbaceous materials would be available most readily due to rapid decomposition. It is also significant that leaves, needles, and herbaceous materials are produced annually and, consequently, provide more frequent inputs into the nutrient cycle.

Mann et. al. (1988) compared nutrient removal by sawlog or pulpwood only harvesting and whole-tree harvesting for six hardwood and five conifer stands throughout the United States. This study estimated that merchantable stem biomass was approximately 60 percent of total tree biomass in hardwood stands and 80 percent of total tree biomass in coniferous stands. This study and an extensive review of previous studies indicated that the relationship of stem to above stump biomass was remarkably constant for both hardwoods and conifers with some interspecies variations.

In contrast, the average proportion of above stump nutrients in merchantable conifer and hardwood stems, compared to tops and foliage, varied considerably by species and stand age but was generally correlated to total above stump biomass. This suggests that as stands age and total above stump biomass increases, the proportion of nutrients contained in merchantable stems increases relative to that in tops and foliage. On average, this study found that approximately 60 percent of total above stump nutrients (nitrogen, phosphorus, potassium, and calcium) were contained in both hardwood and conifer stems and 40 percent in the tops and foliage. It should be kept in mind that this study looked at only above stump biomass and nutrient levels in trees and did not include biomass and nutrient levels in the soil or other on-site vegetation. The following table summarizes the results in this publication for the stands examined.

Above Ground Biomass (in Mg/ha and % of tree total) and Nutrients (in kg/ha and % of tree total) in the Merchantable Portion of Various Stand Types					
Site	**SAW biomass (Mg/ha) & % of total in stem**	**SAW (kg/ha) & % of total in stem**			
		N	**P**	**K**	**Ca**
Washington - High Douglas Fir	281, 88%	478, 66%	56, 58%	225, 69%	23, 6%
Maine – Red Spruce & Balsam Fir	155, 67%	141, 34%	19, 32%	121, 49%	272, 51%
Washington – Low Douglas Fir	134, 81%	161, 49%	27, 48%	81, 58%	NA
South Carolina – Loblolly Pine	85, 77%	63, 51%	6, 60%	35, 62%	71, 64%
Florida – Slash Pine	58, 55%	59, 54%	5, 50%	20, 57%	80, 58%
North Carolina – Oaks, Red Maple & Yellow Poplar	43, 24%	58, 21%	7, 17%	48, 22%	130, 24%
Tennessee – Oaks, Hickorys & Red Maple	64, 36%	110, 34%	7, 30%	36, 28%	410, 38%
Connecticut – Oaks, Hickorys, Red Maple & Sweet Birch	121, 76%	162, 59%	5, 26%	108, 67%	442, 83%
Washington – High Alder	137, 93%	287, 83%	41, 87%	151, 87%	388, 91%
Washington – Low Alder	111, 92%	311, 82%	22, 81%	122, 85%	NA
New Hampshire – Sugar Maple, Yellow Birch & Beech	48, 20%	67, 28%	4, 21%	43, 34%	129, 38%

SAW = sawlog removal with clear-cut
Mg/ha = metric tons/hectare
Kg/ha = kilograms/hectare
High = high productivity site, Low = low productivity site
NA = not available

The website of Fall Line Consulting Foresters/Timberland Managers states that their clients experience a 20-35 percent increase in biomass yield by whole-tree chipping at the landing compared to that produced by stick only harvest.

Research contained in Cramer (1974) found that the largest proportion of essential elements is contained in foliage and that "… nutrient return to the forest floor is largely through litter fall." Especially fine residues (more so if incorporated into the soil) provide soil protection, enhanced infiltration of moisture, reduced evaporation, and maintenance of vigorous soil microbial activity. Miller et. al. writing in the same publication, concluded that retention of small branches, twigs, and needles was most important in maintaining soil productivity.

A similar conclusion was reached in a publication entitled "Environmental issues during the production and handling of wood fuels" by an unknown author. That publication concluded that a major part of the nutrients are bound in the needles and bark of trees that make up a relatively small portion of the biomass with the exception of calcium. This study estimated that 80 percent of the biomass was contained in stems, 30 percent of the nitrogen, 25 percent of the phosphorous, 41 percent of the potassium, and 50 percent of the calcium. More nitrogen and phosphorus are contained in the needles (40 and 45 percent respectively) than either branches or stems (Unknown). These results were from experiments undertaken in Sweden, Finland, and Norway and included 16 locations of Scotch pine and Norway spruce. Four years after whole-tree harvests, growth rates slowed as a result of nitrogen deficiency. The supply of nutrients derived from weathering and deposition (such as calcium, phosphorus, potassium, etc.) was apparently sufficient to compensate for loss from whole-tree harvesting. The study concluded that: "It is only on nutrient poor localities that loss of nutrients may cause concern. Clear-cutting cleaning by chipping of logging residues often substitutes a normal cleaning by burning the logging waste."

Wells and Jorgensen (1975) found that the stems of 16 year old loblolly pine contained 80 percent of the above ground biomass, 45 percent of the nitrogen, 48 percent of the phosphorus, and 54 percent of the magnesium. These results are consistent with studies done in the Northeast for other species (Hornbeck and Kropelin, 1982; White, 1974; and Freedman et.al., 1981).

