United States
Department of
Agriculture

Forest Service

Northeastern Forest Experiment Station

General Technical Report NE-159

Ecology and Management of Northern Hardwood Forests in New England

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Abstract

Ecological, silvicultural, and hydrological knowledge of the northern hardwood forest type in New England is summarized for use by practicing foresters, landowners, managers, and planners. The summary draws heavily on research results from the Bartlett and Hubbard Brook Experimental Forests located in central New England and includes information on mature, recently-harvested, and regenerating stands. Guidelines are presented for harvesting northern hardwoods and for protecting stream-water quality, wildlife, and esthetics.

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Acknowledgment

Tracey Taylor-Lupien, Kenneth Dudzik, and Jane Hislop assisted with proofreading of text and preparation of figures and tables. Reviewers included M. Yamasaki, K. Smith, L. Tritton, S. Fay, R. Ferrin, and P. Pohl.

Manuscript received for publication 15 July 1991.

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July 1992

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Introduction

Today's practicing foresters and landowners must draw from a broad range of knowledge. Traditional management tools such as stocking guides and yield tables have important roles, but they must be supplemented with information on forest ecology. This combination, often termed the "ecosystem approach," permits forest managers to address wood production concurrent with concerns about ecology, environment, biodiversity, continued productivity, and forest amenities.

In this paper we summarize ecological and management information for one of New England's major forest types—northern hardwoods. Species and stand characteristics are presented for mature northern hardwoods, including methods of regeneration, damaging agents, hydrologic and nutrient cycles, and wildlife inhabitants. Impacts of harvest are discussed with regard to hydrologic and nutrient cycles, wildlife, esthetics, and stand regeneration. Guidelines are presented for harvesting northern hardwoods and for protecting stream-water quality, esthetics, and wildlife. The paper draws from research at the Bartlett and Hubbard Brook Experimental Forests located in the White Mountains of New Hampshire, and from other studies published over the past several decades.

Background

The northern hardwood type is identified by a predominance of American beech, yellow birch, and sugar maple, occurring either singly or in combination. There are a variety of associated species, with some of the more important being red maple, white ash, eastern hemlock, paper birch, quaking and big tooth aspen, eastern white pine, red spruce, and northern red oak (scientific names of plants mentioned in this paper are given in the appendix). Within the United States the range extends south from Maine to the southern Appalachians, and west to Ohio, upper Michigan, and eastern Wisconsin. In New England, the subject area, northern hardwoods occur on over 10 million acres, including small portions of Maine, Massachusetts, and Connecticut, and much of the forested areas of New Hampshire and Vermont (Fig. 1).

A variety of goods and services is provided by this northern hardwood forest. In 1985 there were approximately 175 forest-products plants within the mapped boundaries of the northern hardwood type in New England (Kingsley 1985). In addition, by the end of 1987 there were at least nine wood-fired electric generating plants utilizing some portion of northern hardwoods for fuel. The largest of these, a 50-megawatt plant operated by the Burlington Electric Department in northern Vermont, can consume over 600,000 tons of wood per year (Gove 1986).

In addition to providing wood products, northern hardwood forests serve as a base for recreation, especially for the approximately 100 million residents of the eastern United States and Canada who are within a one-day drive. The White Mountain National Forest, near the center of New England's northern hardwoods, has an estimated 2.3 million visitor days per year for activities ranging from viewing forested, mountain scenery—particularly during autumn coloration—to hiking and cross-country skiing. Several communities such as Lancaster, Woodsville, Littleton, and Twin Mountain, New Hampshire, rely on northern hardwood forested watersheds for municipal water supplies, and some small towns and recreation areas use forests to recycle municipal and industrial wastes. Northern hardwood forests also serve inadvertently as waste disposal sites by receiving industrial and other human-related pollutants in the form of wet and dry atmospheric deposition.

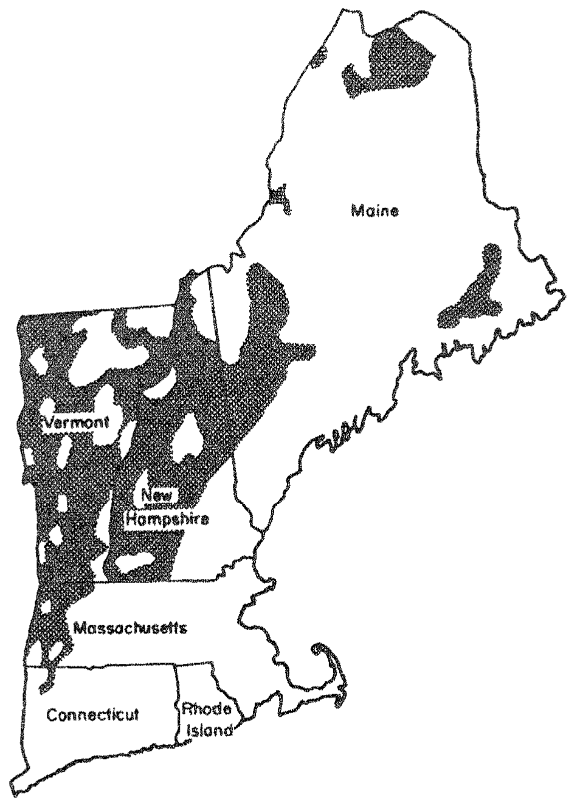

Figure 1. —Cross-hatching shows New England areas forested predominantly in northern hardwoods (Kingsley 1985).

The many demands on the northern hardwood resource sometimes conflict; the problem is made more difficult by diversity in land ownership. At present 9 percent of the northern hardwood lands in New England are in National Forest or other public holdings, 31 percent are owned by forest industry, and 60 percent are owned by other private landowners. This latter group includes many small holdings of a few acres, often held by absentee owners. The variety of uses and owners has made it impossible to develop any kind of regional or standardized approaches for managing northern hardwoods. Practically every stand must be considered as needing specially tailored recommendations.

Natural History

Studies of pollen in lake sediments show that northern hardwoods have been part of the New England landscape for the past 10,000 years (Davis et al. 1985). They are thought to have become dominant through their present range approximately 4,800 years ago by replacing dense stands of hemlock that had died throughout the region (Davis 1981).

Indians inhabited the northern hardwood forests in New England before European settlement, but seem to have had minor influence on the hardwoods (Likens 1972). Small populations are thought to have practiced agriculture along river bottoms and to have had no need for widespread clearing or burning. Also, there is little evidence that the presettlement forest was strongly affected by wildfire or catastrophic weather events. Lake sediments do not exhibit charcoal that would have washed in after periodic wildfires, and as pointed out by Bormann and Likens (1979), undisturbed northern hardwoods in New England do not seem especially susceptible to disastrous fires.

When European settlers arrived, the northern hardwood forest probably was much like that presently found in the Bowl Research Natural Area, a watershed in central New Hampshire that has had no logging or other major human disturbance. Leak (1973) and Martin (1974) describe the virgin stands at the Bowl as dominated by beech, yellow birch, and sugar and red maple, with admixtures of red spruce, balsam fir, and paper birch at higher elevations. The stands can be classed as old growth, but natural wind disturbances have caused a mixing of ages, ranging from seedlings to trees well over 200 years The basal area and above-ground biomass at the Bowl Research Natural Area are not significantly different from stands harvested 90 or more years ago, and there are few exceptionally large trees or parklike conditions often associated with virgin forests.

During the first half of the 19th century, European settlers developed hill farms by clearing large areas of northern hardwood forests from less steep slopes (Hamburg 1984). Some of these farms existed through the end of the century, but many were soon abandoned and began to revert to northern hardwoods (Bormann 1982). Logging began in earnest around the middle of the century, and reached a peak around 1900-1910. By 1920, supplies of readily accessible sawlogs and pulpwood were nearly exhausted, and practically all old-growth northern hardwood forests had been cut over. These early harvests were often in the form of "highgrades," removing only the high-value trees and leaving those of low quality and very young or very old ages. The area that presently comprises the Hubbard Brook Experimental Forest in central New Hampshire was harvested during the heydays, with horse-logging starting in 1908 and ending in 1918. The Bartlett Experimental Forest, located further to the east, was cut over in the years 1870 to 1900.

By the 1960's large areas of the northern hardwood forest had regrown to the point of being ready for another commercial harvest. For both economical and silvicultural reasons, much of the harvesting in the 1960's and early 1970's was carried out on clearcut blocks (Fig. 2).

Figure 2.—Block clearcuttings of northern hardwoods in New England (Photographed in 1971).

Concerns about the impact of clearcutting on nutrient cycles, forest productivity, esthetics, and recreation resulted in a national controversy (Horwitz 1974), and led to a more cautious approach to managing and harvesting northern hardwoods. Today's northern hardwood forest continues to be in a state of readiness for harvest. About 58 percent of the total area is classed as sawtimber, 33 percent as poletimber, and 9 percent as saplings and seedlings (Powell and Dickson 1984; Frieswyk and Malley 1985a, b; and Dickson and McAfee 1988a, b, c).

The Mature Northern Hardwood Forest

Species Characteristics

Sixty-five species of trees and shrubs have been cataloged on the Bartlett Experimental Forest, New Hampshire, a 2,600-acre tract typical of northern hardwoods in mid-New England (Filip and Little 1971). Of these, twenty are classified as large-to-medium trees, or those that attain commercial proportion. However, only species of 11 large trees and 2 small trees comprise the bulk of the northern hardwood community; the silvical characteristics of these species are listed in Table 1. Sugar maple and beech, with some component of red spruce, eastern hemlock, and striped maple, are the primary shade-tolerant species that dominate old-growth northern hardwood stands. Aspen, paper birch, and pin cherry are intolerant species that characterize young successional stands. Species of intermediate tolerance—yellow birch, white ash, and red maple (with some oak on certain sites)—are most predominant in mid-aged stands of approximately 80-120 years old.

