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# Whole-tree Clearcutting in New England: Manager's Guide to Impacts on Soils, Streams, and Regeneration

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## Abstract

Intensively harvested forests in New England have shifted partially from conventional stem-only clearcutting using chainsaws and skidders to whole-tree clearcutting using harvesting machines. We have studied the impacts of whole-tree clearcutting on soil, water, and revegetation in spruce-fir, northern hardwood, and central hardwood forest types. This report summarizes the relevance of our findings to forest management and suggests various management considerations, guidelines, and further readings. The intended audience consists of practicing foresters, land managers, environmental protection agencies and organizations, and the general public.

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## Acknowledgment

We would like to thank several landowners and their representatives for providing land and conducting the harvest operations on which our studies were conducted: Tony Filauro and Great Northern Paper Co., Bill Kropelin and the James River Corporation, Tim Hawley and the Connecticut Department of Environmental Protection, Division of Forestry, and the Green Mountain National Forest. Max McCormack and the Cooperative Forestry Research Unit, University of Maine, Orono, were closely associated with the work in Maine. A number of people assisted in lab and field work, particularly Jane Hislop, Russ Briggs, Florence Peterson, Ray Gomez, and Bart Hawley. We thank David Brynn, Tony Filauro, Walt Winturri, and Bill Leak for providing helpful comments on an earlier draft of this paper.

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## Conversion Table

To promote the universal adoption of standard metric units, we have expressed values in metric units in this publication. However, we recognize that English units still are used widely in the U.S. The table below is provided to ease conversion of values. For the data in this publication, these conversions need only be approximate, so easily remembered and approximate equivalents are given.

Length:	100 mm (millimeter)	= 4 in	Combined:	1 m <sup>2</sup> /ha (square meter per hectare)	= 4.4 ft <sup>2</sup> /acre								
	10 cm (centimeter)	= 4 in		1 kg/ha (kilogram per hectare)	= 1 lb/acre								
	1 m (meter)	= 3.3 feet		1 Mg/ha (megagram per hectare)	= 0.4 ton/acre								
	1 km (kilometer)	= 0.6 mi		1 mg/L (milligram per liter)	= 1 ppm (part per million)								
Area:	1 m <sup>2</sup> (square meter)	= 11 ft <sup>2</sup>	Temperature:	1° C (degree Celsius)	= 1.8°F (degree Fahrenheit)								
	1 ha (hectare)	= 2.5 acre											
Volume:	1 L (liter)	= 1 qt											
	3.6 m <sup>3</sup> (cubic meter)	= 1 cord											
Mass:	1 kg (kilogram)	= 2.2 lb											
	1 Mg (megagram or tonne)	= 1.1 ton											
			°C	-10	-5	0	5	10	15	20	25	30	35
			°F	14	23	32	41	50	59	68	77	86	95

## Introduction

Forest biomass harvesting, the practice of removing the entire above-ground portions of trees by harvest machines, is in part, changing the management of forests in New England. Such harvesting can increase utilization by including trees that are dead or dying and those of undesirable form, size, or species. Various forms of mechanical equipment cut trees at the stump, transport the whole tree to a landing, separate out veneer and sawlogs, and chip the remainder, including tops, branches, stem, bark, and leaves. The chips are used for pulp, for reconstituted wood products, and for fuel.

Biomass harvesting may be used either to remove selected individual trees throughout the stand or to clearcut all trees in blocks, strips, or larger areas, including whole watersheds. When the cut area exceeds about 1 ha, we call the harvest method whole-tree clearcutting (WTC). The research discussed in this paper focuses on WTC because it represents a more severe disturbance to forest ecosystems than does a stem-only harvest, or a whole-tree selection or small block cut.

Maintenance of long-term forest productivity is a fundamental goal of ecologically sound forest management. In these studies, we define long-term productivity to mean sustainability of the forest ecosystem, allowing for short-term disturbances if they do not degrade the capacity of the ecosystem to support a healthy, vigorous forest. Therefore, because WTC removes virtually all above-ground woody vegetation and utilizes mechanical equipment, such harvesting raises questions about potential impacts on the forest environment and on long-term forest productivity. For example:

- How does soil disturbance caused by harvest equipment affect tree regeneration? How does mixing of organic and mineral soil affect germination and regrowth of the forest?
- To what extent does harvest removal of the nutrients in tops, branches, and leaves, as well as in the stems, deplete site nutrient capital? What are the impacts on regrowth, species composition, or future productivity?
- Does ease of harvesting using mechanical equipment promote shorter rotations and thus accelerate nutrient depletion?
- How will site exposure by removal of tops and branches affect available nutrients for regeneration and nutrient losses to streams?
- What are the impacts on stream water quality or quantity?

To address these and related questions we have conducted research on WTC for the past decade on three major New England forest types: spruce-fir in Maine, northern hardwoods in New Hampshire and Vermont, and central hardwoods in Connecticut. Our aim was to examine the possible impacts of WTC on the soil, vegetation, and water components of the forest ecosystem. Although we still cannot answer precisely the questions above, our findings can be helpful in assisting the forest manager to make decisions about WTC.

Details of the research summarized have been published in a number of technical reports, scientific journals, and management symposia over the last decade. This literature is not cited directly in the text: the reader is referred to "Further Reading" at the end of each section.

Conclusions and guidelines are given in the final paragraphs. The guidelines are addressed to practicing foresters, land managers, environmental protection agencies and organizations, and the general public.

## Further Reading

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## Field Experiments

### Study Sites

To determine the impacts of WTC, we used case studies within three of the four major forest types of New England: spruce-fir, northern hardwoods, and central hardwoods (Fig. 1). Criteria used in selecting study sites were:

1). Criteria used in selecting study sites were:

1. located where WTC either was currently being practiced or might soon be employed,
2. representative of their region in terms of stand type and stocking, land-use history, topography, and physical and chemical characteristics of soils, and
3. if possible, comprised of two or more small watersheds from which a stream flowed during most of the year.

These criteria were met on three of the four sites chosen for study: a spruce-fir site in central Maine (Fig. 2), a northern hardwood site in northern New Hampshire (Fig. 3), and a central hardwood site in south-central Connecticut (Fig. 4 and 5). On these sites one watershed was selected as a control, the other for whole-tree harvest. Watersheds are convenient landscape units for measurement of input and output of water and nutrients. The fourth site, a northern hardwood site in Vermont, was not conducted as a whole watershed study, but instead used replicated control and

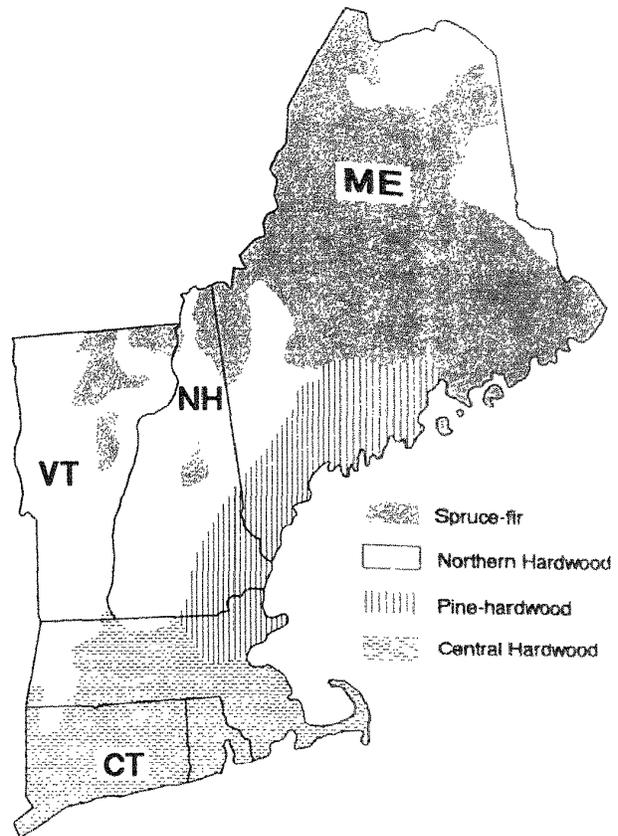


Figure 1.—Major forest types of New England. State abbreviations designate approximate location of study sites.

Table 1.—The study sites

	T4, R12, Maine	Success, New Hampshire	Bristol, Vermont	Chester, Connecticut
Designation	Maine	New Hampshire	Vermont	Connecticut
Latitude	45°56'N	44°30'N	44°24'N	41°24'N
Longitude	69°17'W	71°3'W	73°32'W	72°32'W
Land owner	Great Northern Paper Co.	James River Co.	National Forest	State of Connecticut
Forest type	Spruce-fir	Northern hardwoods	Northern hardwoods	Central hardwoods
Major species	<i>Abies balsamea</i> <i>Picea rubens</i> <i>Acer rubrum</i> <i>Betula</i> <i>alleghaniensis</i>	<i>Acer saccharum</i> <i>Fagus grandifolia</i> <i>Betula</i> <i>alleghaniensis</i>	<i>Acer saccharum</i> <i>Fagus grandifolia</i> <i>Betula</i> <i>alleghaniensis</i>	<i>Quercus rubra</i> <i>Quercus velutina</i> <i>Quercus prinus</i> <i>Betula lenta</i>
Basal area, uncut forest m <sup>2</sup> /ha	48	26	29	23
Land use history	Severe budworm epidemic, 1913-1919; Selection cuttings in late 1800's and early 1900's	Last harvest in 1936 when 50% of basal area was removed	Grazed until late 1800's, not harvested since	Farmed until around 1900, not harvested since
Soils	Telos, Monarda: coarse loamy, mixed, frigid; Aquic Haplorthod/Aeric Haplaquept	Becket: coarse loamy, mixed, frigid; Typic Haplorthod	Marlow: coarse loamy, mixed, frigid; Typic Haplorthod	Chatfield: coarse loamy, mixed; Typic Dystrochrept
Average slope	<5%	10%	10%	10%
Area harvested	47ha	7 ha	8 ha	6 ha