Morrison and Foster (1979) indicated the following nutrient quantities contained in various parts of trembling aspen in Minnesota.

Distribution of Biomass and Elements (kg/ha) Among Tree Components of Trembling Aspen.

		Total Content						
	Age	**Component**	**Biomass**	**Nitrogen**	**Phosphorus**	**Potassium**	**Calcium**	**Magnesium**
Trembling Aspen	40	Foliage	3,600	87	9	47	37	6
		Branches	16,600	82	11	42	215	12
		Wood	119,000	84	10	112	171	19
		Bark	27,600	115	16	86	435	20
		Roots	3,800	89	20	80	216	18

Johnson et. al. (1982) found that:

> "Whole tree harvesting increased the export of biomass, nitrogen phosphorus potassium, and calcium by 2.6, 2.9, 3.1, 3.3, and 2.6 times, respectively, compared to sawlog harvesting in an upland mixed oak forest in eastern Tennessee. Whole tree harvesting after leaf fall reduced the potential drains of nitrogen, phosphorus, potassium, and calcium by 7, 7, 23, and 5 percent, respectively, compared with potential removal by harvesting during the growing season."

Smith et. al. (1986) in studying whole-tree harvesting in balsam fir found that such harvest:

> "… removed 90 percent of the biomass; 91 percent of the nitrogen, phosphorus, potassium, and calcium; and 90 percent of the magnesium in the above stump portions of the forest. These removals were from two to four times the amount of nutrients that would have been removed by bole-only harvest, while increasing biomass removals by 1.4 times. The nutrients removed by the harvest were between 0.1 and 5 percent of the total soil reserves."

Little and Klock (1985) also documented minimal loss of one percent of total site nitrogen by complete harvest of all above ground biomass.

Boyle and Ek (1971) found that minimum soil reserves of nitrogen, phosphorous, and magnesium were 5-15 times greater than the amounts removed by a whole-tree harvest of a mixed hardwoods site in Wisconsin at the end of a 45-year rotation. Total reserves of potassium and calcium were more limited, only 1-3 times greater than harvest removals.

Suadicani and Gamborg (1999) suggest that allowing slash to dry over a summer season before it is chipped reduces the loss of nutrients, since leaves and needles remain, while improving the fuel quality of the chipped material.

Winter only harvesting in hardwoods and/or a delay in slash collection to allow the needles and leaves to dry are two management alternatives if site nutrient budgets are of concern. This and other research suggests that alterations in harvest that retain foliage and twigs on-site may be a way to lessen the impact of bole and biomass removals from a site. Some level of incorporation and mixing of remaining leaves/needles and small twigs into the upper soil horizons may also be beneficial in addressing possible short-term deficiencies in available nutrients.

3.2 Species and Site Influences on Nutrient Levels.

Morrison and Foster (1979) illustrated the interspecies differences in nutrient content for 18 different forest types as identified in the literature. This information is for total stand biomass and will vary based on stocking and age. The following table summarizes that information for species common to the Lake States in well stocked stands on average to good sites.

Some Estimates of Biomass (t/ha) and Element Content (kg/ha) for Various Forest Stands of Medium Age on Average to Good Sites

		Total Content					
Species	**Age**	**Biomass**	**Nitrogen**	**Phosphorus**	**Potassium**	**Calcium**	**Magnesium**
Jack Pine	40	175,300	296	30	119	241	46
Jack Pine	45	124,482	182	22	140	150	26
Red Pine	32	142,777	307	33	83	295	28
Red Pine	40	243,400	421	50	205	335	72
Norway Spruce	33	61,411	399	59	44	376	19
Norway Spruce	55	367,000	770	87	437	459	69
Aspen	40	204,800	457	66	367	1074	76
Aspen	45	166,945	207	21	107	441	43
Oak/Beech	70-75	156,000	533	44	342	1,248	102
Oak/Hickory	uneven	156,000	470	--	340	980	--
Oak/Hickory/Maple	uneven	190,000	995	--	400	830	--
Oak	<80	232,468	1,157	101	1258	4,549	311
Maple/Birch	55	161,070	532	87	218	484	49

Kimmins (1977) contains similar information for tree species of different ages and estimates of the annual turnover of nutrients in tree foliage and minor vegetation for two forest types in British Columbia. Alban (1979) also contains a review of information documenting nutrient content differences by species. He takes the analysis one step further, however, by including information for different species on adjacent identical sites. This eliminates differences due to site characteristics and age.

Above Ground Biomass (t/ha) and Nutrients (kg/ha) in 40 Year Old Adjacent Stands by Species in Minnesota.

	Biomass	**Nitrogen**	**Phosphorus**	**Potassium**	**Calcium**	**Magnesium**
Trembling Aspen	167	368	46	287	858	58
White Spruce	151	382	57	229	719	40
Red pine	199	346	42	175	291	58
Jack Pine	147	259	25	97	199	38

He also studied the nutrient content of jack pine on sites with different site indices and found that nutrient content was not correlated with site quality. This suggests that removal of biomass which creates a nutrient deficiency might differentially impact different tree species in the subsequent rotation. Deficiencies in calcium, for example, would more negatively impact aspen and spruce regrowth because of their higher uptake of these nutrients compared to red or jack pine.