The category of "early relative height growth" in Table 1 refers to the growth rate of seedlings or saplings, or both, growing in the open. Average diameters by species in a 25-year-old stand follow a similar trend, although pin cherry at this age probably is past its peak and is being overtaken by other species (Table 2). For stands beyond the seedling-sapling stage, annual diameter growth rates have been summarized by age, residual basal area, and species (Table 3). Hemlock, white ash, and red maple tend to be the fastest-growing long-lived species. Note also that

Table 1.—Silvicultural characteristics of northern hardwood species

Species	Shade tolerance	Early relative height growth	Potential life span, years	Relative site require-ments	Natural pruning	No. years between good seed crops	Sprouting vigor	Delayed germi-nation
Large trees								
Sugar maple	Tolerant	Slow to moderate	200-300	High	Poor to medium	3-7	Moderate—small stumps	Negligible
American beech	Tolerant	Slow	300-400	Medium	Poor	2-5	Low—stump sprouts High—root suckers	None known
Yellow birch	Intermediate	Moderate	300+	Medium to high	Medium	1-3	Low	Seldom
Paper birch	Intolerant	Fast	100-200	Medium	Good	2	Moderate—small stumps	None known
White ash	Intermediate (more tolerant as a seedling)	Moderate	200-250	High	Good	2-5	Moderate to high	Up to 75 percent
Red maple	Intermediate	Moderate	150	Low	Medium	1	High	Moderate[a]
Aspen	Intolerant	Very fast	30-100	Low	Good	4-5	High—root suckers	None
Northern red oak	Intermediate	Moderate	300+	Medium	Medium	3-5	High	None
Red spruce	Tolerant	Very slow	300-400	Low	Poor	3-8	None	None known
Eastern hemlock	Tolerant	Very slow	400+	Low	Poor	2-4	None	None known
Eastern white pine	Intermediate	Slow to moderate	400+	Low	Poor	3-10	None	None known
Small trees								
Pin cherry	Intolerant	Very fast	50	Low	Good			Up to 75-100 years
Striped maple	Tolerant	Moderate	70	Unknown	Medium			None known

[a]percentage may germinate 2nd spring

most species show a moderate response to lowered stand density, even in 70-year-old stands.

Diameter growth during the course of a growing season typically ends abruptly, as shown by cumulative growth curves for several white ash (Fig. 3); curves for other northern hardwood species in this study were comparable. Some response to rainfall occurred, but the nearly complete cessation of growth by August 1 appears related to some other factor, perhaps day length.

Life spans of northern hardwood species are highly variable. In stands free of major disturbances, maximum ages can range from 30 to 50 years for short-lived species such as aspen and pin cherry and from 300 to 400 years or more for beech, birch, and hemlock (Table 1). Leak (1985) gives a method for using tree diameter to predict ages of individual northern hardwood trees. The method works best for trees in old-growth stands or in stands that have been maintained in stable condition through partial

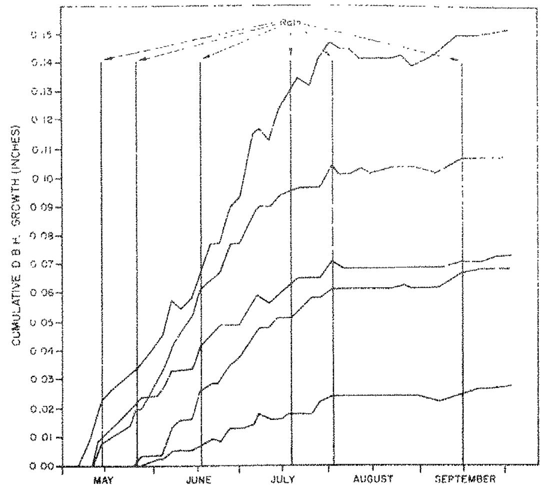

Figure 3.—Cumulative growth at d.b.h. of five fastest-growing white ash, 80-year class, over date, 1960.

Table 2.—Characteristics of a 25-year-old stand before thinning (Marquis 1967)

Species	Entire stand[a]			Crop trees only		
	Stems per acre	Basal area per acre	Mean diameter	Stems per acre	Basal area per acre	Mean diameter
	No.	Square feet	Inches	No.	Square feet	Inches
			Tolerants			
Beech	1,029	11	1.3	24	1	2.7
Sugar maple	1,041	11	1.3	73	3	2.8
Striped maple	126	2	1.4	—	—	—
Conifers	58	1	1.8	—	—	—
			Intermediates			
Yellow birch	474	10	1.7	67	4	3.2
White ash	93	3	2.3	31	3	3.9
Red maple	176	5	2.0	21	2	3.5
			Intolerants			
Paper birch	401	24	2.7	169	20	4.4
Aspen	54	9	5.1	—	—	—
Pin cherry	636	23	2.4	—	—	—
All species	4,088	99	1.8	385	33	3.7

[a]Includes all trees 0.5 inches d.b.h. and larger.

Table 3.—Annual diameter growth in inches by species, stand age, and residual basal area. Site index 55 to 65 (Leak 1980)

Species	25-year stand Residual basal area (ft^2)			50-year-stand Residual basal area (ft^2)			70-year-stand Residual basal area (ft^2)			
	100	72	56	100	75	60	100	80	60	40
Beech	.04	.07	.11	.06	.08	.12	.08	.10	.12	.14
Yellow birch	.06	.08	.12	.06	.07	.10	.05	.05	.08	.16
Sugar maple	.06	.09	.12	.05	.07	.10	.04	.04	.07	.13
Red maple	.10	.15	.19	.08	.13	.16	.07	.11	.13	.17
Paper birch	.11	.16	.17	.08	.12	.13	.06	.07	.09	.07
White ash	.18	.20	.20	.14	.17	.18	.11	.14	—	.21
Hemlock	—	—	—	—	—	—	.16	.18	.24	.30

cutting or natural processes. Table 4 gives an indication of maximum diameters that northern hardwoods obtain in old-growth stands.

Site requirements. Table 1 lists relative site requirements of the major species, which refers to the general levels of fertility, moisture, and depth required for competitive success. Species such as white ash and sugar maple are abundant only on organically enriched sites or deep, fine-textured tills (Fig. 4) while red maple, softwoods, and others are common on soils that are dry, shallow, wet, or stony. The relationships of the habitats in Figure 4 to site index (Table 5), mean diameter (Table 6), and soil series have been developed (Leak 1982). Northern hardwood species also vary in their elevational range (Leak and Graber 1974), which reflects species' abilities to tolerate climatic extremes. Elevation tends to be an important site factor, affecting both tree diameter and mean annual diameter growth (Fig. 5).

Pruning, seed production, rooting. Table 1 ranks the natural pruning ability of the major species from poor to good. Those species with good, natural pruning develop clean, straight boles under a range of stand densities. Those with poor, natural pruning require high stand densities at an early age, or mechanical pruning, to develop clean, high-quality boles. Even under high densities, the dead limbs of white pine remain attached, causing loose, black knots in the lumber.

The remaining entries in Table 1—years between good seed crops, sprouting vigor, and delayed germination—are self-explanatory. The seeds of pin cherry (as well as *Rubus* and perhaps other shrubs or herbs) are believed to remain dormant in the upper soil for 75-100 years (Graber

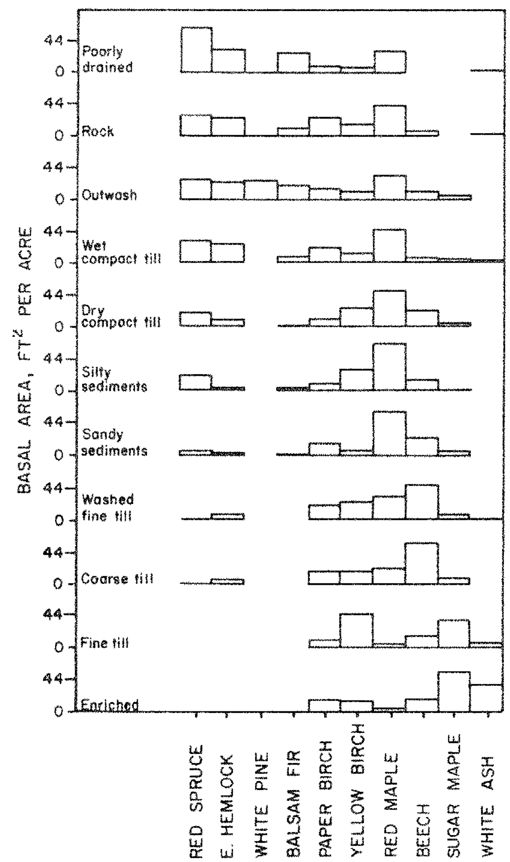

Figure 4.—Basal area in ft²/acre, by habitat, for major species occurring in northern hardwood forests.

Table 4.—Basal area per acre (ft², 2-inch class plus) and maximum d.b.h. (inches) for climax stands by species and study area (Leak 1987)

	Bowl		Mt. Pond North		Williams Tract		Bartlett Ridge		Bartlett 19	
Species	Basal area	Maxi-mum d.b.h.	Basal area	Maxi-mum d.b.h.	Basal area	Maxi-mum d.b.h.	Basal area	Maxi-mum d.b.h.	Basal area	Maxi-mum d.b.h.
Beech	45.0	24	36.4	26	25.2	28	19.7	24	3.6	20
Yellow birch	33.5	36	10.0	30	14.8	32	6.7	16	15.7	14
Sugar maple	46.1	34	69.0	36	28.2	36	—	—	—	—
Red maple	0.4	14	1.0	8	29.2	28	10.3	20	45.0	24
White ash	—	—	5.3	36	3.5	20	—	—	—	—
Red spruce	1.7	24	1.3	14	—	—	29.4	22	25.7	22
Eastern hemlock	0.4	26	—	—	3.8	16	111.7	32	140.0	26
Paper birch	—	—	—	—	—	—	6.7	14	0.7	8
White pine	—	—	—	—	—	—	—	—	2.1	28
Basswood	—	—	5.3	26	—	—	—	—	—	—
Striped maple	6.0	10	3.7	10	2.0	8	0.5	2	—	—
Red oak	—	—	—	—	—	—	1.7	20	—	—
Hophornbeam	—	—	1.3	8	—	—	—	—	—	—
Black cherry	—	—	—	—	3.5	16	—	—	—	—
All	133.1		133.3		110.2		186.7		232.8	

Table 5.—Mean site index in feet plus and minus one standard error of the mean. Base age 50 years. Based on 122 samples (Leak 1978)

Habitat	Paper birch[a]	Yellow birch[a]	Red maple[b]	Beech[b]	Sugar maple[a]	White ash[a]	Red spruce[b]	White pine[b]	Balsam fir[b]
Poorly drained	—	48	—	—	—	48	44±4	—	—
Rock	56	48±4	60±0	—	—	—	44	60	—
Outwash	—	60±6	63±3	—	—	—	40±3	56±3	54±6
Wet compact till	54±3	57	52±6	—	—	70±2	38±2	—	—
Dry compact till	70	56±3	60±2	57	—	—	44±4	—	—
Silty sediments	62±0	62±7	64±4	—	—	—	51±2	—	—
Sandy sediments	68±2	61	52±2	—	60	—	—	—	—
Washed fine till	66±5c	80c	—	57	—	—	—	—	—
Coarse till	66±2	55±4	—	65±4	50±8	—	—	—	—
Fine till	77	68	—	—	68±6	76	—	—	—
Enriched	74±6	63	—	—	72±4	81±3	—	—	—

[a]Breast-high age 50 years.
[b]Total age 50 years.
[c]Consists of, or contains a measurement on, a young stand (35 years), which may overestimate site index.