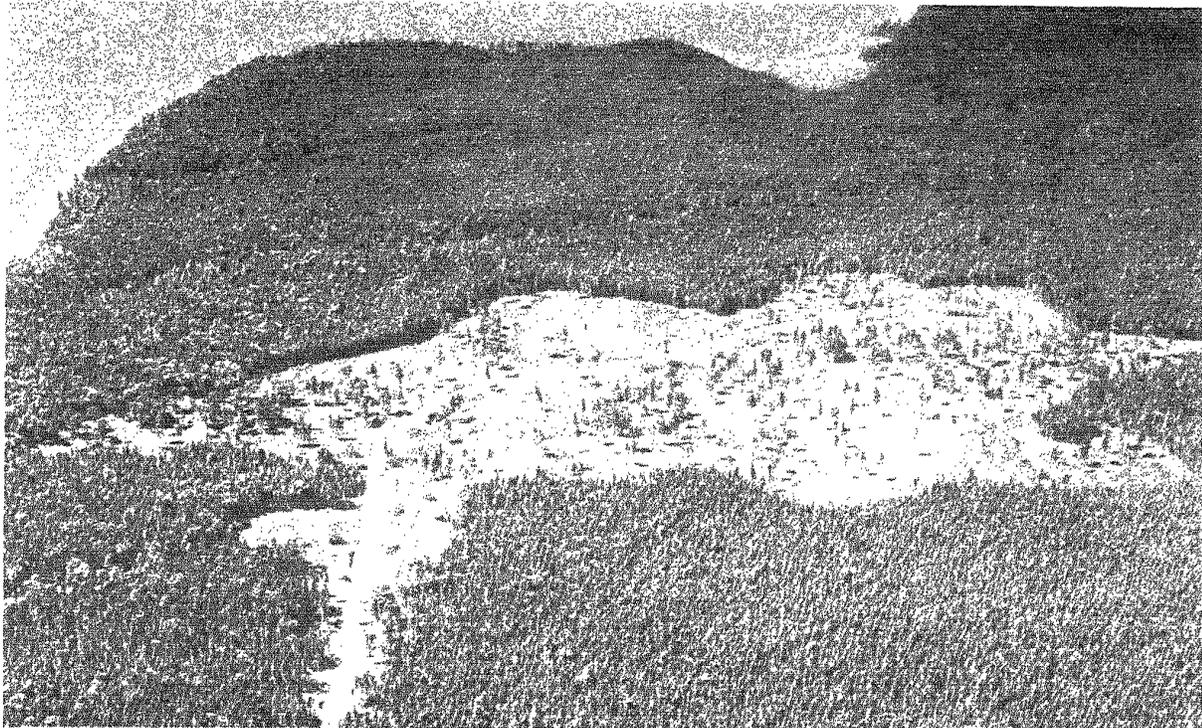


Figure 2.—Whole-tree, harvested watershed at spruce-fir forest in Maine. Chesuncook Lake in background.

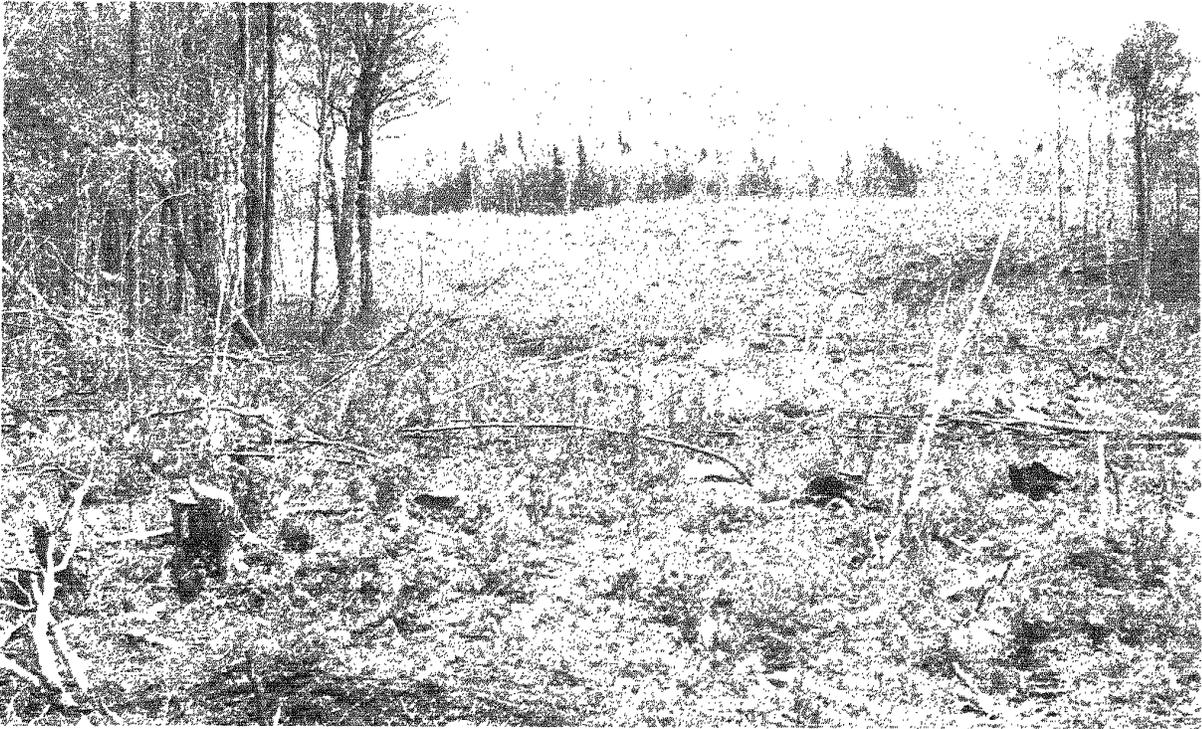


Figure 3.—Whole-tree, harvested watershed at northern hardwood forest in New Hampshire.

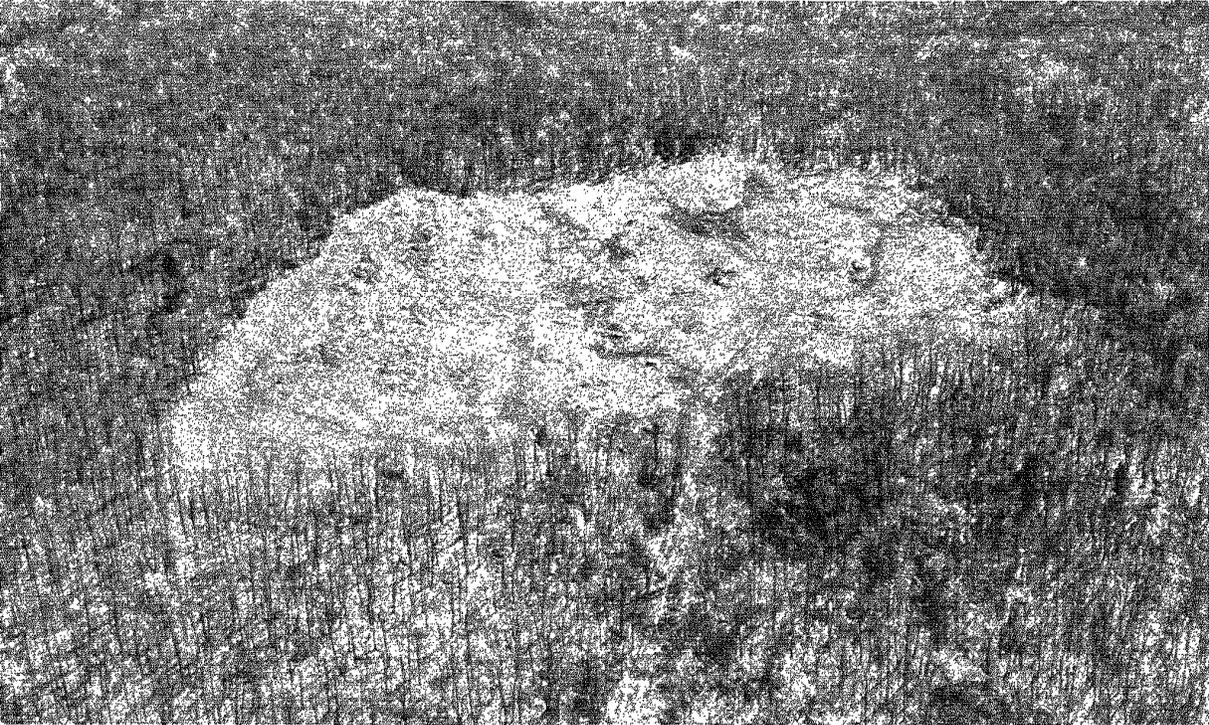


Figure 4.—Whole-tree, harvested watershed at central hardwood forest in Connecticut.



Figure 5.—Central hardwood stand in Connecticut before harvest.

harvested blocks (Fig. 6). Important characteristics of the study sites are summarized in Table 1.

The sites in Maine and New Hampshire are on industrial lands where WTC is common, and the study sites were logged as part of normal operations. WTC was not as prevalent near the Connecticut State Forest and Vermont National Forest sites; therefore, direction and supervision were provided to ensure that the logging operation was consistent with the nearest harvests in terms of equipment, biomass removal, and protection of soils and streams.

### Logging Operations

At the Maine site, whole trees were felled mechanically and forwarded to the roadside to be used primarily for pulpwood. Large rubber-tired feller-forwarders (Fig. 7) capable of 10-cord loads were used on one portion of the watershed, while a track-mounted feller-buncher followed by rubber-tired grapple skidders was used on another. Trees were delimited at the roadside before trucking of tree-length boles. The branch and needle residue was piled at the roadside. Merchantable materials included spruce and fir boles > 14 cm d.b.h. to a 10-cm top, and sound sawlogs of other species. The harvest was conducted from June through August, 1981. Herbicide was applied aerially to the watershed 4 years later, in August, 1985, to eliminate herbaceous weeds and hardwood species and to release spruce and fir seedlings.

The New Hampshire site was logged using a track-mounted feller-buncher (Fig. 8) and rubber-tired grapple skidders. All

trees > 5 cm d.b.h. were felled and whole trees were transported to a landing where sawlogs were separated and remaining biomass was chipped into vans for hauling to a pulp mill. A 10- to 30-m-wide buffer strip of trees was left along both sides of stream channels to shade the stream and to protect against sedimentation. One-half of the area was harvested in January 1978, with snow cover present and the other half was harvested the following July. Trees felled in July were left on the ground for approximately 3 weeks before skidding to allow leaves to dry and drop on the harvested site.