Harvest of different species will also differentially affect site nutrient reserves. Silkworth and Grigal (1982) found that after whole-tree harvesting of aspen in northeastern Minnesota, only calcium showed a statistically significant loss five years after harvest. As indicated in the table, aspen biomass contains high levels of calcium which creates a greater absolute loss to the system by harvest than, say, the harvest of jack pine. Calcium depletion by whole tree harvests of mixed oak forests in Tennesee was also found by Johnson et. al. (1982) which was attributed to the species harvested and low soil calcium content. Impacts on future productivity will depend on existing site reserves and the species being harvested.

Johnson and Todd (1987) found that nitrogen, phosphorus, and particularly calcium concentrations were greater in harvested mixed oaks compared to harvested loblolly pine growing on similar sites in Tennessee. Relative to soil reserves, however, only export of calcium via whole tree harvests were higher for the mixed oaks sites compared to the pine sites. Again, it appears that it is the relative proportion of nutrient reserves removed by harvest that is more important in maintaining site productivity rather than the absolute amount contained in the biomass.

Adams (personal communication) suggests that there are so many variables that come into play in assessing biomass harvest site impacts that quantitative analysis is difficult.

> “Little research has been done particularly in the Midwest on how much can be taken off a site before negative effects start to occur. Some studies done in the West show strong correlations between site productivity and logging residue retention … This research shows that eliminating all the logging residue from a site is a detriment to productivity no matter what the soil properties are. The reduction in productivity does decrease as soil texture becomes finer.”

Adams further states that retention of needles, leaves, and small twigs are most critical the first few years after harvest in maintaining soil nutrient properties, especially nitrogen. Small branches become more important 5-10 years following harvest as decomposition proceeds followed by bole wood. The amount of material that needs to be retained will vary by species due to differing composition rates. Decomposition rates will be impacted by soil moisture, temperature, and other micro-site and microbial characteristics.

Through preliminary investigation done on Blandin lands, several habitat type groups have been identified which seem to have more logging residue than others and that are differentially impacted by the amount of residue retained. Very sandy types require more slash retention than heavier textured soils. Blandin guidelines/recommendations suggest that no more than half the residue be removed on the sandy sites and no more than two-thirds on the better sites. Retention of fine twigs and leaves is most critical.

Mroz et. al. (1985) studied three northern hardwood sites to determine if whole tree chipping differentially affect nutrient level on sites of varying quality. Past researchers have speculated that potential impacts would be highest on lower quality sites (Weetman and Weber 1972, Boyle et. al. 1973, Patric and smith 1975 Jurgensen et. al. 1979) while others have suggested impacts would be more severe on higher quality sites compared to lower quality sites (Rauscher 1980). Mroz’s study results agreed with Rauscher’s – the impact on overall soil nutrient capital was greater as site quality increased.

3.3 Hydrologic Losses of Nutrients

Mann et. al. (1988) also examined hydrologic losses of nitrogen, phosphorus, potassium, and calcium in stem only and whole-tree-harvests. The study concluded that hydrologic losses generally increased immediately after harvest but returned to levels comparable to control areas within four years. There were no major differences between stem only and whole-tree-harvested sites.

> "In most cases, removals of nutrients in wood with whole-tree harvest exceeded hydrologic nutrient losses. Accelerated hydrologic losses of potassium often exceeded harvest removals; but at several sites, losses returned to preharvest levels [four years following harvest]. Hydrologic losses of calcium also exceeded harvest removals at several whole-tree harvest sites and decreases followed a similar pattern to that for potassium at most sites. With sawlog only harvest, hydrologic losses of all macronutrients were often comparable to or larger than harvest removals of nutrients; but, as was the case for whole-tree harvests, losses generally decreased with time after harvest."

While available nitrogen increased on most sites following harvest due to increased fixation, phosphorus, potassium, and calcium all showed net decreases due to hydrologic losses regardless of harvest intensity. Calcium losses seemed most problematic especially in hardwood sites in the eastern United States.

> "All of the sites that lost large quantities of calcium were on limestone-derived soils or were high in calcium content. While there were no known calcium deficiencies in any of the stands discussed here, the nutrient that showed the greatest loss in most cases was calcium. This suggests that calcium was not conserved very effectively in these ecosystems and will probably be the nutrient showing greatest declines with intensive management."

Subsequent regrowth on the two types of sites studied varied widely which the authors could not explain. The study concluded that the occurrence or magnitude of regrowth could not be predicted from nutrient budget analysis alone due to the impacts of a multitude of other factors.

Other studies indicate that hydrologic losses of nutrients are minimal and short lived if soil disturbance and run off are minimized and buffer strips are used alongside water bodies. Benson (1982) compared soil erosion over time for a range of residue treatment alternatives. Chipping and spreading residues resulted in the lowest erosion rates and most likely the lowest hydrologic loss of nutrients. Undisturbed forest experienced the next lowest erosion rate followed by broadcast burning and plots where residue was removed. In the case of broadcast burning, erosion rates decreased steadily over time. Where residue was removed, erosion rates peaked two years after treatment and then declined. Where residue was windrowed and burned, erosion rates continued to increase from the year of treatment through the study period (four years).