Table 6.—Mean diameter of largest trees (average, one tree per plot) at 100 years and in climax stands by species and habitat, in inches (Leak 1982)

Habitat	Beech	Yellow birch	Sugar maple	Red maple	Paper birch	White ash	Red spruce	Eastern hemlock
	At 100 years							
Enriched	—	17.3	19.6	—	—	21.1	—	—
Washed tills	15.2	14.2	12.5	13.4	15.4	16.8	—	13.3
Sandy sediments	14.8	—	—	17.0	13.6	—	—	—
Silty sediments	12.0	12.6	—	16.9	—	—	—	22.2
Dry compact till	12.5	12.0	9.6	14.6	13.8	—	—	—
Wet compact till	9.8	11.2	9.4	16.8	14.3	16.0	14.8	18.6
Poorly drained	—	—	—	—	—	—	13.6	—
	Climax							
Fine tills	23.1	20.3	18.0	—	—	—	—	22.0
Silty sediments	13.2	11.2	—	—	—	—	17.6	21.2
Outwash	18.6	—	—	20.0	—	—	16.9	20.0
Bedrock	—	—	—	—	10.0	—	18.3	25.7
Loose rock	14.0	14.3	—	17.7	—	—	14.0	21.3

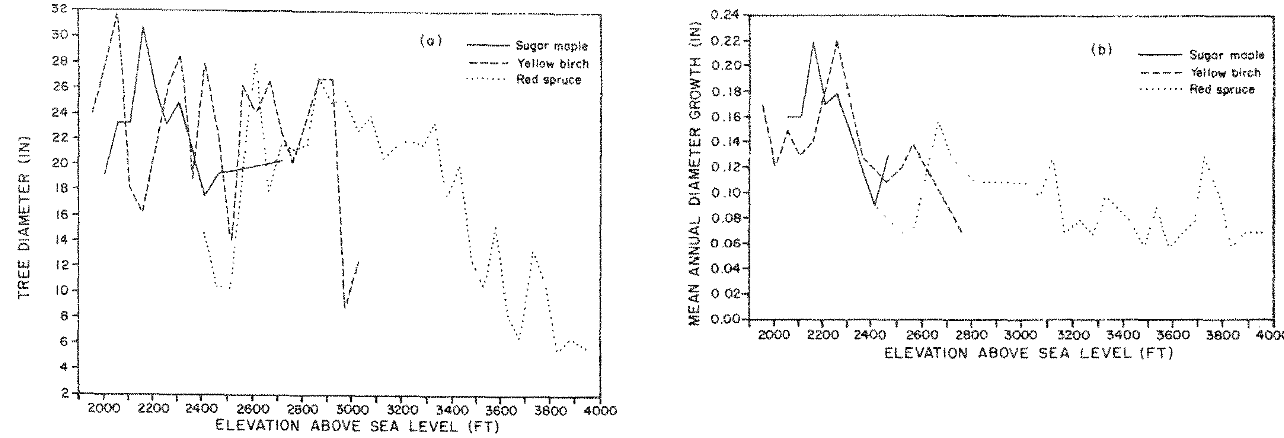

Figure 5.—Maximum tree diameter above the root swell (stump height) (a), and mean annual diameter growth (tree diameter divided by age) (b), over elevation for three species in the Bowl, an old-growth forest in central New Hampshire.

and Thompson 1978), ready to germinate when the overstory is disturbed. Inputs of seed by birds is too small to account for the large numbers of buried viable seed.

Rooting characteristics of northern hardwood species are greatly influenced by soil and drainage conditions and stone content. Root studies of young seedlings show that the typical tendency for yellow birch is to develop a shallow, laterally-oriented root system as compared to the taproots of sugar maple and white ash with weak lateral systems (Leak 1959). Soil restrictions cause either type of system to remain relatively shallow throughout tree life, resulting in northern hardwoods being fairly susceptible to windthrow, especially on shallow, moist sites.

Stand Characteristics

Species composition. The species composition of northern hardwood stands varies with site; the range of composition in Figure 4 is fairly typical for mid-aged stands. Younger stands may be dominated by early successional (intolerant) species such as pin cherry (Table 7) so that differences

Table 7.—Species composition of sapling and poletimber stands, in percent basal area, and stand characteristics, by habitat, of the study areas (Leak 1979)

Habitat	No. of areas	Mean age (yrs)	No. stems	Mean d.b.h. (inches)	Eastern hemlock	Red spruce	Balsam fir	Paper birch	Yellow birch	Red maple	Aspen	Beech	Sugar maple	White ash	Pin cherry	Striped maple	Other
					percent												
Sapling stands																	
Rock	1	11	20,414[a]	0.85	—	0.6	—	0.6	—	5.0	—	53.6	—	—	24.6	15.5	0.1
Outwash	2	7	43,577	0.50	—	0.4	—	15.0	42.8	—	0.6	30.6	—	—	10.6	—	—
Wet compact till	2	9	30,919	0.74	—	—	—	15.3	2.2	33.4	8.3	4.0	5.1	1.6	5.4	6.8	17.9
Dry compact till	3	13	17,321	1.14	—	1.1	—	12.5	4.3	19.0	0.1	10..8	—	—	50.4	—	1.8
Washed till	5	8	25,934	0.78	—	—	—	36.3	5.1	0.6	1.7	21.1	0.4	—	27.5	7.3	—
Poletimber stands																	
Rock	4	69	1,034[b]	5.73	15.9	14.0	5.8	18.7	8.1	15.9	10.5	10.2	—	—	0.2	0.7	—
Dry compact till	4	62	1,318	4.54	—	—	—	47.6	10.6	23.5	2.0	14.8	0.2	—	—	1.1	0.2
Washed till	1	64	1,032	4.70	—	—	—	38.3	5.4	23.2	14.2	18.2	0.1	—	—	0.6	—
Fine till	2	62	607	5.99	—	—	—	—	31.0	4.5	—	4.8	59.7	—	—	—	—
Enriched	1	65	961	5.75	—	—	—	4.1	3.4	16.6	8.5	1.0	55.2	11.2	—	—	—

[a]Stems per acre 1 ft tall or taller.
[b]Stems per acre 4.5 ft tall or taller.

among sites are obscured. Old stands, on the other hand, contain 70-80 percent tolerant species: beech-sugar maple, or red spruce-hemlock, depending upon site (Table 4). Trends in species composition on typical northern hardwood sites show that beech and sugar maple increase or maintain over time; yellow birch, paper birch, red maple, and pin cherry increase in percentage and then decrease; while eastern hemlock and red spruce maintain small, fairly steady percentages (Fig. 6). "Succession" in these forests consists of change over time in the dominance of species rather than replacement of one unique community with another.

Herb and shrub communities vary widely across the northern hardwood region. Several attempts have been made to organize or explain this variability. As soils decrease in base saturation or fertility, the herbaceous community has been shown to decline in richness or numbers of species (Siccama et al. 1970). Within any one area, such as the granitic areas of the White Mountains in New Hampshire, the number of herb-shrub species varies with soil materials (Leak 1982) (Table 8). However, there are no distinct relationships with fertility or moisture; certain species are characteristic of fertile sites (e.g. wild oats) or wet sites (e.g. wood sorrel or goldthread) while others occur across a broad range of sites (e.g. Indian cucumber). Research in the Lake States (Spies and Barnes 1985) has provided a classification of herb and shrub species by moisture-fertility groups that generally applies in New England as well (Table 9).

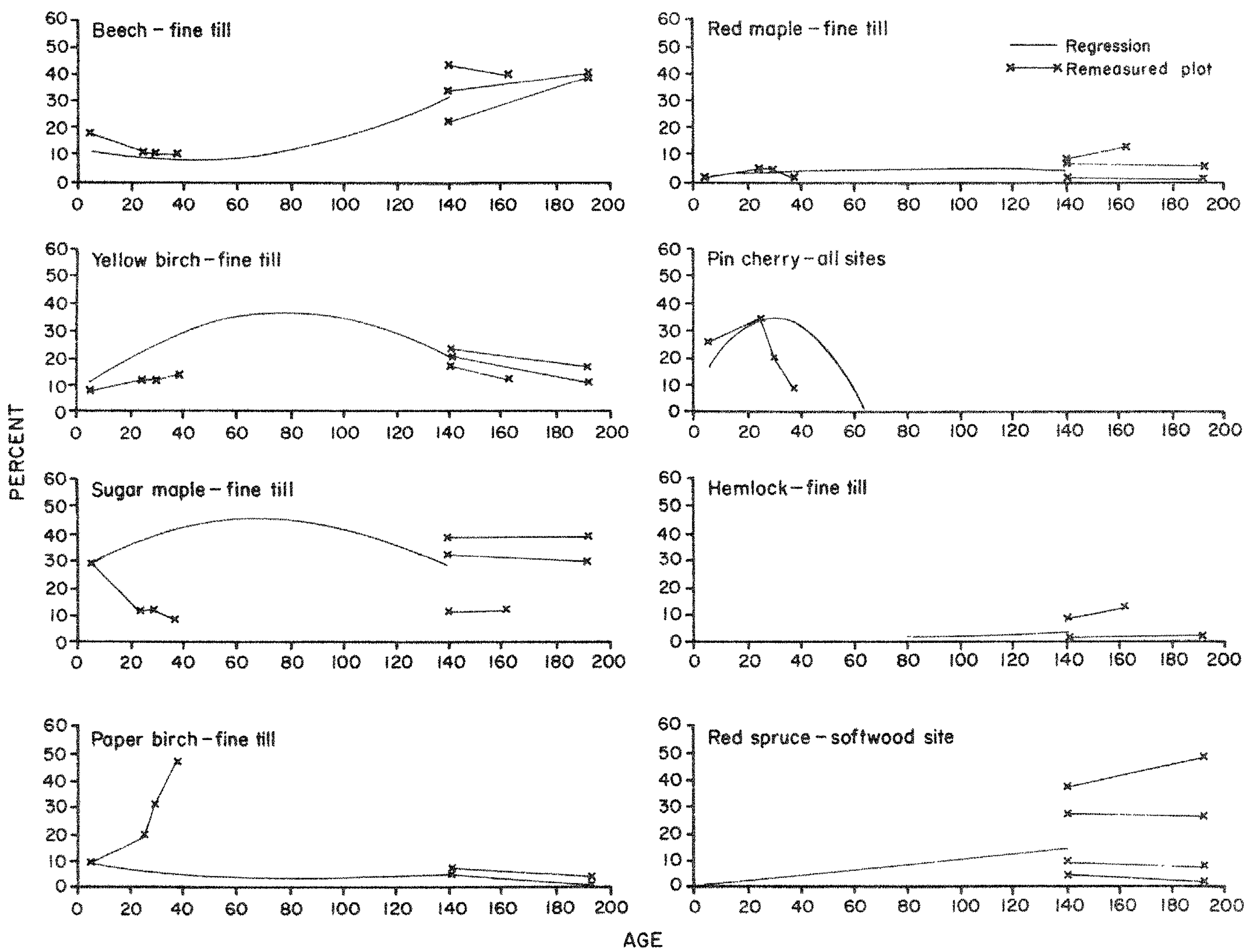

Figure 6.—Stand composition over time for species in northern hardwood stands (Leak 1991).