At the Connecticut site approximately 60 percent of the trees were felled with a rubber-tired feller-buncher. The remaining trees were felled with chain saws; these trees either were too large for the hydraulic shears or were growing on steep slopes that were inaccessible to the mechanized harvest equipment. Whole trees of all diameters were skidded with rubber-tired grapple skidders to a landing and separated into sawlogs and firewood or chipped for boiler fuel. The harvest began in December 1981, and was completed by March 1982. A snow cover existed during much of the harvest period but the ground was very soft for part of the time.

Trees at the Vermont WTC site were felled with a track-mounted feller-buncher, then skidded with rubber-tired grapple skidders. At the landing, all trees were chipped and used as fuelwood for an electric power plant. The harvest took place in July and August, 1982. Skidding occurred immediately after felling so that leaves were removed as part of the harvest.

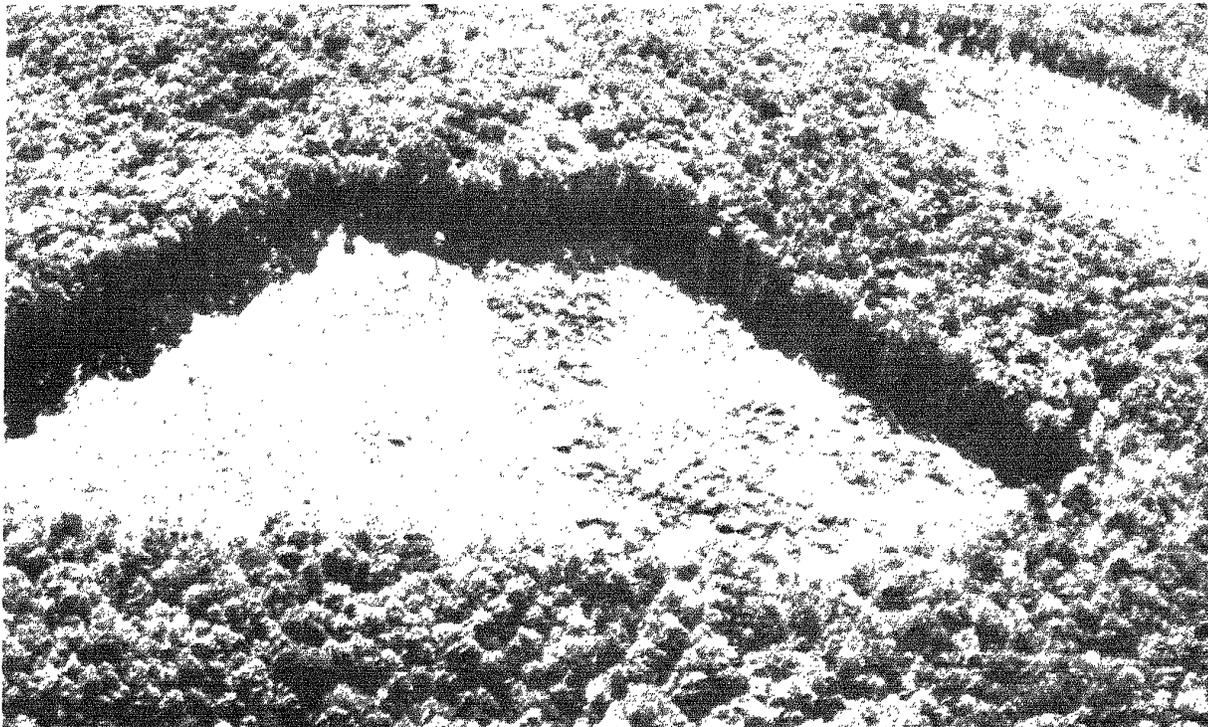


Figure 6.—Whole-tree, harvested blocks at the northern hardwood site in Vermont.

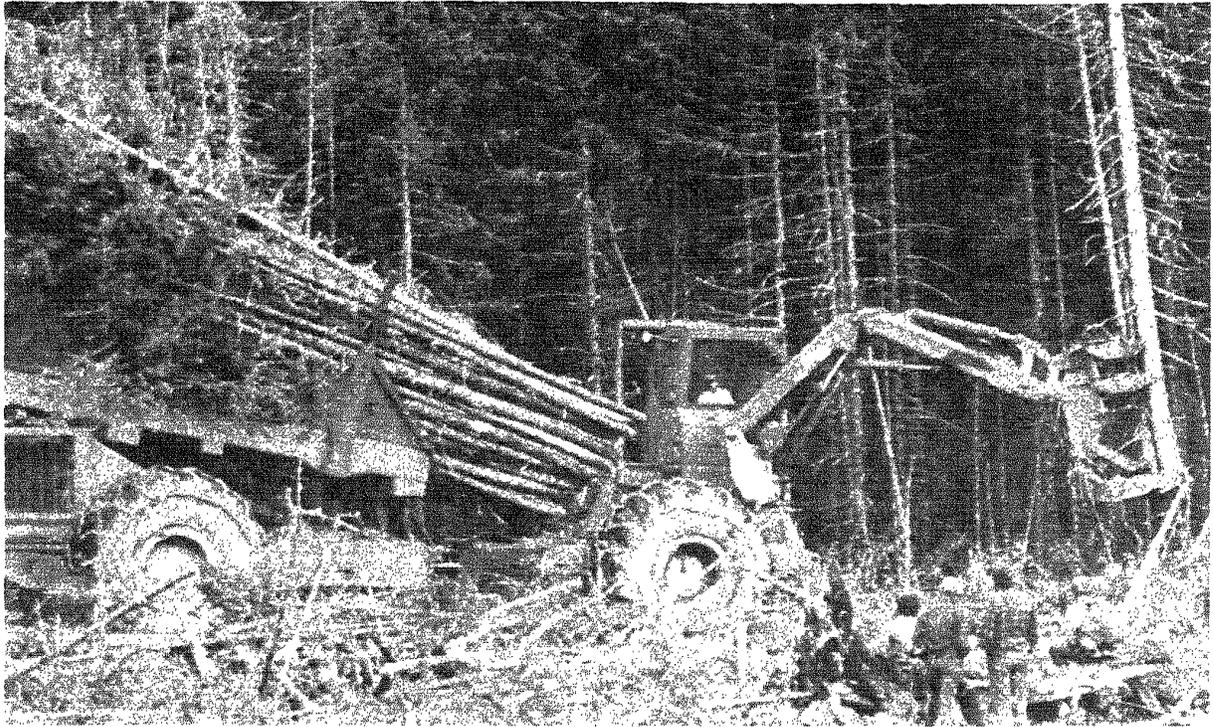


Figure 7.—Feller-forwarder in use at the Maine site.



Figure 8.—Feller-buncher in use at the New Hampshire site.

## Measurements

Our research approach uses the concepts of the "watershed as ecosystem" and a paired treatment and control watershed. A whole watershed or drainage basin is a useful measurement and treatment unit because the streamwater flowing from it integrates the chemical behavior of the whole area and is the dominant output of any nutrient element from the undisturbed system. The dominant input, via precipitation, also is easily measured. The inputs and outputs of any element then can be related to the storages or pools of that element within the system. Pairing of a treated (harvested) watershed with a control (undisturbed) watershed allows easy determination of treatment effects because the relationship between the two watersheds is calibrated before treatment.

At the New Hampshire, Vermont, and Connecticut sites, tree biomass was estimated before harvest by measuring d.b.h. and height of standing live trees, then applying published equations to obtain total tree biomass and nutrient content. At the Maine site biomass equations were developed by felling and weighing sample trees. The validity of the equations was confirmed by sampling of some trees (Fig. 9). Estimates of nutrients removed in harvested products were obtained either by sampling trees for weight and nutrients at the landing as they were bucked or chipped, or by using the biomass data of the harvested trees. Broken and unmerchantable material that remained on site after harvest was measured for weight and nutrients on a series of sample plots.



Figure 9.—Dissected red spruce for determining weights and nutrient contents of leaves, branches, and stems.

Streamwater samples were collected biweekly during the 2 years preceding harvest. The samples were analyzed for turbidity, temperature at time of collection, pH, and the nutrients important to water quality and plant growth, including nitrogen (N), potassium (K), magnesium (Mg), calcium (Ca), and phosphorous (P), as well as sulfate ( $\text{SO}_4$ ), chloride (Cl), and sodium (Na). Soil solution, which is the water held within the soil, was analyzed for the same elements about once per month from May to November using suction lysimeters (Fig. 10). Lysimeters were located at several sites and depths on both the control and treatment watersheds. Precipitation was measured and chemically analyzed biweekly.

During and immediately after harvest, streamwater was sampled more frequently, sometimes daily, until obvious effects of harvest began to lessen. Stream sampling was then continued at biweekly intervals for several years, or until nutrient concentrations, sediment, and temperature returned to preharvest levels. Sampling of soil solution was continued at monthly intervals through the third growing season after harvest.

Physical soil disturbances due to logging at each site were measured and categorized into five classes (Fig. 11). Regeneration on the harvested sites, including herbs, shrubs, and tree seedlings and sprouts, was counted periodically on permanent plots, and sampled for biomass and nutrient content.

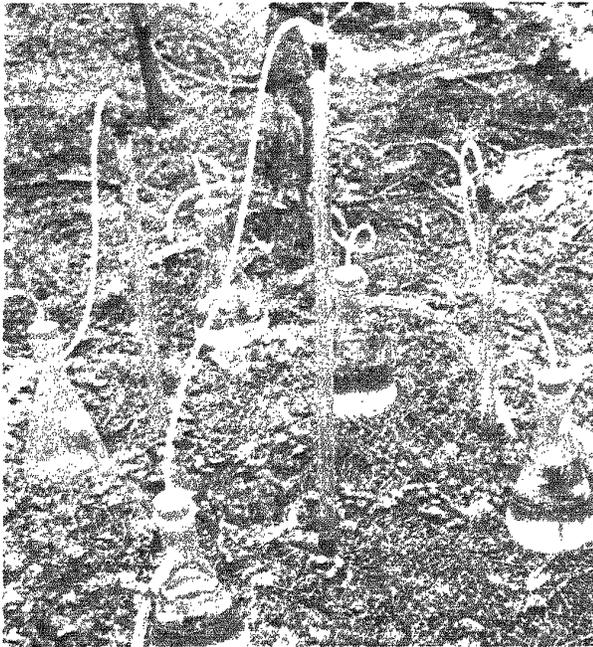


Figure 10.—Samples of soil solution being extracted with suction lysimeters.