3.4 Nutrient Losses from Organic Matter

Trees are only one source of nutrients on forest sites. Understory vegetation and organic material contained in forest floor surface layers (duff layers) and surface horizons of mineral soil (neither of which would be removed by logging residue removal) are also important contributors to site nutrient sinks.

Moore and Norris writing in Cramer (1974) stated that "Nutrient capital contained in organic surface layers and in the organic matter of the surface horizon of mineral soil is extremely important to site productivity even though it may represent only a small percentage of the total nutrient capital on the site. These nutrients are being actively recycled … therefore, destruction of surface organic layers will have a significant impact on both nutrient capital and availability." While nutrient cycling is temporarily interrupted by harvest and residue removal, cycling is restored as revegetation proceeds.

Ruth and Harris (1975) cited a similar conclusion. “On nutrient-deficient forest soils and soils low in clays or organic material, the nutrient capital stored in forest residues, especially in the forest floor, is needed for tree nutrition. Only large residues should be removed from these areas …”

Smith (1985) also emphasized the importance of distinguishing between sites with differing levels of natural productivity in making residue management decisions.

The impact of clearcutting and different post-harvest residue treatments on residual organic matter and post harvest nutrient levels was studied by Benson (1982) in lodgepole pine forests. Four treatments were applied – residues removed, residues chipped and spread, residues broadcast burned, and residues piled and burned. Woody material weights and the percentage of change from pre-harvest to post-harvest were as follows:

Impact of Clearcutting and Different Residue Treatments on Residual Organic Matter.

	Pre-harvest (tons/acre)	Post-harvest (tons/acre)	Percent change
Residue removed	141	19	-87
Residue chipped and spread	141	68	-52
Residue broadcast burned	149	34	-79
Residue windrowed and burned	149	20	-87

Approximately 400 lbs/acre of understory vegetation existed on all sites prior to harvest. Fifty lbs/acre remained post-harvest. Despite a drastic reduction of woody material and understory vegetation on all study plots, remaining organic material in litter showed modest change (except for one treatment) compared to an uncut control plot. Litter weights ranged from 28,537 lbs/acre under burned piles to 161,124 lbs/acre on plots where residues were chipped and spread. Litter weight on plots where residue was removed totaled 37,662 lbs/acre compared to 31,667 on uncut forests serving as a control.

The immediate impact on the nutrient content of surface organic material was dramatically different across treatments as illustrated in the table that follows. After five years, however, nutrient levels in surface organic material approached those in the uncut forest. The treatment that resulted in the closest reversion to nutrient levels of the uncut forest in five years was where the residue was removed.

Nutrient Content of the Surface Organic Horizon Immediately After Harvest and Treatment

Treatment		Nitrogen	Phosphorus	Potassium	Calcium	Magnesium
Uncut Forest	Lbs./acre	412	30	66	156	54
Broadcast Burn	Lbs./acre	311	50	105	284	94
	% of control	75%	167%	159%	182%	174%
Pile/burn (under)	Lbs./acre	115	46	107	310	96
	% of control	30%	153%	162%	199%	178%
Pile/burn (between)	Lbs./acre	309	28	70	115	80
	% of control	75%	93%	106%	74%	148%
Residue removed	Lbs./acre	273	37	118	168	87
	% of control	66%	123%	179%	108%	161%
Chipped & spread	Lbs./acre	NA	NA	NA	NA	NA

Nutrient Content of the Surface Organic Horizon Five Years After Harvest and Treatment						
		Nitrogen	**Phosphorus**	**Potassium**	**Calcium**	**Magnesium**
Uncut Forest	Lbs./acre	450	35	61	299	73
Broadcast Burn	Lbs./acre	398	34	59	374	75
	% of control	88%	97%	97%	125%	103%
Pile/burn (under)	Lbs./acre	257	28	45	320	57
	% of control	57%	80%	74%	107%	78%
Pile/burn (between)	Lbs./acre	272	24	45	196	54
	% of control	60%	68%	74%	65%	74%
Residue removed	Lbs./acre	409	34	65	267	69
	% of control	91%	97%	106%	89%	94%
Chipped & spread	Lbs./acre	508	69	148	408	165
	% of control	113%	197%	243%	136%	226%

The organic matter content of the 0-5 cm and 5-15 cm layer of forest soil also varied by residue treatment. The organic matter content of the mineral soil increased where treatments did not involve burning. The impact was most dramatic and long-lasting in the 0-5 cm layer. Within the 5-15 cm layer, higher levels of organic matter immediately following logging on the residue removed and chipped plots had returned to that of the uncut forest after five years.