Table 8.—Average frequency (percent occurrence on n,3x3 ft plots) of tree, shrub (including small trees), and herb species per stand, by habitat and successional stage (includes only those species greater than or equal to 5 percent frequency on all areas in each habitat-successional category) (Leak 1982)

Species	Enriched	Fine till	Coarse washed till	Fine washed till	Sandy sedi-ments	Silty sedi-ments	Silty sedi-ments	Dry compact till	Wet compact till	Out-wash	Bed-rock	Loose rock	Loose rock	Poorly drained
	Succes-sional (n=80)	Climax (n=96)	Succes-sional (n=80)	Succes-sional (n=136)	Succes-sional (n=128)	Climax (n=40)	Succes-sional (n=96)	Succes-sional (n=80)	Succes-sional (n=192)	Climax (n=56)	Climax (n=56)	Climax (n=48)	Succes-sional (n=56)	Succes-sional (n=16)
						Trees								
Beech	32	52	68	69	57	25	44	45	17	—	—	58	9	—
Sugar maple	68	51	15	22	10	—	—	—	—	—	—	—	5	—
Red maple	—	—	15	37	31	22	—	—	14	—	—	—	—	56
Yellow birch	—	—	—	—	—	—	—	—	—	—	—	—	—	19
White ash	28	—	—	18	—	—	—	12	—	—	—	—	—	—
Red spruce	—	—	—	—	—	28	—	—	—	25	21	19	—	31
Eastern hemlock	—	—	—	—	—	40	14	—	—	21	14	33	—	56
Balsam fir	—	—	—	—	—	—	—	—	14	—	—	—	—	6
						Shrubs								
Hobblebush	42	35	16	33	—	12	44	64	42	11	—	29	43	—
Striped maple	36	40	—	—	16	5	—	34	40	—	11	17	12	—
Canada yew	—	—	—	—	—	—	—	—	—	—	—	8	5	—
Blueberry	—	—	—	—	—	—	—	—	—	—	—	—	—	62
Wintergreen	—	—	—	—	—	—	—	—	—	—	—	—	—	38
Sheep laurel	—	—	—	—	—	—	—	—	—	—	—	—	—	25
Wild raisin	—	—	—	—	—	—	—	—	—	—	—	—	—	6
						Herbs								
Wild oats	49	—	—	—	—	—	—	—	—	—	—	—	—	—
Indian cucumber	20	—	—	—	25	—	8	30	—	23	—	12	5	—
Wild lily-of-the-valley	—	—	—	—	85	—	—	26	—	—	—	—	—	—
Starflower	—	—	—	—	51	—	—	—	—	—	—	—	—	—
Sarsaparilla	—	—	—	—	18	—	—	24	—	—	—	6	20	—
Club moss	—	—	—	—	36	—	—	—	—	—	—	—	5	—
Trillium	—	—	—	—	—	—	—	6	—	—	—	—	—	—
Clintonia	—	—	—	—	—	—	—	—	22	—	—	—	—	—
Wood sorrel	—	—	—	—	—	—	—	—	36	—	—	—	—	—
Moccasin flower	—	—	—	—	—	—	—	—	—	—	—	—	5	—
Woodfern	—	—	—	—	—	—	—	—	—	—	—	—	7	—
Sphagnum	—	—	—	—	—	—	—	—	—	—	—	—	—	94
Goldthread	—	—	—	—	—	—	—	—	—	—	—	—	—	6

Table 9.—Grouping of herb/shrub species by soil moisture and fertility (Spies and Barnes 1985)

Very dry to dry sites	Moist to very moist sites[a]			Broad range, soil moisture-soil fertility (increasing ecological amplitude)
	A	B	C	
White moss group	Blue-bead lily group	Solomon's-seal group	Twisted-stalk group	Starflower group
White moss	Blue bead lily	Downy Solomon's-seal	Rose twisted-stalk	Starflower
Reindeer moss	Goldthread	Great-spurred violet	Shining club moss	Bristly club moss
Sedge (deflexa)	Bunchberry	Leatherwood	Beaked hazel	Wood fern
Common polypody fern	Wood sorrel	False Solomon's-seal	Spotted coralroot	
	Rattlesnake plantain	Nodding trillium	Kidneyleaf violet	Club moss group
Rice-grass group	Canada yew	White baneberry	Adam-and-Eve orchid	Ground pine
Rice grass	Indian pipe	Largeleaf white violet		Sedge (arctata)
Sedge (peckii)		Prickly gooseberry	Lady fern group	Sedge (pedunculata)
Running club moss	Canada honeysuckle group	Red elderberry	Lady fern	Partridge-berry
Ground cedar	Canada honeysuckle	Sedge (Dewey's)	Oak fern	Pipsissewa
	Mountain maple	Millet grass		Shin leaf
		Spring beauty	Shorthusk-grass group	
		Dogtooth violet	Shorthusk	Canada mayflower group
			Interrupted fern	Canada mayflower
		Jack-in-the-pulpit group		Sarsaparilla
		Small jack-in-the-pulpit		
		Sedge (intumescens)		Shield-fern group
				American shield-fern
		Sweet cicely group		Bigleaf aster
		Sweet cicely		Red raspberry
		Downy yellow violet		Bedstraw
		Large-flowered bellwort		False-melic
		Rattlesnake fern		
		Dutchman's breeches		
		Toothwort (diphylla)		
		Ginseng		
		Cohosh group		
		Blue cohosh		
		Maidenhair fern		
		Bitter currant		
		Wild leek		
		Alternate-leaved dogwood		
		Bloodroot		
		Beech-fern group		
		Broad beech-fern		
		Ostrich fern		

[a]A, infertile soils; B, fertile to very fertile soils (in order of increasing fertility); C, broad range of soil fertility, but characteristic of very moist sites (in order of increasing restriction to very moist and wet sites).

Age distribution. Plottings of numbers of stems against age-class midpoints for a virgin northern hardwood stand in the Bowl Research Natural Area in New Hampshire showed two distinctive relationships (Leak 1974, 1975). Climax species such as sugar maple and beech produce a descending linear relationship, signifying a sharp decrease in numbers of trees per acre with increasing age (Fig. 7). Species such as yellow birch or red spruce, which are declining or are maintained through disturbance cycles, show an irregular or bell-shaped distribution (Fig. 7). In these climax stands, tree size and age are well correlated since all trees have developed under fairly consistent conditions. In the typical cutover or high-graded northern hardwood stand, however, there is a great deal of variation in tree size and age.

The age distribution of nonclimax, northern hardwood stands in New England is often strongly structured due to past land use and harvesting. Many present stands have large numbers of trees in the 40-60- and 60-80-year-old classes as a result of harvests around the turn of the century (Smith et al. 1990).

Diameter distribution. Diameter distributions in northern hardwood stands can be characterized by an array of J- or S-shaped distributions. Diameter distributions in old, undisturbed stands tend to follow a negative exponential J-shaped curve with a constant ratio among trees in successive diameter classes (Fig. 8). However, in managed unevenaged stands the curve may become steeper, or it may become somewhat flattened (S-shaped)

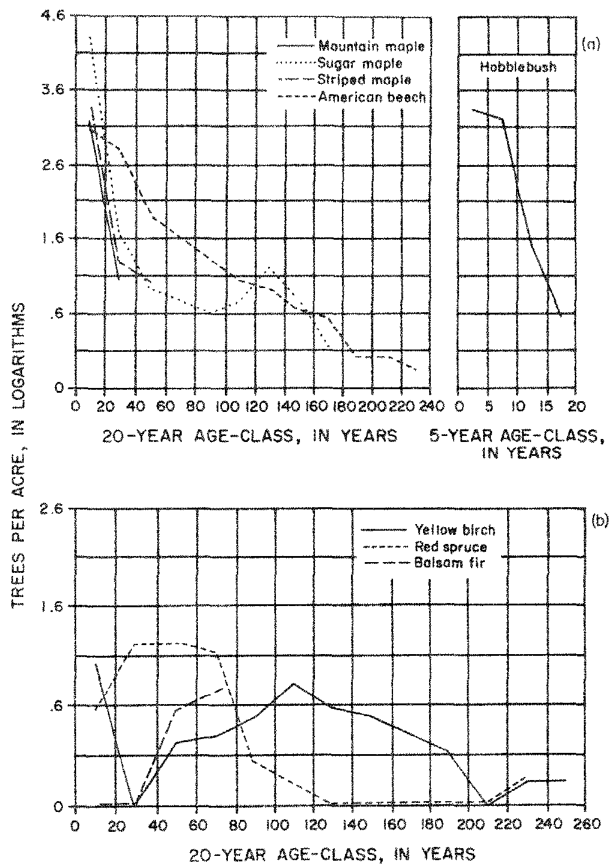

Figure 7.—Numbers of trees per acre (log) in virgin northern hardwoods over midpoints of 20-year age classes (log) for climax species (a) and declining species (b) (Leak 1974).

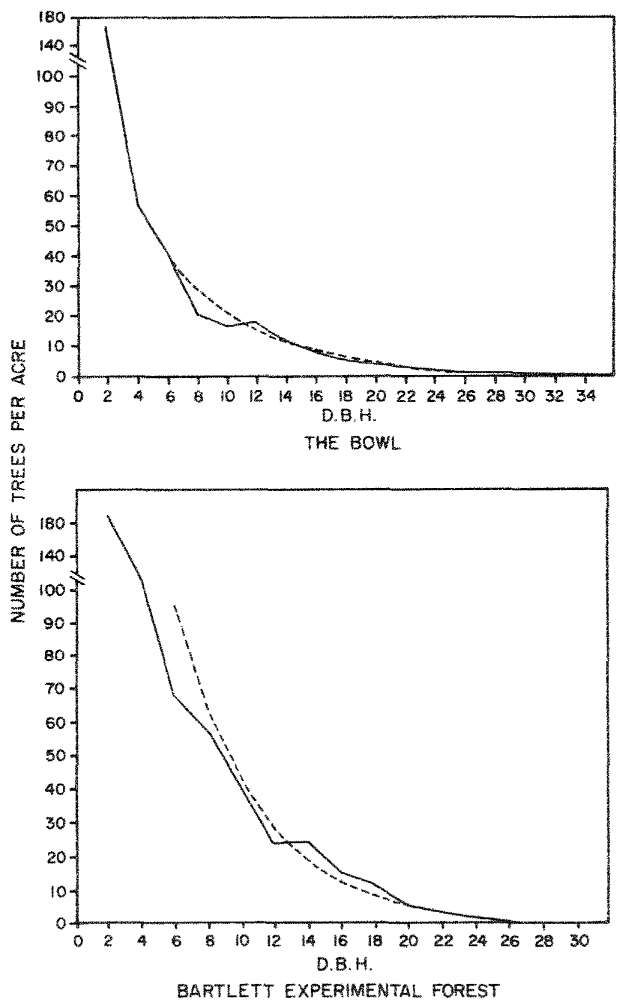

Figure 8.—Diameter distributions in older, undisturbed stands at The Bowl and Bartlett Experimental Forest, New Hampshire (Leak 1987).

in the middle due to the pattern of cutting, growth, mortality, and regeneration (Trimble and Smith 1976). In younger northern hardwood stands, even in even-aged, the diameter distribution tends to be J-shaped due to the layering of species with different growth rates and shade tolerance (Fig. 9).