Figure 11.—Categorizing and measuring depth of soil disturbances along a transect at the Vermont site.

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## Disturbances to Forest Floor and Mineral Soil

Over the last four decades, it has become increasingly economic on large forest tracts to use WTC rather than partial cuts, mechanical harvesters rather than chainsaws, and wheeled skidders rather than the crawler type of forwarding equipment. These changes have brought about an increase in soil disturbance of the harvested area. At the New Hampshire and Maine whole-tree clearcuts, more than 92 percent of the soil surface was disturbed; at the Vermont site, 98 percent of the area was disturbed. Only 71 percent of the Connecticut site was disturbed because the remainder of the area was too steep and rocky for the operation of heavy mechanical equipment.

Whole-tree clearcutting can disturb the structure and function of forest soils through physical damage by logging equipment. Mechanical soil disturbance can range from light scarification, often beneficial, to regeneration, to complete removal of the forest floor, exposing usually less fertile mineral soil, to severe compaction and deep ruts, which destroy soil structure and reduce or eliminate regrowth for at least several years.

## Scarification

Scarification, the mixing of the organic layers in the forest floor with the mineral soil beneath, without compaction, occurred on 6 to 24 percent (Fig. 12) of the area for all sites. Scarification can serve as a beneficial seedbed preparation in the northern hardwood forest type where birch is the preferred species for natural regeneration. However, it is of little value in the oak-hickory type, and is detrimental where birches are undesirable competitors in the spruce-fir type. Yet, scarification was most prevalent at the spruce-fir site. In addition, much of the advance reproduction of spruce and fir seedlings was destroyed during the harvesting operation.

## Compaction

Compaction reduces the large pore space in soils, thus inhibiting root penetration, aeration, and infiltration capacity, which may lead to soil saturation, erosion, and reduced seedling growth. Compaction from all sources occurred on 48 to 81 percent of the areas at three sites (compaction and ruts were not measured at the Vermont site), of which 39 to 74 percent were machine-made wheel or track ruts. Potentially serious compaction caused by wheel ruts deeper

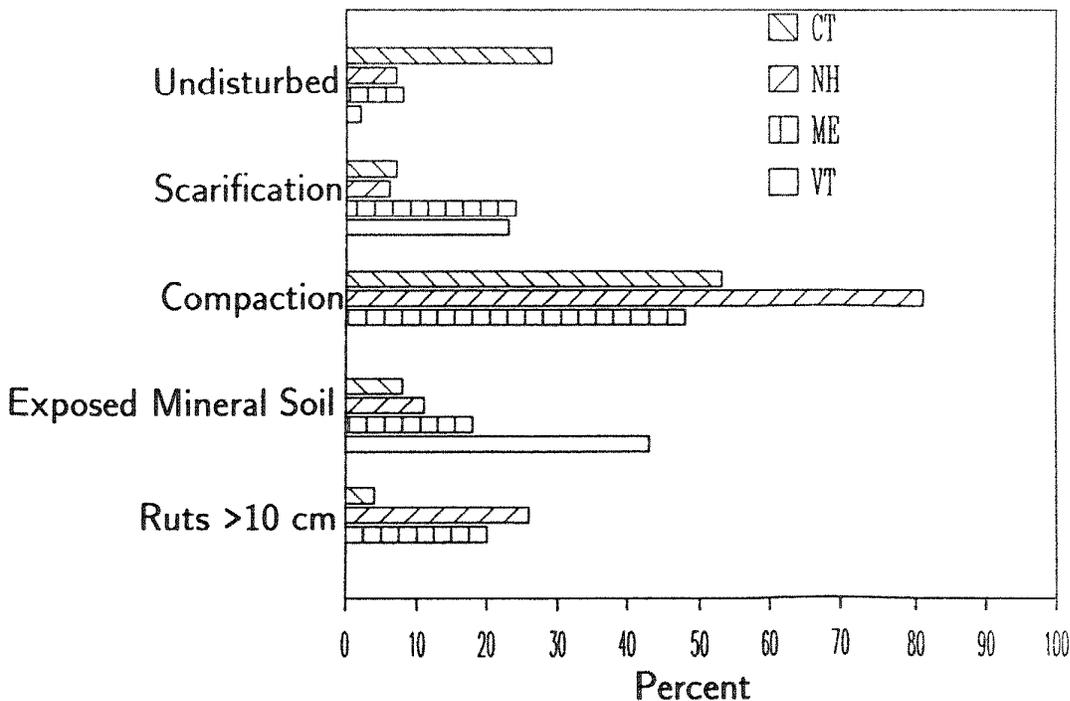


Figure 12.—Percentage of soil disturbances by category for three whole-tree clearcuts. Percentages for each site do not sum to 100, since ruts are a form of compaction and often contain exposed mineral soil.

than 10 cm, usually into mineral soil, occurred on only 4 percent of the Connecticut site because the soils were well- to excessively well-drained and stony. Soil compaction on the well-drained Vermont site, as measured by increase in bulk density, was negligible. On all sites, slight to moderate surface compaction probably is alleviated by frost and water action in a few years.

### **Exposed Mineral Soil**

Exposed mineral soil (8 to 43 percent at the four sites) generally is considered detrimental to regeneration. Glacially derived mineral soils at these sites are low in fertility and are not conducive to vigorous regeneration. Exposed mineral soil can become crusted and compacted, solely by rainfall impact, to the point where seedling roots may have trouble penetrating the soil.

### **Ruts**

Ruts deeper than 10 cm occurred on 26 percent of the New Hampshire site, which had little microtopography, allowing skidder operators to drive extensively over the site. The

Maine site had the deepest ruts with 3 percent of the area in ruts greater than 30 cm. Deep ruts may divert subsurface water flow, channel it, and lead to severe erosion. Ruts also may form pools of stagnant water, which disappear only through evaporation. This water-logging, though often only temporary, may be deleterious to regeneration.

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## Beginnings of the Next Forest

In northeastern forests, WTC is a silvicultural tool for even-aged management. In general, WTC dramatically alters the vegetative characteristics of a stand. Basal area and biomass are reduced nearly to zero and 50 to 100 years may be required for another forest to mature. During this time, basal area and biomass increase, density of stems decreases, and several definite shifts in species dominance take place.

### Basal Area, Density, and Biomass

Before cutting, basal areas were 23, 26, 29, and 48 m<sup>2</sup>/ha in Connecticut, New Hampshire, Vermont, and Maine, respectively. The higher basal area in Maine is typical of shade tolerant species, for example, spruce and fir. With a minimum diameter of approximately 5 cm d.b.h. for WTC, effectively all of the basal area was cut on each site.

Stump sprouting and germination of new seedlings began in the first growing season after harvest. Within 5 years after cutting, young, dense stands (3000 woody stems/ha or more) were established on all four sites. Above-ground living biomass of saplings 72 cm d.b.h. had increased from near zero to 6.5 Mg/ha in Connecticut by 5 years after cutting. Within 6 years after cutting, above-ground biomass averaged 9.5 Mg/ha in Vermont. We expect that 75-100 years will be required on each site to establish pre-cutting levels of basal area, biomass, and density. We continue to monitor regrowth, but it does not appear that WTC has permanently altered the overall character and species composition of these forests.

### Age Structure

Before cutting, all of the study sites were occupied by mature stands, dominated by trees 65 years old in Vermont, 80 years old in Connecticut, and mixed ages in New Hampshire and Maine. WTC imposed a distinct even-aged structure, likely to persist for 75-100 years, on the forest. Mechanical activity of skidders over most of each site crushed or damaged existing seedlings. Thus, WTC did not favor release of advance regeneration at the New Hampshire, Vermont, and Connecticut sites. Regrowth was composed primarily of stump sprouts and seedlings germinating from buried seeds and propagules borne by wind or animals. Advanced conifer regeneration on the Maine site was damaged during harvest, yet many seedlings were released and survived to start the next generation.

### Species Composition

Major changes in the forest environment brought about by WTC initiate a series of shifts in species dominance over several decades. Although the relationships between precut forests, young revegetation, and the desired commercial forest are not obvious or well understood, some patterns have been noted.

The openness of the cutover area, scarification of the soil surface, and the absence of extensive slash on WTC sites

favored initial dominance by shade-intolerant species. Species like pin cherry and aspen in Vermont and New Hampshire, and chestnut and red maple stump sprouts in Connecticut, have dominated the respective sites in the first decade. Though commercially undesirable now, these trees serve an essential function in holding nutrients that otherwise might be lost through leaching from the site (Fig. 13). We expect that later emergence of more tolerant, commercially valuable species will be enhanced by this nutrient conservation.

At all four sites, species present in the pre-cut mature forest also are present in the regrowth, although the proportions are different. Typical of young stands, a wider diversity of species tends to be represented. Although the stand in Connecticut is currently dominated by red maple stump sprouts, we expect that the vigorous red oak and chestnut oak component, present in the understory, will emerge into dominance over the next 15 to 20 years. Application of herbicides to the site in Maine has promoted spruce and fir dominance.

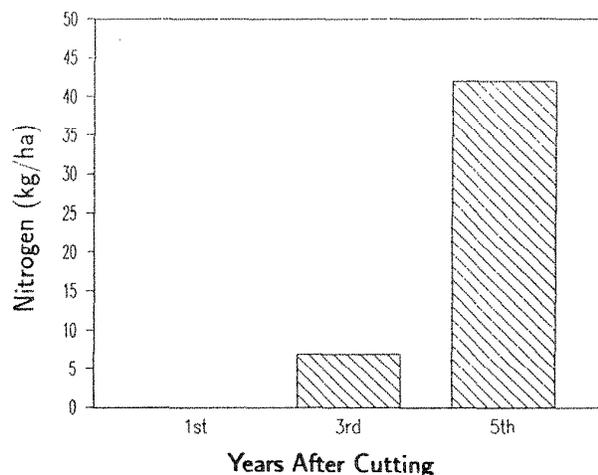


Figure 13.—Accumulation of N in biomass of saplings of commercial and noncommercial trees 72.0 cm d.b.h. at Connecticut site.