Aber et. al. (1978) reached a different conclusion in modeling the effects of different intensities of forest management on forest floor organic matter and nitrogen availability in northern hardwoods based on data collected in the Hubbard Brook Ecosystem Study. A clearcut, whole-tree harvest and whole-tree harvest with all dead wood removed were modeled with rotation lengths of 30, 45, and 90 years. The model found that organic matter declined for 15 to 30 years following cutting and required 60-80 years to recover to precut levels. With clearcutting, organic matter declined from 55 metric tons/hectare to a low of approximately 35 metric tons/hectare 20 years following harvest. Whole-tree harvesting reduced organic matter to a low of 30 metric tons/hectare 15 years following harvest, while removal of all biomass alive and dead reduced organic matter to a low of 25 metric tons/hectare 15 years following harvest.

Increased removal of woody material lead to greater availability of nitrogen 5 to 10 years following harvest but reduced availability from year ten on. The study concluded that "… dead wood acts as an important buffer, minimizing nitrogen losses immediately after cutting by providing a carbon-rich substrate for immobilization of nitrogen by microbes and then gradually giving this nitrogen back through its slow rate of decomposition." Rotation length had a much larger influence on both organic matter and nitrogen availability than did harvesting intensity. Under a 30-year rotation, forest floor biomass was reduced to approximately half of that which accumulated under a 90-year rotation.

In a subsequent article under the same title (Aber et. al., 1979) the researchers concluded that maximum yields would occur from intensive harvesting under long rotations due to the fact that a higher proportion of standing crops are removed and the period of low nitrogen availability in years 10 to 30 is minimized. The authors express caution, however, in interpreting this too literally since their research did not examine possible reduced growth over subsequent rotations.

Slash retention can also impact the pH of the humus layer. Slash significantly increased soil pH in the humus layer compared to sample plots where slash was removed in a study by Nykvist and Rosen (1984). The authors suggest that this effect could last up to 20 years after harvest. Similar results were reported by Staaf and Olsson (1991).

4. REGENERATION AND STAND DEVELOPMENT

Leaving logging slash untreated can provide benefits in some situations. Potential benefits to soils, advance regeneration, and wildlife habitat must be weighed against potential fire hazards and the obstructions created for planting or other regeneration and the opportunity for removal of competing vegetation and other post-harvest management activities. Retention and/or removal of logging residue can profoundly impact regeneration success and subsequent stand development and composition (Ruth and Harris, 1975). Heavy concentrations of logging slash form a physical barrier on a site and make planting, natural seeding, and subsequent management activities difficult. Such concentrations may also tie up available nitrogen to the detriment of seedling establishment or suppress seedling growth (Cramer, 1974; Ruth and Harris, 1975). Complete removal of logging residues on the other hand, creates greater exposure of seedlings to heat and drought which can impact survival especially on dry sites.

Regeneration success and seedling survival are critically dependant on microclimate conditions on harvested sites. Slash management is one of the principle influences on subsequent microclimates on harvested sites. Ruth and Harris (1975) found that moisture and temperature were particularly important.

In a study in the Pacific Northwest, Zabowski et. al. (2000) found that soil temperatures on areas where residue was burned were higher than on areas where residue was retained, roller chopped, or removed. Minimum and maximum air temperatures were affected by shading and storage of heat followed by reradiation from various combinations of retained slash compared to burned sites. These differing microclimatic effects were most pronounced in only the first two years. No consistent changes in bulk density by treatment across all sites were observed.

In this particular study, seedling survival was best on burned sites compared to sites where slash was roller chopped, retained, or partially removed. Subsequent height growth at year three and five was also poorer at all sites where residues were chopped, partially removed, or left intact compared to removal by burning. Results also differed somewhat by species. In this study the author concluded that if slash burning in Douglas Fir or Lodgepole Pine could not be conducted then leaving slash untreated appeared to be the best alternative for seedling growth. Roller chopping and removing slash with a cable system produced the worst results in terms of seedling survival and subsequent growth on some sites but not on others.

Benson (1982) reported similar results for Lodgepole Pine in the Intermountain West.

> “Planted seedlings survived very well on the areas that had been dozer-piled and burned and those broadcast burned, exceeding 95 percent at three years, 87 percent at five years and 80 percent at nine years. Meanwhile, their counterparts in the residue removed and chip spread treatments fared poorly; although, the planted seedlings in the residue removed treatment were surviving at the rate of over 90 percent at three years, they declined rapidly to 59 percent at five years and 52 percent at nine years. Planted seedlings in the chip spread treatment declined in a similar fashion.”

Height growth also lagged in this study on plots where residue was removed nine years after planting. Similar results were reported for natural regeneration and regeneration as a result of seeding on these sites. These impacts occurred despite the fact that, with the exception of iron, the percentage of ash and most nutrients were not statistically different among treatments. Also, the residue removed and chip spread sites contained the highest levels of organic matter. The authors speculate that differing soil temperatures across treatments or a flush of phenols in the residue removed and chip spread treatments the first year the seedlings were planted account for these differences.