Volume production. In an evenaged, uncut stand, volume production over time in board and cubic feet varies with site (Table 10). Production is increased by silvicultural thinning due to the added yield from thinnings and the reduced time required for trees to reach merchantable size (Table 11). The best comparison of the effects of management is through the use of mean annual increment (yield divided by stand age) at its maximum (cumulation) point. The age of this culmination point is commonly used as an estimate of optimum rotation length. On this basis, management can increase cubic and board foot yields by 54 to 73 percent (Table 12).

Table 10.—Volumes per acre in cubic feet (4.0-inch ib top) and board feet (8.0-inch ib top) for unmanaged northern hardwood stands, by mean stand diameter, age, and site index (Leak et al. 1987)

Mean d.b.h. (inches)	Site 50			Site 60			Site 70		
	Age (years)	Cubic feet	Board feet	Age (years)	Cubic feet	Board feet	Age (years)	Cubic feet	Board feet
4.0	35	—	—	30	—	—	25	—	—
6.0	59	1289	—	49	1547	—	41	1821	—
8.0	83	1606	2983	67	1924	3560	55	2254	4258
10.0	120	1934	5554	87	2311	6640	69	2675	7632
12.0	182	2272	8259	114	2700	9783	85	3144	11461
14.0	—	—	—	157	3102	13048	102	3579	15079
16.0	—	—	—	196	3154	13257	127	3654	15390

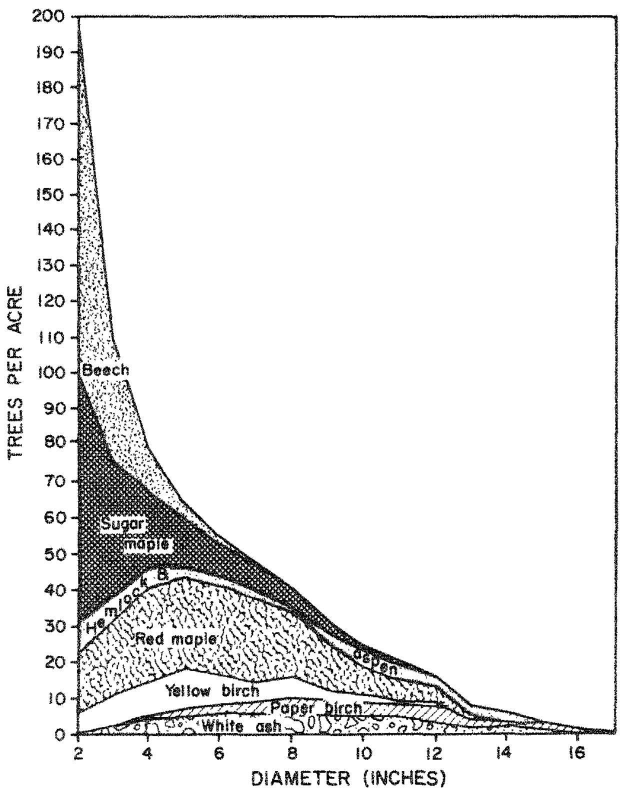

Figure 9.—Diameter distributions of a younger northern hardwood stand (Wilson 1953).

Table 11.—Volumes per acre, by age, in cubic feet (4.0-inch top) and board feet (8.0-inch top) for intensively managed, evenaged hardwoods (Leak et al. 1987)

	Site 60					
	Cumulative thinnings		Standing		Total	
Age (years)	Cubic feet	Board feet	Cubic feet	Board feet	Cubic feet	Board feet
48	269	—	1418	—	1687	—
61	1243	895	1189	2211	2432	3106
72	1243	895	1912	5471	3155	6366
83	1854	2680	2039	7375	3893	10005
95	2602	5633	2011	8449	4613	14082
107	2602	5633	2449	10289	5051	15922
119	3394	8960	2085	8760	5479	17720

Table 12.—Approximate mean annual increment (MAI) and culmination age for unthinned and intensively thinned northern hardwoods at site index 60 (Solomon and Leak 1986)

	MAI			Culmination Age	
Unit of measure	Unthinned	Thinned	Percent increase due to thinning	Unthinned	Thinned
Board feet	85.8	148.2	73	114	95
Cubic feet	31.6	48.6	54	<49	95

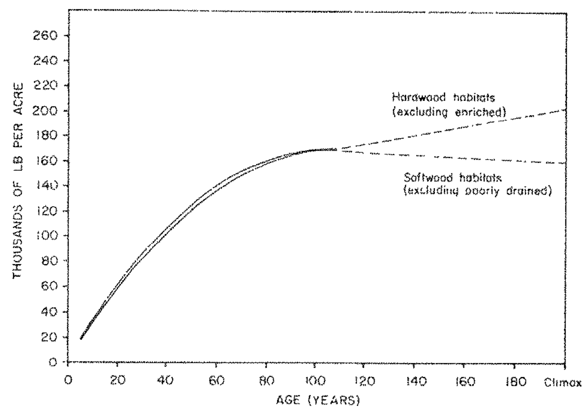

Figure 10.—Aboveground biomass (stems and branches) in dry weight over stand age by habitat groups (Leak 1982).

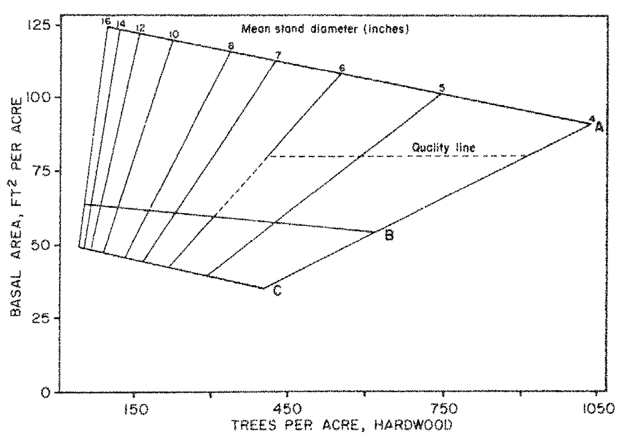

Figure 11.—Stocking guide for main crown canopy of evenaged hardwood stands (beech-red maple, beech-birch-maple) shows basal area and number of trees per acre and quadratic-mean stand diameter. The A line shows fully stocked; the B, residual stocking; and the C, minimum stocking. The quality line represents the density required to produce high quality stems of beech, sugar maple, yellow birch, and red maple (Solomon et al. 1986).

In the absence of major disturbance, biomass production over time rises to a peak at about 100 years; differences between hardwood and softwood stands are minimal (Fig. 10). Over longer periods of time, living biomass may decline, perhaps by 10 to 20 percent during a "transition" period to an oscillating, "steady state" beginning at about age 350 (Bormann and Likens 1979).

Stocking. Stocking of evenaged stands commonly is defined in terms of basal area of species in the main crown canopy in relation to mean stand diameter (excluding suppressed trees) (Fig. 11). The A-line represents the stocking of an undisturbed stand; the B-line represents minimum stocking after thinning; and the quality-line shows the stocking required to ensure rapid natural pruning in young stands. Comparable stocking lines for mixed wood stands (25 to 65 percent softwood) are higher in the basal area because softwood crowns are smaller than those of hardwoods (Fig. 12) and allow for much higher basal areas per acre (Fig. 13).

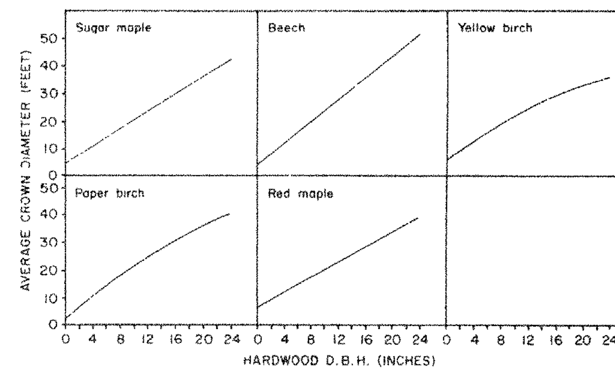

Figure 12.—Crown width over d.b.h. for dominant sugar maple, beech, yellow birch, paper birch, and red maple (Leak 1983).

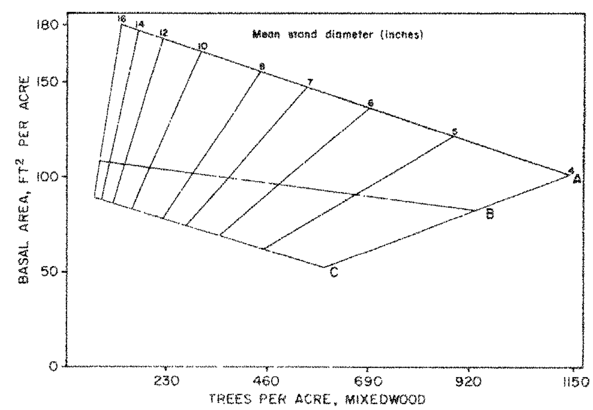

Figure 13.—Stocking guide for main crown canopy of mixedwood stands (25 to 65 percent softwoods) shows basal area and number of trees per acre and quadratic mean stand diameter. The A line shows fully stocked, the B, suggested residual stocking, and the C, minimum stocking (Solomon et al. 1986).

In unevenaged stands, stocking guidelines specify basal area per acre and basal area or number of trees by diameter class or diameter group (Table 13). The parameter "q" represents the ratio between numbers of trees in successive 2-inch-diameter classes. High "q" values (e.g. 1.7), which represent stands with steep curves of tree numbers over d.b.h. class, have rather low amounts of saw timber. Low "q's" reflect large amounts of sawtimber. Much of the information used to develop stocking and structural standards comes from designed growth studies on the effects of stand density and diameter distribution (Solomon 1977).

Damaging Agents

Whether northern hardwoods grow and develop along the dimensions discussed above depends on the impacts of damaging agents including insects, diseases, weather, and human-related disturbances.

Insects. Table 14 includes a list of major insects and diseases affecting northern hardwoods. The most important insects include the beech scale, which allows entry of beech bark disease and formation of *Nectria* canker; the saddled prominent and forest tent caterpillar that sporadically are serious defoliators, especially of sugar maple; and the sugar maple borer that reduces the market value of butt logs of half or more of the trees in sugar maple-dominated stands. In the 1980's the pear thrips defoliated sugar maples over extensive areas, especially in Southern New England, but it has not been determined whether this insect poses a serious threat to the sugar maple resource.