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## Nutrient Losses and Long-Term Productivity

Forest harvest of any kind removes some nutrient elements in the harvested product; clearcutting may cause further nutrient loss by increased soil leaching. In WTC, harvest removal of nutrients is maximized and rotations are often expected to be shorter. What does this mean in terms of maintaining long-term forest productivity?

### Biomass and Nutrient Removals

Whole-tree clearcutting removed 91 percent of the above-ground biomass in Connecticut and Vermont, 90 percent in Maine, and 96 percent in New Hampshire (Table 2). At the Connecticut site removals were reduced because there were substantial amounts of unmerchantable shrubs, principally laurel, that were felled but not skidded, and also standing dead material that broke during felling or skidding and remained on site. In contrast, the New Hampshire site was a young, vigorous stand with practically no understory, and most trees were felled and skidded with a minimum of breakage and loss.

In addition to the whole-tree clearcuttings, a stem-only clearcutting was conducted at the Vermont site, and

**Table 2.—Above-ground biomass and removals for the four study sites. The numbers in parentheses are percent of above-ground biomass removed**

Site	Uncut forest	Removed by whole-tree clearcutting		Removed by stem-only clearcutting	
		Mg/ha	%	Mg/ha	%
ME	232	211	(90)	151	(65 <sup>a</sup> )
NH	116	111	(96)	87	(75 <sup>a</sup> )
VT	212	193	(91)	137	(65)
CT	181	158	(91)	121	(67 <sup>a</sup> )

<sup>a</sup>Estimated from biomass equations.

biomass equations were used to estimate stem-only removals at the Maine, Connecticut, and New Hampshire sites. WTC removed from 24 to 26 percent more of the original biomass than stem-only harvest in Maine, Connecticut, and Vermont, and 21 percent more in New Hampshire (Table 2), (Fig. 14).

Nutrients, such as N, Ca, and K, are removed in the harvested biomass. Nutrient contents in whole-tree harvested biomass are much higher than in stem-only



**Figure 14.—Whole-tree clearcut on the Vermont site removed. Ninety-one percent of the above-ground biomass removed, leaving a relatively slash-free surface.**

harvested biomass (Table 3) because large proportions of the nutrients are located in the branches and leaves (approximately 1/2 the above-ground biomass). The combined effect of removing 21 to 26 percent more of the original biomass in a WTC compared to a stem-only clearcut, and the richer concentration of nutrients in a WTC, account for the greater removal of nutrients. As a result, depending upon the site and the nutrient, WTC removed from 1.2 to over 3 times the nutrients removed with conventional stem-only clearcutting (Table 3).

The difference in nutrient removals between whole-tree and stem-only clearcutting is greater in young stands than in older stands, because a greater proportion of stand biomass is contained in the nutrient-rich crowns of young stands.

### Nutrient Availability

Amounts of soil nutrients may be divided into "plant available" nutrients, which include nutrients in soil solution and those held loosely by soil particles, and "unavailable" nutrients, which include nutrients contained within primary and secondary minerals and undecomposed organic matter. The "total" reserve of soil nutrients includes both available and unavailable forms of each element required for plant nutrition (Table 4). Because there may be large differences between the total nutrient reserves of the soil and the plant-available soil nutrient contents, the estimated ability of the soil to supply future rotations with adequate amounts of nutrients depends upon the form of the nutrient required for plant growth and upon those soil processes that regulate the availability of nutrients to plants.

**Table 3.—Biomass and nutrients removed from whole-tree clearcut sites (WTC) compared with removals from stem-only clearcuts (SOC). SOC values for Maine, New Hampshire, and Connecticut were estimated from equations of biomass and nutrient concentrations in biomass**

	Biomass			Nitrogen			Calcium			Potassium		
	--kg/ha-- WTC	--kg/ha-- SOC	--ratio-- WTC/SOC									
ME	211	151	1.4	376	112	3.4	494	226	2.2	224	100	2.2
NH	111	87	1.3	242	136	1.8	344	224	1.5	129	84	1.5
VT	193	137	1.4	398	207	1.9	1136	761	1.5	282	197	1.4
CT	158	121	1.3	273	162	1.7	530	442	1.2	162	108	1.5

**Table 4.—Total on-site amount of N, Ca, and K, and annual input in precipitation and output in streamflow for five mature forests. ME, NH, VT, and CT represent the four WTC sites. HB indicates a northern hardwood forest at the Hubbard Brook Experimental Forest, New Hampshire**

Location	Above ground	Roots	Forest floor	Mineral soil	Total	Annual input (precipitation)	Annual output (streamflow)
	<i>kg ha<sup>-1</sup></i>					<i>kg ha<sup>-1</sup> yr<sup>-1</sup></i>	
NITROGEN							
ME	410	140	920	5830	7300	4	0
NH	260	190	1740	4800	6990	6	3
VT	400		2970				
CT	300	120	1000	3600	5020	8	0
HB	350	180	1300	5900	7730	6	4
CALCIUM							
ME	540	190	380	10330	11440	1	16
NH	360	120	490	7570	8540	1	15
VT	1140						
CT	590	240	100	3320	4250	2	10
HB	380	100	370	9600	10450	2	12
POTASSIUM							
ME	240	80	70	10000	10390	0	2
NH	140	70	80	5080	5370	1	2
VT	280						
CT	180	70	70	5040	5360	5	5
HB	160	60	70	5080	5370	1	2

The rate at which nutrients become available for plant growth from sources such as organic matter decomposition, primary and secondary mineral weathering, and precipitation, will be crucial to maintain forest productivity in the long run. There is considerable uncertainty regarding the rate of replenishment by these natural sources of nutrients.

Although the proportion of the total soil nutrient capital required to resupply a succeeding rotation with nutrients appears small for most elements, our estimates indicate that the available amounts of K, Ca, and Mg may not be adequate for the requirements of the next rotation on some sites. Further, if rotation lengths are considerably reduced, and the practice of WTC continued, nutrient removals will be accelerated, perhaps to levels that are critical for sustained forest growth.

The greatest potential for reductions in productivity after WTC may be in the early stages of the following rotation when the trees depend on the nutrient supplying power of the soil to meet their demands. After canopy closure, the recycling of nutrients by standing trees probably will reduce overall demands on soil nutrient reserves and lessen the impact of the reductions in site fertility caused by whole-tree removals. This reduction in nutrient demand from the soil reserves will occur for two major reasons. First, after canopy closure, the annual increment in crown biomass is reduced greatly, and trees satisfy a significant percentage of current-year nutrient demand with nutrients recycled within the crown. In addition, the majority of stand biomass increment after crown closure will take place in stem-wood production; and since stemwood has relatively lower nutrient concentrations, the annual uptake rate of nutrients also will be reduced. The second important reason the stand will depend less on the soil nutrient reserves after crown closure is that the amount of nutrients annually recycled within the forest floor is capable of supplying a significant portion of stand uptake requirements. Sites with existing shortages of nutrients, either because of small total supplies or limiting amounts of plant-available nutrients, should not be whole-tree clearcut if long-term productivity is to be maintained, unless future management plans include the addition of fertilizer or another source of nutrients, such as sludge or wood ash. Soils of immediate concern include glacial outwash sands, shallow-to-bedrock soils, and other soils of suspected low fertility.

### Forest Floor

The organic matter accumulated on the soil surface is variously called the "forest floor," "litter," or "humus layer," but is most properly called the "O horizon." This layer is composed of organic debris derived primarily from dead plant material, such as leaves, twigs, tree trunks, and roots. The organic matter is in various stages of decomposition by soil organisms, and is an important source of many nutrients. Clearcutting of northern hardwoods leads to a decrease in thickness, organic content, and nutrient content of the O horizon. Within 3 to 15 years after cutting, the O horizon is reduced by about one-half. The reduction is caused by: 1) increased decomposition through physical, chemical, and biological activity because the soil

surface is warmer and has more fluctuating moisture conditions. 2) mechanical mixing into mineral soil during harvest, and 3) movement into mineral soil by organisms and organic leaching. Over the next 50 to 100 years, barring a major disturbance, the O horizon tends to reaccumulate. The relative magnitudes of the three reduction processes, and their effects on nutrient availability over a rotation, are not fully known. Effects of WTC on O horizons in spruce-fir and central hardwoods are insufficiently studied, but WTC by heavy machinery in spruce-fir causes considerable mixing of O horizon and mineral soil (see Disturbances to Forest Floor and Mineral Soil).

Because of both O-horizon reduction, or disappearance, and lack of woody litter in the early years of succession, nutrient availability, particularly of N and P, probably is lowest in the second and third decades after cutting. Fertilization may have the maximum effect at this time, but very little research has been done in the northeast to substantiate this claim.

### Nitrification

Decomposition of organic matter produces ammonium ions ( $\text{NH}_4$ ), a form of N that can be used for tree growth. The ammonium ions are held primarily by organic or mineral particles on soil cation exchange sites, from which they can be taken up by plant roots. Such ammonium ions are not easily leached. However, within a few months after clearcutting or WTC, there is an increase in the populations of bacteria able to convert ammonium to nitrate ( $\text{NO}_3$ ) nitrogen in the nitrification process. Soil nitrate can be used by plants but also is dissolved in soil water and therefore, is easily leached from the root zone. The causes of increased nitrification following cutting are not definitely known but may be related to reduced ammonium uptake by plants, to reduced inhibition by plant-produced tannins or increased ammonium substrate leading to increased nitrifier populations. At the Maine study site, nitrification increased the most in the better-drained soils and was very small in poorly drained soils. Nitrate in lower mineral horizons of our WTC areas increased manyfold in the first or second year after cutting. Nitrate levels consequently increased in streams draining the cut areas (see Protecting Forest Streams).