Fowler and Helvey (1981) noted air and soil temperature differences on sites treated by broadcast burning, pile and burn, chipping, cleared and scarified, and slash left as is. They speculated that these differences would impact seed germination. Both burning treatments had increased air and soil temperatures while the other three treatments did not create significantly different temperatures. Very significant differences in biomass production occurred between treatments. Biomass was poor on scarified sites due to compaction and poor on chipped sites where the depth of the chips impeded rooting. The highest biomass growth occurred on sites that were broadcast burned followed by sites where the slash was left in place. Results on piled and burned sites were inconclusive.

In an extreme example of residue management impacts on subsequent tree growth, Weber et. al. (1985) applied three treatments to a sandy and nutrient poor jack pine site: one-time complete removal of the forest floor to mineral soil; annual removal of the forest floor to mineral soil; one-time complete removal of the forest floor, ashing of the material, and broadcast spreading of the ash. Eight years after treatment, radial tree growth on the treated plots showed a 30 percent reduction compared with untreated plots. The effect was most severe on the treatment which removed the forest floor annually but the authors concluded that the effects were still significant for the other two treatments.

In contrast, Corns and Maynard (1998) found only short-term (three year) impacts on aspen regeneration and growth on plots where three depths of chipped aspen residue and three levels of soil compaction were applied. On plots with over 10 centimeters of chipped aspen residue and compacted by 16 skidder passes, the density of aspen suckering was reduced but only for two years following harvest. The experimental sites had mesic, moderately well drained soils, and were classified as clay-loam tills.

Hungerford (1980) developed some predictive models to evaluate microsite conditions and suggested residue management strategies to alter the microenvironment to improve regeneration. Suggestions are made for altering shade, thermal properties, light, and other site characteristics to improve temperature, moisture, light, and gaseous micosite regimes. This publication is interesting in that it offers a variety of residue management strategies designed to improve regeneration success *depending on the characteristics of the individual site.* Many studies which have evaluated residue treatment effects on micro-climate suggest that one or the other produces better results. This study suggests otherwise and provides suggestions to leave residues in some cases, burn them, and remove them in others. Also to compact the soil in some cases, scarify in others, etc. This illustrates the site specific nature of residue management decisions.

Results from Brais et.al. (2002) suggest a reason why growth rates of seedlings may slow over time with increasing biomass removal. They found that whole tree harvesting of balsam fir, white birch, and white spruce on clay soils in Quebec reduced forest floor nitrogen; but that the reductions did not become significant until 15 years after harvesting.

Smith et. al. (2000) undertook a study specifically designed to test the hypothesis that harvest residue and forest floor removal are negatively correlated with tree growth in the next rotation. This research involved radiata pine on sites of differing fertility. On all sites, slash and forest floor retention increased mortality in the first five years. On the least fertile site, diameter trends since age five showed that differing residue treatments had a significant impact on growth. Tree diameter growth was significantly less following removal of organic matter and slash compared to treatments where the forest floor and slash were retained. A double layer of slash further improved long-term growth. These results were correlated with nitrogen availability which reached deficient levels on this poor site when organic matter was removed. On the other two sites which were more fertile, differing residue treatment had no affect on growth after age five. The authors recommend retention of organic matter on the poorest sites but offer no recommendations for more fertile sites.

Smethurst and Nambiar (1990), also studying radiata pine on a poor site, found that the supply of nitrogen seemed adequate to maintain satisfactory tree growth three years after harvest irrespective of slash and litter treatment. The treatment differences strongly impacted the soil but not short-term tree growth. Treatments included slash and litter retained, litter only retained, litter ploughed, and slash and litter removed. Soils without slash and litter were four degrees warmer on average than those that retained slash and/or litter. Temperature extremes were also higher where slash and litter had been removed. Plowing doubled the concentrations of mineral nitrogen in the soil and did impact early growth, but these higher levels largely disappeared within 40 months compared to other treatments. The authors suggest that long-term growth benefits may be higher if slash is retained.

Cramer (1974) agreed: "Once established, conditions favorable to tree growth are enhanced if residues are left on site to decay and release nutrients." This contrasts with the results reported in Zabowski et. al. (2000).

Most studies focused on residue treatment influences on regeneration concern influences on seedling establishment. Mann (1984) examined the impact of conventional clearcut and whole-tree harvesting on both seedling establishment and stump sprout growth in upland hardwood stands. Differences in sprouting and seedling abundance were apparent the first year following harvest. Reduced stump sprout density was observed for all species at whole-tree harvested sites. The authors attribute this to increased stump damage and soil disturbance with this harvest method. As measured by stump sprout height growth, conventional clearcuts favored some species but not others. In contrast, most species produced more seedlings if residue was removed as a result of greater soil disturbance.

The response of understory and ground vegetation to different residue treatments has been studied by several authors. Scherer, et. al. (2000) examined understory plant response to a range of residue treatments including fall and spring broadcast burning, chopped slash, piled and burned slash, piled slash, and slash left in place. The authors found that:

> "Slash treatment increased the abundance of weedy species that are not normally present in these forests. Treatments such as broadcast burning and pile/burn showed greater dominance by invader species. Overall, harvesting reduced species diversity but the response among slash treatments varied. After three growing seasons, species cover, richness, and diversity had no clear effect on seedling growth in slash-treatment plots."