Trees most susceptible to insect problems are those growing in nearly pure stands (sugar maple is a prime example), or having low vigor, or having been injured by natural or human-related causes. Those who work with northern hardwoods and want to recognize pest insects, to diagnose unhealthy trees, and to be aware of susceptible conditions are referred to Allen (1987), Houston (1986), Martineau (1984), and U.S. Department of Agriculture, Forest Service (1979, 1985).

Table 13.—Minimum stand-structure objectives for residual hardwood (beech-birch-maple and beech-red maple) and mixedwood stands (Leak et al. 1987)

D.b.h. class (inches)	q^a=1.7		q=1.5		q=1.3	
	Hardwood	Mixedwood[b]	Hardwood	Mixedwood[b]	Hardwood	Mixedwood[b]
	Ft^2 of basal area/acre					
6-10	38	54	30	42	21	30
12-14	18	26	20	28	20	28
16+	14	20	20	30	29	42
All	70	100	70	100	70	100

[a]The ratio between numbers of trees in successive 2-inch diameter classes.
[b]Softwood basal area 25 to 65 percent of total.

Table 14.—Major insect pests and diseases of northern hardwood species, summarized from Allen (1987) and Houston (1986)

Insects	Damage
Forest tent caterpillar *(Malacosoma disstria)*	Defoliation leading to reduced radial and terminal growth. In severest form, results in dieback, decline, and mortality
Saddled prominent *(Heterocampa gattivitta)*	Defoliation leading to reduced radial and terminal growth. In severest form, results in dieback, decline, and mortality
Fall cankerworms *(Alsophila pometaria)*	Defoliation leading to reduced radial and terminal growth. In severest form, results in dieback, decline, and mortality
Spring cankerworms *(Paleacrita vernata)*	Defoliation leading to reduced radial and terminal growth. In severest form, results in dieback, decline, and mortality
Pear thrips *(Taeniothrips inconsequeris)*	Defoliation leading to reduced radial and terminal growth. Long-term impacts unknown
Beech scale *(Cryptococcus fagisuga)*	Stresses tree, allows invasion of canker fungi, lumber degrade, mortality
Sugar maple borer *(Glycobius speciosus)*	Sapwood injury, girdling, swelling, lumber upgrade

Diseases	Damage
Beech bark disease *(Nectria coccinea* var. faginata and *N. galligena* after *Cryptococcus fagisuga)*	Mortality of large trees in "killing front"; extreme defect in smaller "aftermath zone" trees
Nectria canker *(Nectria galligena)*	Target-like cankers on branches and main stems, lumber degradation and defect, weakening resulting in breakage
Eutypella canker *(Eutypella parasitica)*	Enlarged distorted stem canker, stem weakening and breakage, lumber degradation
Armillaria root rot *(Armillaria spp.)*	Killing and decaying of stressed trees
Sapstreak *(Ceratocystis coerulescens)*	Watersoaked stain of xylem, dieback, degradation of lumber from stain, mortality
Wood decay pathogens	Breakage of branches and main stems, degradation and devaluation of lumber

Diseases. Disease problems of northern hardwoods are mostly the result of individual, or combinations of, fungi gaining entrance through wounds in bark or roots (Table 14). Subsequent wood decay processes are the largest source of loss of standing timber volume and quality.

Beech bark disease is the most lethal stem disease affecting beech. *Nectria* and *Eutypella* cankers affect most species causing breakage of boles and branches and reduction in market value of logs. *Armillaria* is the most widely known root disease in northern hardwood forests, and affects all species (Wargo and Shaw 1985). Sapstreak disease of maple is another important root disease that gains entry through wounds, especially those resulting from logging or sugar bush operations. Sugar maple logs with sapstreak stain lose an estimated 40 to 60 percent of their value (Smith 1990).

Fungi and rots often are involved in dieback and decline diseases of northern hardwoods. These diseases occur when trees are stressed by weather events or insect attacks, or a combination, and are then invaded and possibly killed by "secondary" agents (Houston 1981, 1986). Examples include maple decline, beech bark disease, birch dieback, and ash decline. Millers et al. (1989) present a chronology of the many diebacks and declines that have affected northern hardwoods over the past century.

Except for beech bark disease, direct mortality from diseases usually is not a major concern when managing northern hardwoods. Rather, diseases are a problem of reduction in timber quality, and growth loss. Eradication of diseases is impossible, but sound forest management, with a goal of minimizing wounds, will help keep diseases in check (Houston 1986; Filip 1978).

Atmospheric deposition. Acidic nitrogen and sulfur compounds arising from natural and human-related sources occur in both atmosphere and precipitation over New England. Also, ozone occasionally exceeds levels considered toxic to plants. A variety of hypotheses has been proposed regarding effects of these substances on northern hardwood species, including: physiological changes; predisposition of trees to drought, insects, and winter injury; changes in soil nutrients, aluminum, and trace metal concentrations; and alteration of nitrogen relationships. So far there is insufficient evidence to attribute symptoms in northern hardwoods to atmospheric deposition. The problem is under intensive study, but quick answers are unlikely. Symptoms are expected to be subtle and slow to develop, and may be masked by secondary agents that attack affected trees (Houston 1986). Northern hardwood species have not shown extended periods of decreasing growth rates like those that have occurred since the 1960's in red spruce and balsam fir (Hornbeck et al. 1988).

Weather. Northern hardwoods experience a variety of potentially harmful weather events. Drought, though seldom prolonged, can have important effects on tree vigor. Drought followed by insect defoliation followed by fungi is the usual sequence of maple decline. Wind is a factor in most northern hardwood stands as evidenced by the pit-mound microtopography that develops from upheaved roots and soil of blown-down trees. Most blowdowns result from the sporadic fall of individual older or weaker trees during modest winds (Bormann and Likens 1979). Hurricanes in 1815 and 1938 caused blowdowns of both individual trees and sizable blocks of complete stands over southern and central New England, but northern hardwoods were less affected than other forest types. Intense winds associated with localized storms have blown down far more trees in northern hardwood forests than have hurricanes. Wounds resulting from wind or ice storms, or both, are entry points for fungi, and can cause extensive degradation in log quality. Frost sometimes destroys flowers before pollination is complete. In frost-prone areas, the potential for several years without seed crops must be considered when deciding management options.

The damage agents named above combine to produce continuing mortality. Tritton and Siccama (1990) found that, despite a wide diversity of stand histories, species, and sites, the proportion of standing dead trees in most forests in the Northeastern United States ranged from 5 to 16 percent of basal area and stand density.

The Hydrologic Cycle

Northern hardwood forests have important impacts on the hydrologic cycle, especially with regard to supplies of high quality water for surface streams and groundwater. Management activities can affect the hydrologic cycle in a variety of ways, some of which are quite dramatic. Thus, it is important to understand the distribution and transport of water within forest ecosystems. In this section we discuss the hydrology of undisturbed northern hardwoods. Later sections discuss effects of management activities on the hydrologic cycle.

Baseline data on the hydrologic cycle have been collected since 1955 at the Hubbard Brook Experimental Forest in central New Hampshire (Federer et al. 1990). Eight small watersheds, ranging from 29 to 189 acres, are equipped with streamgaging and climatic stations (U.S. Department of Agriculture, Forest Service 1986). Six of the watersheds are adjacent and have southerly aspects. The other two watersheds are located about 3 miles away on north-facing slopes of the Hubbard Brook basin.

Annual precipitation averages 53 inches on the south-facing watersheds, and 57 inches on the north-facing (Table 15). The considerable year-to-year variation as indicated by the ranges in annual values (Table 15) and by the 7-inch standard deviation about both means, is typical for the region. There also is spatial variation as shown by the 4-inch difference between north- and south-facing watersheds, and by the fact that values for both watersheds are higher than the regional averages of 40 to 48 inches shown in Kingsley (1985).

Table 15.—Annual means and one standard deviation for data from the Hubbard Brook Experimental Forest, 1966-1987. All values are inches depth over the watersheds

	South-facing Watershed No. 3	North-facing Watershed No. 7
Annual precipitation	53±7	57±7
Range	43-71	46-71
Annual streamflow	34±7	37±7
Range	22-55	27-56
Difference (Evapotranspiration)	19±2	20±2
Range	14-22	15-25

On average, about two-thirds of the precipitation at Hubbard Brook becomes streamflow (Table 15). Contributions to groundwater are felt to be minor since bedrock underlying Hubbard Brook is relatively tight and prevents downward movement of water. Thus, precipitation that does not become streamflow is returned to the atmosphere by processes of evaporation and transpiration. Transpiration is moisture that passes in vapor form from plant stomates. Evaporation includes vapor losses from the forest floor and soil, and also from plant surfaces during and immediately after rainstorms. This latter process is termed interception and usually amounts to 10 to 20 percent of total rainfall (Leonard 1961).

It is nearly impossible to separate transpiration and evaporation from forests, so these processes are usually lumped under the term evapotranspiration. At Hubbard Brook, where groundwater losses are thought to be small, evapotranspiration can be estimated by subtracting annual streamflow from precipitation. The result is about 19 inches per year for both north- and south-facing slopes (Table 15). This value is the most stable among the three components of the hydrologic cycle (Table 15), which means that evapotranspiration is fairly uniform from year to year and must be satisfied regardless of how much precipitation occurs.

Annual precipitation at Hubbard Brook is uniformly distributed among months, but streamflow is not (Fig. 14). The imbalance occurs for two reasons. First, most precipitation from December through March occurs as snow, and normally accumulates to a depth of 4 to 6 feet. When this snowpack melts, usually in April, it generates approximately 40 percent of annual streamflow. Second, during the growing season months of June through September, much of the precipitation is lost to evapotranspiration. Total streamflow during this 4-month period usually is less than 5 percent of annual.

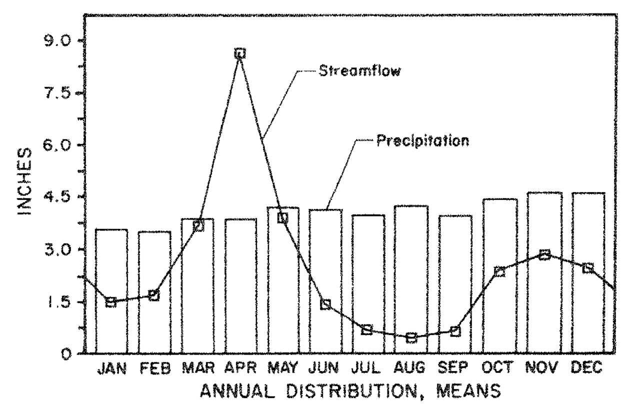

Figure 14.—Mean monthly precipitation and streamflow for the Hubbard Brook Experimental Forest, New Hampshire.