Elevated nitrate after cutting could lead to denitrification, which is the bacterial conversion of nitrate to gaseous  $\text{N}_2\text{O}$  and  $\text{N}_2$ . Denitrification occurs when nitrate moves through saturated organic soils. This may be one reason stream nitrate concentrations sometimes are much less than soil nitrate concentration, but at present we do not know if denitrification removes significant amounts of N. In any case, denitrification loss is a loss from the site capital.

Reestablishment of vegetation on the harvested sites rapidly reduced nitrification again. At all of the sites, soil nitrate levels were back to pre-cut values within 3 years after cutting. However, in Maine a herbicide application to suppress herbaceous vegetation and regenerating hardwoods and to release conifers induced a second flush of nitrification, with consequent additional leaching loss of N.

### Cation Leaching Losses

The nitrification process releases hydrogen ions; these, in turn, displace cations, such as Ca, Mg, and K, from exchange sites. These cations then leach from the soil with the nitrate, and their concentrations in streamflow increase (see Protecting Forest Streams). Loss of cations continues for a greater period than that of nitrate after WTC. Potassium concentration in streamwater, in particular, may remain elevated for more than 10 years after cutting in northern hardwoods. The reasons for continued elevated cation losses are not known.

The leaching loss of nutrients following cutting is small compared to nutrients removed in the harvested products (Table 5). However, the leached nutrients are in forms most readily available to plants. Leaching loss thus affects availability in the short term, for the several years just after cutting. In contrast, harvest removal affects availability in the long term, over the next rotation, or perhaps permanently.

### Long-Term Recovery

Biomass removal by WTC represents an important reduction of the total amount of N, Ca, and K on the site.

**Table 5.—Harvested removal and additional leaching loss caused by WTC and the fraction of total amount of N, Ca, and K removed by both processes, for five study sites. ME, NH, VT, and CT are the four subject WTC sites. HB is a northern hardwood forest at the Hubbard Brook Experimental Forest, New Hampshire**

Location	Harvested	Additional Leaching	Fraction of total removed
	-----kg ha <sup>-1</sup> -----		%
Nitrogen			
ME	380	6	5
NH	240	6	4
VT	380		
CT	270	19	6
HB	315	58	5
Calcium			
ME	500	43	5
NE	340	30	4
VT	1090		
CT	530	28	13
HB	340	48	4
Potassium			
ME	220	29	2
NH	130	5	3
VT	270		
CT	160	23	3
HB	140	48	4

Additional losses by leaching to streamflow or groundwater are smaller but often are still significant. A single WTC on our study sites removed 4-6 percent of the total N, 5-13 percent of the Ca, and 2-3 percent of the K (Table 5). These results are quite consistent and agree with other studies.

If site productivity is to be maintained, these losses must be made up over a rotation by external inputs. Precipitation provides the most important input of nutrients. This input is routinely measured at many locations. Additional inputs in dry deposition from the atmosphere, for example dust and pollen, and from weathering of rocks, are very difficult to measure. They are thought to be smaller than precipitation input. Fertilizer also is an input option, but often is not used in northeastern forests.

We have estimated the change in total amounts of nutrients over a 100-year period with zero, one, or three whole-tree clearcuts (Table 6). Because of high nitrate input from air pollutants, nitrogen is fully replaced in a 100-year rotation. With three harvests per 100 years, however, N will be depleted by 5 to 10 percent on most sites. We do not know if dry deposition of N is significant enough to improve N recovery.

**Table 6.—Estimated percent change in total amount of N, Ca, and K over 100 years, for no cutting and for whole-tree clearcutting on 100-year and 33-year rotations at four study sites. Calculated as  $[100 \times (\text{Annual Output} - \text{Annual Input}) + n \times (\text{Harvested} + \text{Additional Leaching})] / \text{Total}$ , where  $n = 0, 1$  or  $3$ . ME, NH, and CT are the three WTC sites. HB is a northern hardwood forest at the Hubbard Brook Experimental Forest, New Hampshire**

Location	Change in total amount over 100 years		
	No cuts	1 cut	3 cuts
	----- % -----		
Nitrogen			
ME	+ 5	0	-10
NH	+ 4	+ 1	- 6
CT	+16	+10	- 1
HB	+ 3	- 2	-12
Calcium			
ME	- 13	-18	-27
NH	- 16	-21	-29
CT	- 19	-32	-58
HB	- 10	-13	-21
Potassium			
ME	- 2	- 4	- 9
NH	- 2	- 4	- 9
CT	0	- 3	-10
HB	- 2	- 5	-12

For K, precipitation input and leaching output are nearly balanced in the undisturbed forest, so removals resulting from harvested products and increased leaching associated with WTC are not replaced. Depletion averages 4 percent in 100 years for a single harvest, and up to 10 percent for three harvests. The contribution of rock weathering is not known. The behavior of Mg is similar to that of K. Phosphorous input and leaching output are negligible. A WTC harvest will remove only several percent of total P in 100 years.

Because acidic precipitation in New England causes large annual losses of Ca, even in the absence of cutting, we are concerned about the general depletion of Ca from northern forests. With WTC, the loss of Ca is 13-33 percent in 100 years for one harvest and 21-58 percent for three harvests at the four sites examined. Acid precipitation and WTC harvest removal contribute about equally to Ca depletion. It is likely that repeated harvests over short rotations will lead eventually to Ca deficiencies. Calcium depletion already may contribute to red spruce mortality at high elevations. Replacement of Ca by liming probably will be necessary on sites with high utilization. However in most northeastern forests, liming will be too expensive and impractical. Using stem-only harvest instead of WTC considerably reduces the Ca removal, but does not eliminate it.

The tradeoff between current economic benefits of any management practice and long-term gain or loss of site productivity always has been difficult to evaluate. The results of our research suggest, but do not demonstrate, the rotation lengths necessary to regain lost nutrients in the absence of fertilization. Likewise, our results do not specify how much productivity will be reduced with shorter rotations. Computer simulation models that predict rotation length based on various assumptions about utilization and rates of recovery are beginning to be used. But verification of these models requires time for WTC forests to regrow.

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## Protecting Forest Streams

Whole-tree clearcutting has potential for harming forest streams. However, by understanding the possible impacts and concerns, forest managers can tailor harvest operations to protect streams, and even create some changes that are beneficial.

Stream quality has received increasing attention in the past decade as foresters strive to comply with the Clean Water Act of 1977. The Act designates forest harvesting as a nonpoint source of stream pollution, and mandates state agencies to determine "Best Management Practices" for protecting streams. WTC is a special concern because it is still a relatively new practice and there are uncertainties as to how the accompanying mechanization, increased biomass removals, and soil disturbances will affect stream quality.

### Stream Volume

Harvesting the forest reduces transpiration and the amount of rain and snow that evaporates after being intercepted by leaves, branches, and stems. Evaporation from the forest floor increases after harvest, but only partially offsets the reductions in transpiration and interception. Thus, soils on recently harvested sites are wetter, and more water is available for streamflow. Streamflow for the first year after WTC was increased by 63 percent (310 mm) in Maine, 45 percent (220 mm) in New Hampshire, and 22 percent (270 mm) in Connecticut (Table 7). The increases taper off with revegetation, and it can be expected that annual stream volume after WTC will be nearly like that from uncut forests by approximately the 6th year of regrowth.

**Table 7.—Impact of harvest on annual volume of streamflow**

Location	Year after harvest	Streamflow if uncut	Actual streamflow	Change
		<i>mm</i>		
ME	1	490	800	+ 310
	2	330	620	+ 290
	3	400	610	+ 210
NH	1	490	710	+ 220
	2	350	510	+ 160
	3	600	770	+ 170
CT	1	1210	1480	+ 270
	2	1020	1120	+ 100
	3	580	65	+ 70

Because WTC nearly eliminates evaporation from plants, most of the annual increase comes in the summer or early autumn when streams normally are at low levels. These increases in stream volume provide a more favorable

environment for stream biota, and can be an important benefit when forest streams serve as municipal water supplies. The increases become a concern when they occur as additions to peak flows and overtop culverts, cause flooding, or lead to greater erosion along skid roads and stream channels. This can happen in heavy summer storms.

The amount of streamflow in winter and during spring snowmelt is likely to be about the same for WTC sites and uncut forests because soils in both cases are near saturation. Transpiration processes at this time are not active to create differential soil water contents. However, snowmelt discharge usually will occur earlier in WTC sites compared to uncut forest sites because of greater exposure to sunlight. The difference in timing of snowmelt between recently harvested and older forests helps reduce snowmelt flood peaks.

### Turbidity

We took samples at the base of the control and treatment watersheds, usually at biweekly intervals and during large storms, and analyzed them for turbidity, an indicator of erosion and stream sedimentation. The results are expressed as Jackson Turbidimeter Units (JTU). Streams from undisturbed forests usually have JTU values close to zero. A value of 10 JTU or less usually is considered desirable for drinking water.

At the Maine site, samples with 12 and 17 JTU occurring at the middle of the harvest operation, were the only ones exceeding the usual drinking water standard of 10 JTU. The maximum turbidity sampled on the uncut control watershed was 3 JTU. At the New Hampshire site, measured turbidities for the harvest watershed during and 2 years after harvest were < 1 JTU except for two values of 2,200 and 3,300 JTU. These high values occurred during harvest and resulted from failure of a skidroad culvert. Samples from the control watershed always had < 1 JTU. The maximum value for the harvest watershed at the Connecticut site was 8 JTU, while all values for the control watershed were < 1 JTU.

Except for the two occasions at the New Hampshire site, WTC caused only minor changes in stream turbidity. A large amount of soil disturbance at the Maine site (see Disturbances to Forest Floor and Mineral Soil) did not increase turbidity because the harvest site is fairly level and there is little opportunity for soil to be transported to streams. The New Hampshire and Connecticut sites are steeper, with some slopes exceeding 10 percent. Extra precautions were taken at these sites to prevent turbidity. At the New Hampshire site, a buffer strip left along the stream channel was effective, and half the area was logged when there was a deep snowpack protecting the forest floor. The Connecticut site also was logged during winter. Although

snow cover was not continuous, logging conditions generally were favorable, and efforts were made to keep logging disturbances at a minimum close to the streams. Thus, our findings indicate that WTC need not cause large increases in stream turbidity or sediment so long as care is taken with stream crossings during logging.