Olsson and Staaf (1995) analyzed ground vegetation succession at four coniferous sites in Sweden 8-16 years after clearcutting with all residue removed, all residue except needles removed, and all residue left. Their results suggest that the primary influence differing residue treatments have on sites are their influence on nutrient budgets. Treatment differences in species cover were small and decreased over time.

5. WILDLIFE AND MICROORGANISMS

Impacts on wildlife of residue removal vary based on the species of interest. Retention of slash primarily provides cover for small mammals and birds vulnerable to predation. In cases where these populations greatly increase as a result of residue retention, damage to new regeneration may result (Ruth and Harris, 1975). Residue retention, however, can depress grass and forb production which can negatively impact other species (Cramer, 1974).

Generally, residue treatment or retention does not create disease problems except in the case of buried wood and stumps and roots which can perpetuate root disease inoculum in the forest. Residue does attract a variety of insects that can aid in decomposition but few constitute a major problem with the possible exception of bark beetles where their numbers are large and the infestation can spread to retained living trees (Cramer, 1974).

Microbial activity related to forest residues is controlled by six environmental factors: water, temperature, aeration, pH, food supply, and biological interrelations. The form of residue has a direct impact on microbial activity. Finer residue in close contact or incorporated in the soil will speed microbial decomposition releasing nutrients more quickly to speed plant growth (Bollen, 1974). In contrast, "rapid build-up of microbial populations after additions of large amounts of residue can result in a temporary nitrogen deficiency (Moore and Norris, 1974; Ruth and Harris, 1975). More coarse residue extends the release of nutrients over time.

Nitrogen availability is especially sensitive to changes in microbial activity. Benson (1982) found that microorganism populations on sites where residue was broadcast burned, windrowed and burned, removed, and chipped and spread were not significantly different among these post-harvest treatments three to four years after harvest. On all treatments, however, the number of microorganisms was lower than that on the control plots after three to four years.

The rate of nitrogen fixation was highest in the wood chip layer; however, the overall nitrogen fixation rate was highest in the uncut control due to fixation in the organic and mineral layers of the forest floor. Across treatments, nitrogen fixation rates were much lower in the mineral compared to the organic soil layers, but the greatest nitrogen gains occurred in the mineral horizons due to the high mineral/organic ratio in the soil (Benson, 1982). The author goes on to suggest that on sites considered low in soil organic matter, modest amounts of woody residue should be scattered over the site to upgrade organic matter resources.

Entry, et. al. (1987) documented that microbial activity varied over the course of a year following clearcut harvesting and three types of residue treatment in Lodgepole Pine stands. Residue treatments included residue left, residue removed, and residue burned with an uncut stand serving as a control. Cellulose degradation peaked in spring and fall and was positively correlated with microbial activity in all treatments and periods of high soil moisture. Temperature was the main factor influencing seasonal variations in lignocellulose degradation in both spring and fall. Treatments where residue was left had the highest soil moisture and most moderate soil temperatures due the residue's insulating effect both from freezing in the winter and drying in the summer. As a result of these micro-climatic effects and their impact on microbial populations, decomposition rates were significantly higher than those for the other three treatments. The magnitude of these changes, compared to the volume of residue retained, are as follows:

Treatment	Residue Thickness (in cm)	Decomposition Constant
Residue left	27.0	1.24
Residue broadcast-burned	1.7	0.46
Residue removed	10.7	0.40
Control	12.5	0.45

Bengtsson et. al. (1997) studied the effect of whole-tree harvests on macroarthropods and enchytraeids. They concluded that whole-tree harvesting might result in long-term decreases in the abundances of many soil animal groups. Changes in nutrient cycling and site productivity due to these decreases are likely to be small but may be significant on low quality sites or sites dominated by internal nutrient dynamics.

Slash removal or its retention can impact various species of wildlife. When completely removed, hiding places for prey species are eliminated but forb development is faster which favors other species.

6. CONCLUSIONS

- The majority of the research on management of logging residues in the United States and the impact of various logging slash management alternatives has occurred in the Pacific Northwest and to a lesser extent in the South. Much of this research has centered around the impacts of burning or leaving the slash in place with much emphasis on subsequent fire regimes. Despite the fact that this research was done on forest types which do not occur in the Lake States region, useful information for potential application in this region has resulted, primarily related to slash impacts on microclimate and regeneration success.

- The USDA Forest Service was an early proponent of establishment of slash management guidelines primarily related to management to control fire regimes following harvest. Focus of this type of research seems to have waned since the mid 1980's.

- A majority of the research conducted to date concerning slash removal has focused on softwood species. Slash removal studies in hardwoods has most frequently been associated with comparing bole only removal of biomass to removals by whole tree chipping. In the United States, this research on hardwoods is concentrated in the Northeast.

- Considerably more research on the impacts of slash removal has been done in Canada compared to the United States, and it appears that that research has remained more of an ongoing focus.

- The most extensive research on the effects of slash removal on forest sites has occurred in Nordic countries, especially Sweden. This research has occurred in conjunction with long standing national energy policies to increase use of biomass for energy and development of harvesting machines to economically collect it.