Soil moisture is depleted during the growing season to the extent that by mid to late season, the soil will have room to store as much as 4 to 5 inches of precipitation. This period of drier soils is opportune for logging operations, but it also is the period when streams reach low levels and concerns develop over surface water supplies. The soil water deficits usually last through the end of the growing season and until there is enough precipitation to recharge the soil. At Hubbard Brook, soil water usually is completely recharged by early November, and remains at high levels until the next growing season.

High infiltration capacity is an important hydrologic characteristic of most northern hardwood forests. Nearly all precipitation, regardless of amount of intensity, passes into the soil and moves downward and laterally to the stream channel. Little, if any, water moves over the surface of the forest floor and soil, minimizing erosion and sedimentation of streams. Studies at Hubbard Brook show that forest soils can absorb rainfall at rates as high as 14 to 30 inches per hour, or far in excess of the maximum intensities of about two inches per hour that can occur at Hubbard Brook. The high infiltration capacities result because mineral soils in northern hardwood forests are usually coarse textured, and are covered by thick, absorbent organic horizons (Fig. 15). Infiltration capacities can be reduced dramatically during logging due to soil compaction and disturbance of the organic horizons. Most guidelines for preventing erosion during logging are geared toward protecting infiltration capacity, or toward handling the surface runoff of water that results when infiltration capacities are reduced.

Water moves, not only quickly into but also, through soils of northern hardwood forests, causing streams to be "flashy" or to respond immediately to weather events such as rainstorms, snowmelt, and rain combined with snow.

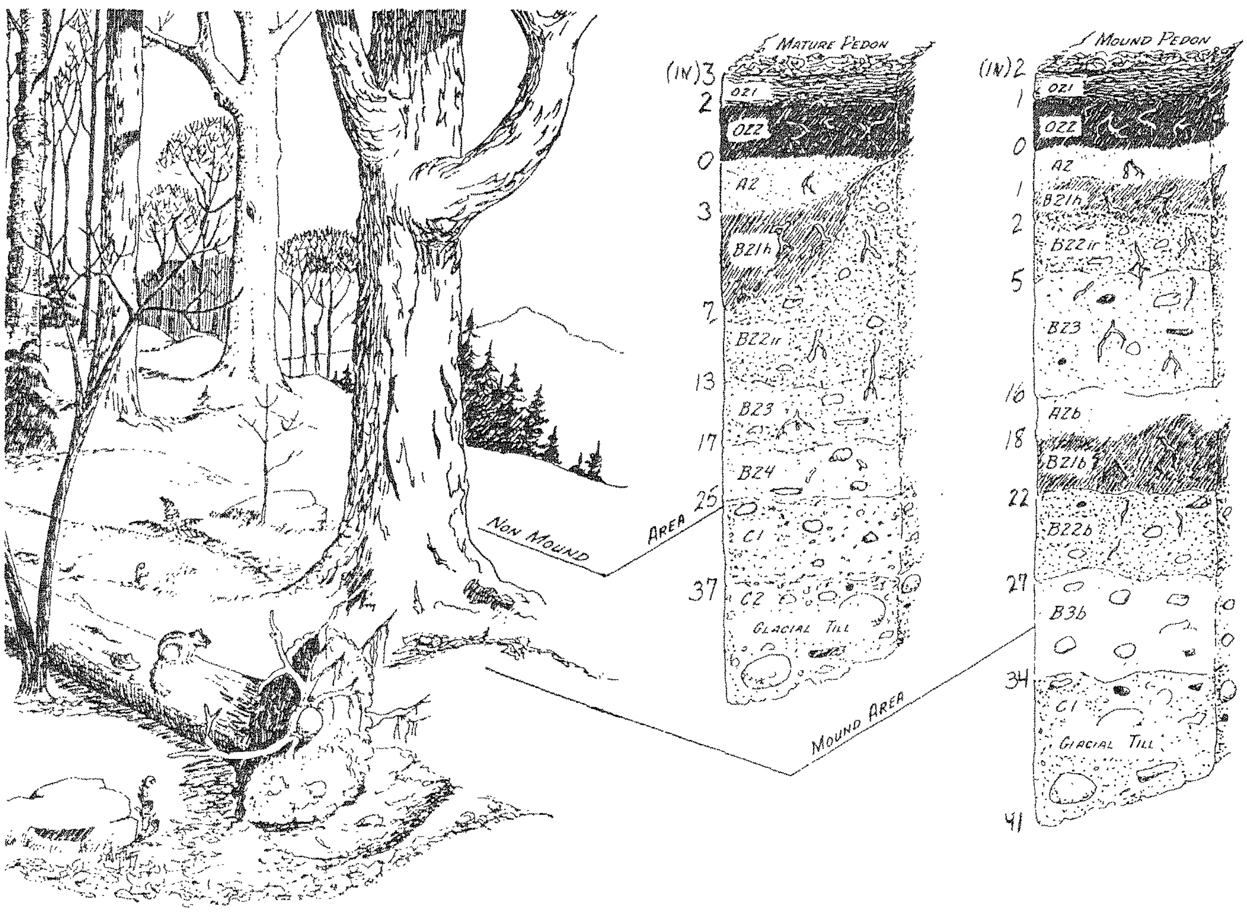

Figure 15.—Soil horizons in northern hardwood forests (Pilgrim and Harter 1977). The thick O (organic) horizons and coarse-textured mineral horizons promote high infiltration and rapid movement of water to streams.

Peak flows during these events sometimes overtop culverts, and may cause erosion along stream channels and skid trails. Table 16 shows the 10 highest instantaneous peak flows since the start of streamgaging at Hubbard Brook in 1955, together with the weather event that caused the peak flow, and the interval for which one such event can be expected to recur. The values in Table 16 are cubic feet of water per second per square mile of forest land and can be used in combination with recurrence interval to determine proper culvert sizes for skidroads and trails. Guidelines for selecting culvert sizes are given by Helvey and Kochenderfer (1988).

Streamwater Quality

Streams from northern hardwood forests that are free of recent disturbances represent a baseline for high quality water. The quality of these streams is judged on three basic parameters: turbidity, temperature, and dissolved chemicals (Hornbeck et al. 1984).

Turbidity consists of temporarily or permanently suspended particles of clay, silt, sand, and organic matter. It is measured with a turbidimeter and expressed in Jackson Turbidimeter Units (JTU). A value of zero represents distilled water while values of several hundred to several thousand represent water with extremely large amounts of suspended materials. A value greater than 10 JTU is considered unsuitable for drinking water. Turbidities in the range of 100 JTU or more can harm aquatic communities by affecting reproduction, respiration, and photosynthesis, and by interrupting the food chain. Turbidity is a direct result of soil erosion. Fortunately, undisturbed, mature, northern hardwood forests are not susceptible to erosion. Soil movement to streams seldom exceeds 0.1 tons/acre/yr, and as a result, turbidities usually are quite low. At Hubbard Brook stream turbidity usually is less than 1 JTU except during storm events, when it may increase from 1 to 5 JTU (Hornbeck et al. 1987).

Temperatures of forest streams are strongly moderated by shade from the forest canopy. At Hubbard Brook average stream temperatures range from minimums of 34±1 °F in January and February to maximums of 58±6 °F in July and August (Federer 1973). These temperatures are within ranges considered refreshing for drinking and water-based recreation, and also within the limits required for survival of native and stocked trout (Hornbeck et al. 1984).

Table 17 shows long-term averages for nutrient ion concentrations in streams at Hubbard Brook. Calcium is the dominant cation (positively charged ion) and sulfate is the most dominant anion (negatively charged ion). The low concentrations reflect the fact that northern hardwood forests are efficient at recycling and holding nutrients on

Table 16.—The 10 highest peak flows recorded at the Hubbard Brook Experimental Forest since start of record collection in 1955

Date	Peak flow level	Accompanying weather evert	Recurrence interval[a]
	$Ft^3/s/mi^2$		—years—
Oct 24, 1959	427	Hurricane, 7 inches of rainfall in 3 days	30
Mar 31, 1987	337	4.5 inches of rain, plus snowmelt	18
Feb 11, 1981	233	3 inches of rain, plus snowmelt	12
Dec 21, 1973	183	3 inches of rainfall in 2 days, plus snowmelt	9
Apr 5, 1984	163	3 inches of rainfall, plus snowmelt	8
Jan 9, 1978	158	2.5 inches of rainfall, plus snowmelt	7
Oct 20, 1975	151	Hurricane, 2 inches of rainfall in 1 day	7
Mar 13, 1977	150	2 inches of rainfall, plus snowmelt	7
June 30, 1973	146	8 inches of rainfall in 4 days[b]	7
Nov. 26, 1979	134	3 inches of rainfall in 2 days	3

[a]Number of years before storm of this magnitude will recur.
[b]See Hornbeck and Federer (1974) for description of this event.

Table 17.—Mean annual chemical concentrations in streams draining northern hardwood forests at Hubbard Brook Experimental Forest (Likens et al. 1977) and Sleeper's River Research Watersheds (Thorne et al. 1988). All values are parts per million (ppm)

Ion	Hubbard Brook Experimental Forest	Sleeper's River Research Watersheds
Calcium (Ca^{2+})	1.7	21.6
Magnesium(Mg^{2+})	0.4	0.9
Potassium (K^+)	0.2	1.0
Sodium (Na^+)	0.9	0.6
Aluminum (Al^{3+})	0.2	a
Ammonium (NH_4^+)	0.04	a
Hydrogen (H^+)	0.01	a
Sulfate (SO_4^{2-})	6.2	a
Nitrate (NO_3^-)	1.9	a
Chloride (Cl^-)	0.5	a
Phosphate (PO_4^{3-})	<0.01	a
Bicarbonate (HCO_3^-)	1.6	a

[a]Data not available.

site. However, there are situations where nutrient capitals far exceed demands of the forest, resulting in higher concentrations of ions in streamwater. Such is the case for northern hardwood forests at the Sleeper's River Research Watersheds located on calcium-rich terrain 40 miles north of Hubbard Brook (Thorne et al. 1988). Calcium concentrations in streams at Sleeper's River are considerably greater than at Hubbard Brook (Table 17).

Nutrient Cycles

Compared to other forest types, northern hardwoods generally occur on sites neither nutrient rich nor nutrient poor. The challenge for forest managers is to keep as much of the nutrient capital as possible within the forest and available for plant growth. Fortunately, the job is made easier for northern hardwoods because they tend to have "tight" nutrient cycles. Large stores of nutrients accumulate in organic matter and few nutrients are lost to erosion or as dissolved solids in streamflow. However, disturbances such as harvesting, blowdowns, insect defoliations, or additions of chemicals can disrupt nutrient cycles and may affect productivity of the forest. By understanding the movement of plant nutrients into, within, and out of the forest, steps can be taken to ensure that productivity is maintained, and possibly even enhanced.