### Temperature

Harvesting the vegetation shading stream channels increases stream temperatures because it increases exposure to direct sunlight. During our study, stream temperatures were taken at the base of control and harvested watersheds at biweekly intervals. Such periodic measurements indicate whether temperature is affected, but are likely to miss the maximum changes that occur.

After harvest at the Maine site, stream temperatures were frequently 4°C higher for the harvest watershed than for the control, and averaged about 2°C higher. At the New Hampshire site, the buffer strip protected the stream against any significant changes in temperature. Paired measurements for the control and harvested streams were never greater than 2°C apart, and usually were within 1°C. On the other hand, temperatures in streams from the harvest watershed at the Connecticut site, where there was no streamside buffer strip, were as much as 16°C higher than those from the control. This large increase in stream temperature is indicative of what may happen when shade provided by the mature forest canopy is completely eliminated.

Our study sites are drained by small, headwater streams. The changes in temperature caused by WTC are likely to disappear quickly once the streams pass into uncut forests. However, if stream temperature is a concern, data from the New Hampshire site clearly show that temperature increases can be prevented by leaving a streamside buffer strip.

### Chemistry

Forests help regulate stream chemistry by storing nutrients in the standing vegetation and forest floor, and by influencing the flow of water through the soil. Soil disturbances and cutting of the forest can interrupt the nutrient regulating ability and bring about increased leaching of ions to streams (see Nutrient Losses and Long-Term Productivity).

Stream samples from our study sites were analyzed for 10 major nutrient ions (calcium, magnesium, sodium, potassium, hydrogen, nitrate, sulfate, ammonium, chloride, bicarbonate). Concentrations of most of these ions were changed to some extent by harvest. The maximum increase usually was in the nitrate ion ( $\text{NO}_3^-$ ). Nitrate is of special significance since it is a major form in which nitrogen cycles in and out of forests.

At the Maine site concentrations of nitrate in streams draining uncut forests averaged 0.2 mg/L. After WTC, nitrate rose to maximums of 3 to 4 mg/L, primarily during

the dormant season (Fig. 15). For the New Hampshire site, nitrate concentrations began to increase shortly after the summer harvest, and exceeded the control watershed by 1 to 3 mg/L about 6 months later (Fig. 15). Nitrate concentrations usually were extremely low (<0.02 mg/L) in streams draining uncut forests at the Connecticut site. Nitrate began to respond approximately 6 months after completion of the WTC and reached a peak of 6 mg/L during the growing season.

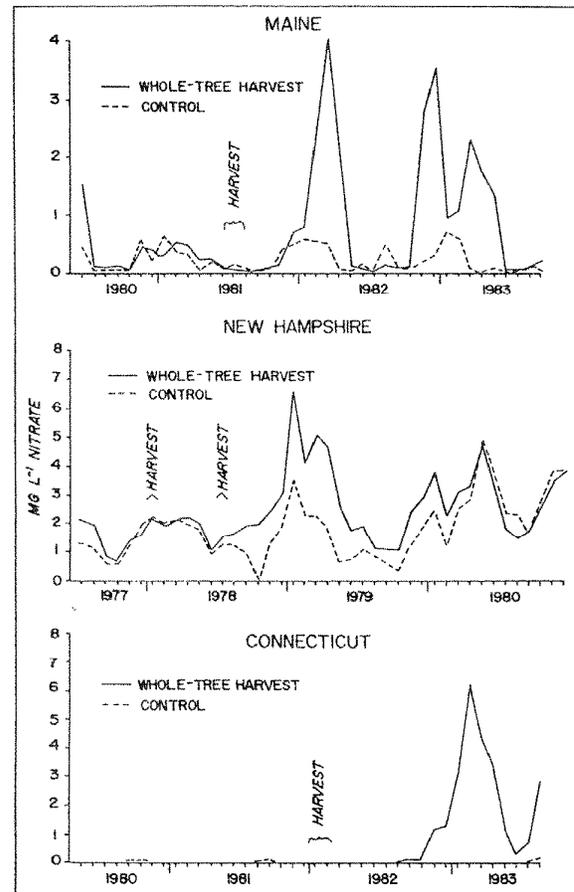


Figure 15.—Mean monthly nitrate concentrations in streamflow from control and WTC watersheds.

Calcium was the second most responsive ion after harvest, but it seldom increased more than 1 mg/L above levels on the control watershed. Stream pH was not adversely affected by WTC. Differences in stream pH between control and harvested watersheds at Maine were about the same before and after harvest (Fig. 16), indicating no response to harvest. The difference of approximately 1.0 pH unit between watersheds in the preharvest period is not unusual and reflects local variability of soils, even though the watersheds are adjoining. Results were similar for the New Hampshire site. Stream pH averaged about 6.5 for both the control and treatment watersheds, and was not changed by

harvest. Stream pH was affected at the Connecticut site, increasing from an average of 5.2 before harvest to an average of 6.4 for the first 2 years after harvest, and then returning to preharvest levels. The increase in pH at the Connecticut site means the stream became less acidic for stream biota and water quality.

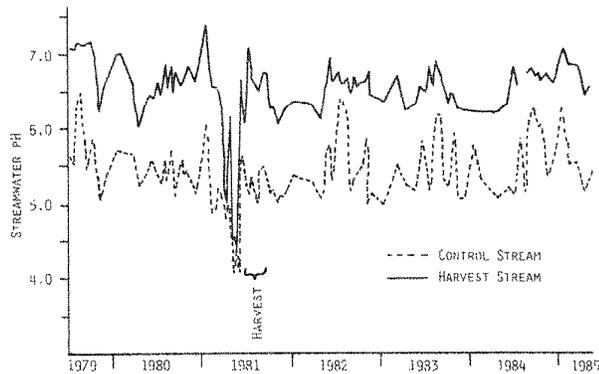


Figure 16.—Streamwater pH for control and WTC watersheds at the Maine site.

The changes in pH and concentrations of nitrate and Ca, and all other ions for that matter, are relatively short-lived. If natural regeneration is allowed to proceed, the ion concentrations in streams draining cutover areas usually return to preharvest levels in approximately 3 years. Site preparation activities such as herbicide application, scarification, prescribed burning, and fertilization may extend the increases.

There are at least three major questions about possible impacts of increased ion concentrations in streams. First, do the increases approach or exceed standards established for domestic, industrial, agricultural, and recreational users at downstream locations? Second, in terms of nutrient capital and future productivity of the harvested site, how important are the added nutrient ions carried away in streams? And third, what are the adverse and beneficial effects on stream biota?

The ion concentration standards established for protecting water use were not exceeded after whole-tree harvest at

any of the three sites. For example, the drinking water standard established for nitrate for health purposes is 45 mg/L. The maximum concentration of nitrate in streams at any of our study sites was less than 10 mg/L.

The importance of increased nutrient ion concentrations to site productivity has been discussed in *Nutrient Losses and Long-Term Productivity*. In general, the increased losses of nutrient ions to streamflow immediately after WTC were small relative to nutrients removed in harvested trees, and would be of concern only on sites having severe nutrient shortages.

### Stream Biology

Increased temperature and nutrients in streams within all clearcut openings usually increase algal and invertebrate populations, and, therefore, may increase fish populations. Species shifts in algae and invertebrates also occur. Temperature quickly decreases to pre-cutting levels wherever streams flow into shaded areas or regrowth provides new shade.

Soil and stream acidification induced by the combination of acid precipitation and WTC could adversely and ultimately affect stream organisms, including fish (see *Soil Acidification*).

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## Soil Acidification

Concern about acidic deposition on New England forests has generated considerable publicity and political activity. Studies link acidification of some lakes and streams with air pollution. Increased acidification rates of forest soils also have been linked to injury of forest trees. These concerns raise questions about the role of WTC in the acidification controversy.

Removal of the aboveground biomass in WTC eventually causes acidification of the system even in the absence of acid precipitation. Uptake of nutrient cations, such as calcium ( $\text{Ca}^{+2}$ ) and potassium ( $\text{K}^{+1}$ ), by the plants is greater than uptake of nutrient anions such as sulfate ( $\text{SO}_4^{-2}$ ) and phosphate ( $\text{PO}_4^{-3}$ ). To maintain charge balance, the growing trees must release hydrogen ions ( $\text{H}^{+}$ ) into the soil. In undisturbed forests, decomposition of organic matter reverses the process, and there is no net long-term effect. When biomass is removed from the site nutrient cations effectively are removed and  $\text{H}^{+}$  is left behind as a replacement. This acidifies the soil. The amount of acidification produced in our harvests is roughly equivalent to that caused by 50 years of pH 4.0 precipitation. (Precipitation of pH 4.0 is common in the northeastern U.S.). Thus, the contributions of harvest removal and acid precipitation to soil acidification are roughly equal in magnitude. This is particularly prevalent in many coarse New England forest soils that have low basic cation levels.

In the short term, however, WTC may lead to less acid conditions on some sites. A wide variety of processes is involved in the acidity of forest soils. Increased nitrification after cutting is acidifying, but increased weathering and decreased sulfate leaching may lead to neutralization. At the Hubbard Brook Experimental Forest in New Hampshire, stream pH tends to decrease briefly immediately after

cutting, and then to increase. We did not find decreases in stream pH at any of our WTC study sites.

Annual precipitation of 1000 mm at a pH of 4.0 is typical for New England and contributes at least 10 times the acidity of unpolluted precipitation. The forest floor, or O horizon, of the sites now has a pH less than 4.0 and will not become more acid. But in the mineral soil, pH increases to about 5.0 at 70 cm depth (the bottom of the root zone).

The buffer "capacity" (capability) of the soil is its ability to absorb acidity while limiting its pH change. The buffer capacity of the root zone of soils in our study areas limits the rate of change of soil pH to a maximum of one pH unit in 20-30 years. Studies on similar soils in the Adirondacks and in Sweden indicate an actual pH decrease of 0.5 units in the past 50 years, in the absence of harvest removal. The impact of this soil acidification on nutrient availability and productivity is not clear, but possibly is adverse. Harvest removal will further acidify the process. Furthermore, as soil pH of the lower mineral soil decreases, more hydrogen ions move through the soil to streams, increasing their acidity and possibly causing serious adverse effects on aquatic organisms.