- The two most useful sources of information on this topic have been the Canadian Journal of Forest Research and the Journal of Forest Ecology and Management published by Elsevier Science Publishers in Amsterdam. Much of the research conducted in the United States has been published in these journals.

- The most concentrated period of research on this topic occurred in the 1970's and 1980's.

- Research has been conducted in a wide variety of forest types growing on different soils. This research seems to suggest that effects of slash removal on nutrient budgets are short-term in nature with sites recovering pre-harvest nutrient levels within approximately five years *if the site has adequate reserves or will obtain adequate available nutrients through deposition.*

- On already nutrient poor sites, the impact of slash removal will be more severe and long term.

- An important variable influencing the impact of slash removal on nutrient budgets is the amount of organic matter that is already incorporated in the mineral soil (which is not removed with the slash). The more that is in place the less influence slash removal seems to have on nutrient budgets. Consequently, slash removal is more problematic on poorer sites compared to more productive sites.

- Any impacts that slash removal has on nutrient budgets appear to occur in the top five centimeters of soil and are influenced by the amount of mineral soil exposure. Extensive mineral soil exposure has been shown to increase hydrologic losses of available nutrients until revegetation occurs. On the other hand, incorporation of fine material into the soil can speed decomposition and increase available nutrients for a period of two to three years.

- It is important in assessing site impacts to distinguish between *available* nutrients and *total* nutrient capital. Harvesting of the bole and slash will remove a much larger proportion of available nutrients compared to total nutrient capital removals. Short-term impacts will depend on how quickly the available nutrients can be replaced through deposition, decomposition, and weathering. Long-term impacts will depend on how much and how often total nutrient capital changes.

- Distribution of nutrients in the different parts of trees is highly variable by species; however, within any single species, the proportions are very consistent. This suggests that residue treatment recommendations would vary not only by the existing productivity of the site but also by species depending upon which nutrient is of concern.

- There is also high variability in the distribution of the different nutrients in the different parts of trees.

- Research seems to suggest that the most important component of the slash which should remain on-site from a nutrient budget perspective is the fine material (needles, leaves, and small twigs). Winter only harvesting in hardwoods or drying of the slash over a summer in softwoods has been shown to conserve nutrients (since the leaves and needles remain on-site) with little loss of biomass and improved chip characteristics.

- Of the research done in the Midwest and/or on trees species common in the Midwest, possible calcium deficiencies appear to be the most likely factor limiting residue removal on some sites and with some species.

- A technical reviewer noted that the issue of possible calcium depletion and extraction of other base cations may have the potential to cause soil acidification in the top few centimeters of soil which has the theoretical potential to be an issue several rotations out. No literature which addressed this question in the long-term was uncovered. This may be an area for further research or investigation.

- Slash removal has little effect on hydrologic properties of a site except at the microclimatic level unless such removal causes erosive action. Hydrologic losses of phosphorus, potassium, and calcium can be problematic on some sites.

- The total amount of and maintenance of organic matter content in the upper soil horizons is an important influence on nutrient site impacts following residue removal.

- An important factor affected by the gross volume of slash remaining on a site is the microclimate. Changes to the microclimate by leaving too much or too little slash can strongly influence subsequent reproduction success and species composition.

- Excess slash can hinder seeding and planting but can be beneficial to advanced regeneration.

- Slash retention policies impact seedling establishment and subsequent growth. The research reviewed was highly contradictory regarding various slash retention alternatives and the impact on these two variables.

- Microbial activity following harvest is a critical factor in replenishing available nitrogen.

- Slash removal or its retention can impact various species of wildlife. When completely removed, hiding places for prey species are eliminated but forb development is faster which favors other species.

The following points were summarized from a number of author's presentations at a symposium on the productivity of northern forests following biomass harvesting (USDA Forest Service 1986). These recommendations were interesting in that many are already incorporated into Minnesota's Best Management Practices Guidelines.

Biomass harvest should be avoided on the following soil types:

- Soils that are shallow to bedrock or hardpan.
- Soils with restricted rooting volumes or high percentages of coarse fragments.
- Coarse-textured outwash sands.
- Soils deficient in phosphorus.
- Poorly-drained soils, especially around streams and stream channels.

Harvest recommendations to minimize soil disturbance include:

- Harvest when soils are dry or under snow cover.
- Plan skid roads along site contours, minimize stream crossings, and concentrate impacts of heavy equipment rather than allowing widespread, diffuse damage.
- Minimize or avoid practices that remove organic layers of soil.
- Use tracked rather than wheeled vehicles wherever possible.

Recommendations to maximize nutrient conservation include:

- Cut in winter or allow trees felled in summer to drop leaves on the site.
- Promote rapid regeneration of the site by avoiding biomass harvesting on certain soil types and minimizing disturbance on others.
- Allow for natural regeneration or accomplish site conversion and planting as rapidly as possible.
- Leave some logs on site to improve organic matter in soils and allow for establishment of seedlings.
- Lengthen rotation to allow for natural replenishment of nutrients removed in products or leached from the site and consider fertilization to offset cation losses.
- Retain buffer strips of trees along streams or use strip cutting to reduce leaching losses to streamflow.

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