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## Conclusions

Forests are extremely complex ecosystems whose existence and sustainability depend on many interacting biotic and abiotic processes. New England forest ecosystems have great amounts of both resistance to disruption of these processes (as indicated by generally small responses to severe disturbances such as WTC) and resilience, as shown by rapid recovery. However, cumulative long-term effects, such as gradual change in species composition, reduction of productivity because of nutrient depletion, and acidification of soils and streams, are still possible.

WTC alters both the forest stand and the site. Prudent forest management must be concerned not only with the most efficient and economical method of carrying out a WTC operation for a one-time gain, but also with the short- and long-term consequences of such practices. We recognize that it is not possible to examine each stand with the intense before and after measurements conducted in our research. It also is not feasible to conduct intensive research on all types of soil, topography, vegetation types, and climate in order to answer all forest management questions for all situations. However, we think the information achieved in our investigations of the four representative sites, which have a broad range of landscapes, soils, and vegetation, allows for meaningful extrapolations of the data to other areas in New England and regions having somewhat similar features where WTC is considered a management option.

The guidelines that conclude this document do not spell out "do's" and "don'ts," but strive to bring about awareness of the major factors to be considered in WTC practices. No two sites are alike. Thus, managers must interpret existing conditions and utilize the best available knowledge to carry out the task, always concerned with the sustainability and long-term productivity of the forest ecosystem.

## Guidelines

The decision to use WTC cannot be made easily or lightly. As with any harvesting practice, consideration must be given to effects on site productivity and regeneration, and to protecting soils, water quality, and other forest amenities. We have developed the following generalized guidelines for the New England region. More detailed information and assistance for a specific site may be available from state agencies, cooperative extension offices, or federal and university research laboratories.

## Protecting Soils and Enhancing Regeneration

Because WTC removes about twice the biomass of stem-only clearcuts, there is increased potential for soil

disturbance and erosion. Precautions usually taken during stem-only logging must be adhered to even more closely to protect soils and provide suitable seedbeds and growing conditions for the regenerating stand. Several precautions follow:

- Have a professional forester or an expert in locating logging roads and skid trails design the transportation network to minimize erosion, soil disturbance, and damage to water quality.
- Carefully select logging methods and equipment to reduce soil disturbance and minimize roads and landings. Newly designed, track-mounted fellers with low centers of gravity (Fig. 17) operate efficiently on slopes up to 20 percent, and usually cause less soil disturbance than rubber-tired equipment. On slopes exceeding 20 to 30 percent, cable systems may cause considerably less damage than fellers and skidders.
- Control erosion on disturbed areas such as skidtrails and roads by maintaining grade at 10 percent or less. On level stretches it may be desirable to excavate a small amount of slope into roads to obtain adequate drainage and prevent ponding. Cross drains and dips should be provided to direct moving water from roads and trails onto the forest floor. Placement interval in meters can be calculated as 300 divided by percent of grade.
- Minimize deep disturbances, such as rutting, that result in compaction, interception and channeling of soil water, and ponding. This can be accomplished by avoiding repeated trips over the same route, especially during wet conditions. Also avoid wet areas such as seeps and swamps. Track-mounted vehicles generally cause less rutting than wheel-mounted.
- Remain flexible regarding weather. When possible, roads should be built during dry weather. Skidding should be discontinued during wet periods, especially on easily compacted soils. Winter logging often is an option for particularly fragile sites. All operations should be completed as quickly as possible without increasing potential for erosion.
- Take extra precautions when incorporating scarification as part of the harvesting operation. Equipment operators should be given detailed instructions on varying routes to achieve scarification. Forwarding equipment that drags the tops of whole trees over the forest floor may provide good scarification.
- Upon completion of logging, check that all drainage devices are open, and revegetate problem areas.

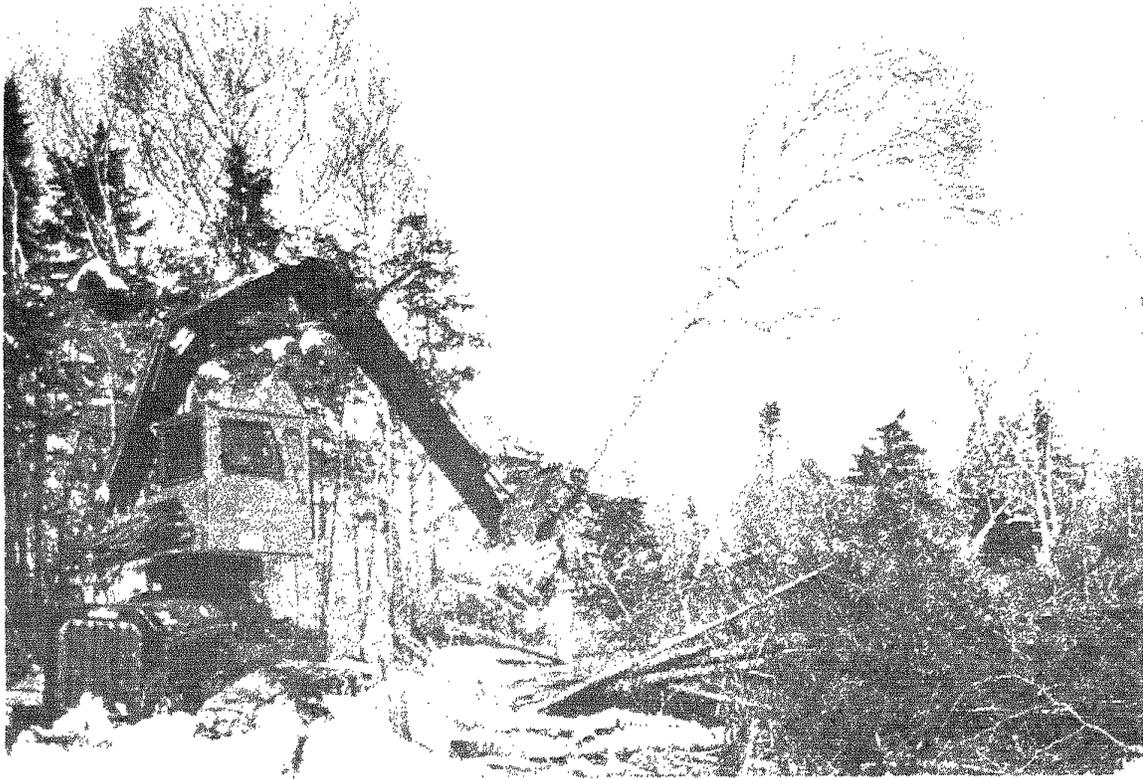


Figure 17.—Track-mounted feller that minimizes soil disturbance on steep slopes.

### Protecting Water Quality

As mandated by the Clean Water Act of 1977, each New England state has established guidelines for protecting water quality during and after logging operations. These guidelines, called Best Management Practices, or BMPs, can be obtained from individual state offices shown in Table 8. Increases in sediment and turbidity during and after logging are the primary concern regarding quality of forest streams in New England. Prevention of erosion is the main approach to protecting water quality, so many of the state guidelines are similar to those given above for protecting soils. Some additional guidelines more specific to streams are given below.

- Consider leaving a buffer strip of living trees along streams to trap sediment and shade the channel. We recommend a variable width of 15 to 30 m on each side of the stream. Actual widths depend upon factors such

as: stream gradient (the steeper the gradient, the wider the buffer); slope gradient and length to stream channel (steep slopes and short distances will require wider buffers); and soil characteristics (clay or highly erodible soils should have wider buffers).

- Keep to a minimum truck roads and skidtrails through buffer strips.
- Locate stream channel crossings, including intermittent ones, on bridges or closed culverts. Bridges usually are preferred because culvert installation and removal causes channel disturbance and produces sediment and turbidity. Stream crossings should be carefully located. A narrow place in the channel with low banks and firm, rocky soil is most favorable for a crossing. Deeply cut channels and those in soft, muddy soil are least favorable. Bridges and culverts should be removed upon completion of logging

**Table 8.—Addresses and phone numbers of state agencies responsible for administering Best Management Practices**

State	Agency address and phone	State	Agency address and phone
Maine	Maine Forest Service Station 22 Augusta, ME 04333 (207) 289-2791	Massachusetts	Division of Forest and Parks 100 Cambridge Street Boston, MA 02202 (617) 727-8893
New Hampshire	Department of Resources and Economic Development Division of Forest and Lands  P. O. Box 856 172 Pembroke Road Concord, NH 03302-0856 (603) 271-3456	Rhode Island	Division of Forest Environment 1037 Hartford Pike North Scituate, RI 02857 (401) 644-3367
Connecticut	Department of Environmental Protection Division of Forestry 165 Capitol Ave., Room 260 Hartford, CT 06106 (203) 566-5348	Vermont <sup>a</sup>	Department of Forests, Parks, and Recreation 103 South Main Street 10 South Building Waterbury, VT 05676 (802) 244-8716

<sup>a</sup>Guidelines for the state of Vermont are termed "Acceptable Management Practices."

### Protecting Site Productivity and Nutrient Capitals

- Avoid WTC on soil types and conditions with low fertility. Examples in the New England region are coarse-textured sands, and soils that are shallow to bedrock or have high seasonal water tables. These soils have either inherently low total nutrient capitals or low quantities of plant-available nutrients due to slow rates of weathering and mineralization. Such conditions are not always easily recognized, but help is sometimes available from maps and descriptions of forest soils.
- Consider existing species composition. Some species, such as oak, tend to sequester greater amounts of Ca. The potential for more rapid depletion of Ca when harvesting oak

stands should be carefully weighed, particularly for low fertility situations such as mentioned above.

- Plan hardwood harvests so that leaves and their associated nutrients remain on site. Harvesting in the dormant season is one option. Another is harvesting in the growing season, but felling several weeks in advance of skidding in order to allow leaves to dry and drop on site.
- Encourage rapid regeneration and renewed nutrient uptake to minimize increased nutrient leaching losses after harvest. Guidelines for protecting soils presented earlier under Protecting Site Productivity and Nutrient Capitals help insure that harvest activities do not interrupt nutrient supplies to regeneration.