Nutrient pools. The bulk of the site-nutrient capital resides in three pools: mineral soil, forest floor, and above-ground vegetation. The pool in the mineral soil is by far the largest. Data from the Hubbard Brook Experimental Forest (Table 18) show that of the total calcium capital of 9,329 lb/acre, 8,565 lb/acre, or 92 percent, occurs in the mineral soil. Only 342 lb/acre, roughly 4 percent of the total calcium capital, is incorporated in above-ground biomass. For the total nitrogen capital of 4,807 lb/acre, 3,212 lb/acre, or 67 percent, is in the mineral soil, 1,121 lb/acre, or 23 percent, is in the forest floor, and 313 lb/acre, or 7 percent, is in above-ground biomass (Table 18).

The soil pools can be divided further into available and bound nutrients. Available nutrients, so named because they are readily available for plant uptake, occur in ionic form (Ca^{2+}, K^+, NH_4^+). Bound nutrients are complexed in organic compounds or in minerals in stones and soil particles and may eventually contribute to the available pool, but the conversion is very slow. Available nutrients are a small fraction of the total capital. For example, of the total calcium capital of 9,329 lb/acre at Hubbard Brook, only 455 lb/acre, or about 5 percent, is in plant-available form (Table 18). As will be shown in later sections, the total capital and the bound and available fractions are all affected by forest management and forest disturbances.

Table 18.—Pools and fluxes for major nutrients at the Hubbard Brook Experimental Forest (Likens et al. 1977; Hornbeck et al. 1987)

Component	Calcium	Magnesium	Potassium	Nitrogen	Sulfur	Phosphorus
	lb/acre					
Above-ground biomass	342	32	138	313	37	30
Roots	90	12	56	161	15	47
Forest floor	332	34	59	1,121	111	70
Mineral soil	8,565	6,833	4,536	3,212	500	2,252
Total capital	9,329	6,911	4,789	4,807	663	2,399
Soil-available nutrients	455	37	67	23	NA	NA
	lb/acre/yr					
Precipitation input	2.0	0.5	0.8	5.8	11.3	0.0
Gaseous or aerosol input	NA	NA	NA	12.7	5.4	NA
Weathering release	18.8	3.1	6.3	0	0.7	NA
Streamwater output:						
Dissolved substances	12.2	2.8	1.7	3.5	15.7	0.0
Particulate matter	0.2	0.2	0.4	0.1	0.1	0.0
Vegetation uptake	55.5	8.3	57.4	71.0	21.9	7.9
Litter fall	36.3	5.3	16.3	48.4	5.2	3.6
Root litter	2.9	0.4	1.9	5.5	0.5	1.5
Throughfall and stemflow	6.0	1.8	26.9	8.3	18.7	0.6
Root exudates	3.1	0.2	7.1	0.8	1.7	0.2
Net mineralization	37.8	5.4	17.9	62.1	5.1	NA
Above-ground biomass accretion	4.8	0.4	3.8	4.3	0.7	0.8
Below-ground biomass accretion	2.4	0.3	1.3	3.7	0.4	1.2
Forest floor accretion	1.2	0.2	0.3	6.9	0.7	0.4

Nutrient fluxes. Nutrients are in constant flux between the atmosphere, vegetation, and soil. Table 18 summarizes the annual rates of flux for various processes in the mature northern hardwood forest at Hubbard Brook. Uptake by vegetation is the largest flux within the forest ecosystem, ranging from 8 lb/acre/yr for phosphorus to 71 lb/acre/yr for nitrogen. Much of the uptake is returned to the forest floor and soil, either in litterfall, root litter, or root exudates, so that accretion of nutrients in above- and below-ground biomass is only a few lb/acre/yr. Mineralization, or the decomposition of organic matter, is the most important process by which plant nutrients are made available, providing an estimated 38 lb/acre/yr of calcium, and 62 lb/acre/yr of nitrogen. Weathering of stones and soil particles is thought to be a somewhat smaller source, but rates are difficult to determine and open to question. Past studies at Hubbard Brook suggest that weathering may release up to 19 lb/acre/yr of calcium (Table 18); however, a recent analysis based on more detailed geologic considerations suggests this amount is far too high (Federer et al. 1989). There is no nitrogen in stones and mineral soil particles at Hubbard Brook, thus, no addition of nitrogen from weathering.

Atmospheric inputs. Small quantities of plant nutrients are added to northern hardwoods in dry form as gases and aerosols, or as dissolved ions in precipitation. Gaseous and aerosol additions are extremely difficult to measure and not much is known about quantities. Additions of ions in precipitation range from <1 lb/acre/yr for magnesium and potassium to over 11 lb/acre/yr for sulfur (Table 18).

Industrial emissions and combustion of fossil fuels are significant sources for much of the chemical input in precipitation and are the precursors of the acid rain and snow that occur on northern hardwood forests. Precipitation at Hubbard Brook has an annual average pH of 4.4, which is typical for New England (Fig. 16). The low pH results mostly from dissociation of the strong mineral acids in precipitation such as sulfuric, nitric, and hydrochloric (giving rise to hydrogen, sulfate, nitrate, and chloride ions in precipitation).

As precipitation strikes the forest canopy, it reacts with previously deposited materials and with leaf and bark tissues, and undergoes enrichment of all major chemicals

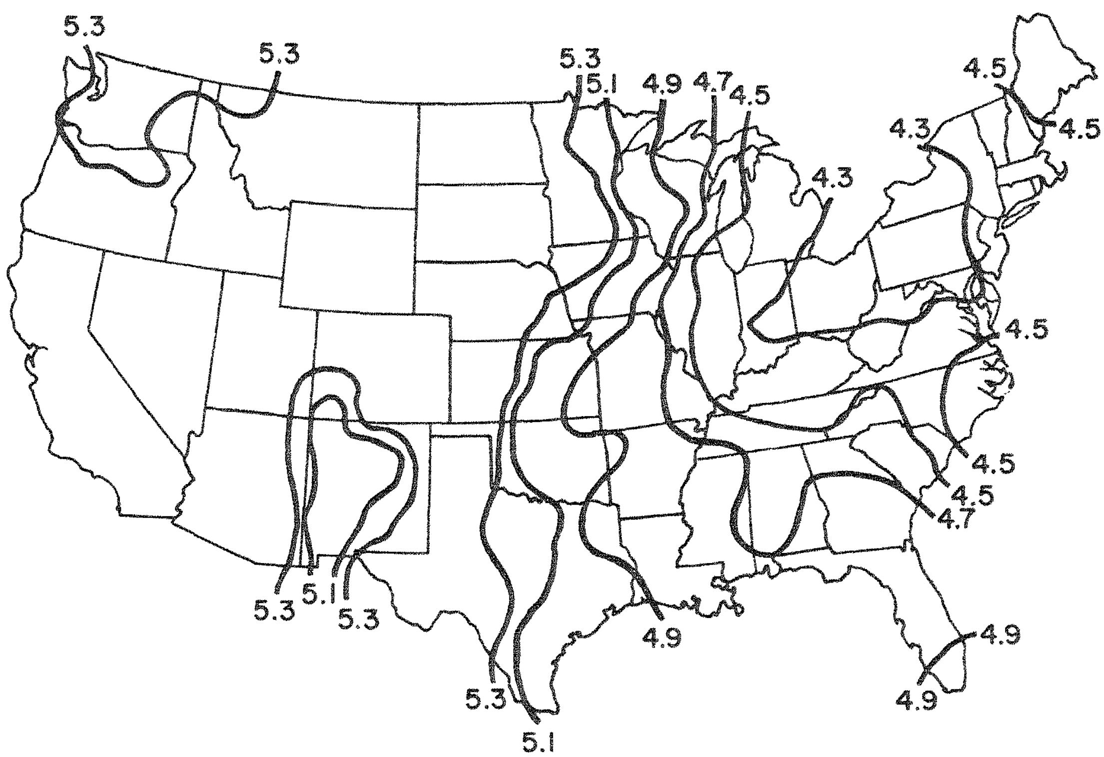

Figure 16.—Mean annual pH of precipitation for 1989 (National Atmospheric Deposition Program 1990).

except hydrogen (Table 19). Much of the hydrogen stays in the canopy, at least temporarily, causing throughfall to be more than one pH unit greater (less acidic) than above-canopy precipitation. Without leaves, the canopy has less effect in the dormant season, although snowpacks are enriched from dry deposition (Hornbeck and Likens 1974).

Table 19.—Concentrations (parts per million) of chemicals in precipitation above and below the forest canopy at Hubbard Brook (Likens et al. 1977; Eaton et al. 1973)

Material	Precipitation above canopy	Precipitation under canopy (throughfall and stemflow)	Net change
Ca^{2+}	0.16	1.59	+1.43
Mg^{2+}	0.03	0.45	+0.42
K^{+}	0.07	6.37	+6.30
Na^{+}	0.06	0.14	+0.08
NO_3^-	0.97	2.97	+2.00
NH_4^+	0.27	1.56	+1.29
Total N	0.44	2.44	+2.00
PO_4^{3-}	0 0080	0.46	+0.452
SO_4-S	2.70	16.18	+13.48
Cl^-	0.45	1.46	+1.01
H^+	0.087	0.010	-0.077
pH	4.1	5.0	+0.9
Organic C	2.4	12.0	+10.00

Streamflow outputs. As streams leave forested watersheds they transport both dissolved nutrients incorporated into sediments consisting mostly of soil and organic particulate matter. Since forests free of recent disturbances produce little sediment, most of the nutrient output is in dissolved form with outputs ranging from near zero for phosphorus to 18 lb/acre/yr for sulfur (Table 18). For all major nutrients except nitrogen, the outputs in streamflow exceed inputs to the forest in precipitation. The net losses from the forest ecosystem raise the concern of possible depletion of nutrient reserves, especially when extrapolated over time. For example, the net annual loss of calcium of about 12 lb/acre/yr becomes a sizable loss from the total calcium capital if projected over 100 years.

Wildlife Habitat

There are 338 nonmarine (inland) wildlife species in New England: 26 amphibians (salamanders, toads, frogs), 30 reptiles (turtles, snakes), 220 birds, and 62 mammals. Out of this number, 266 use the forest at least part of the time and the others are restricted to water or nonforest (e.g. fields). Only 16 of the forest-users stay completely in coniferous forests, e.g. the three-toed and black-backed woodpeckers or the spruce grouse, leaving 250 species that sometimes use hardwood or hardwood-conifer stands. Most of these species are not very specific to a forest type, so it is not surprising that 215 species are listed for northern hardwood stands (Table 20): 61 percent birds, 25 percent mammals, and 14 percent amphibians and reptiles. Only a few of these species are game animals or even well-known songbirds. But they serve several functions, as: food for larger animals; insect, seed, and vegetation eaters; and seed dispersers and buriers. Numbers of species do not vary greatly by stand-size classes (Table 20), but a forest that maintains all sizes and ages of timber, including some temporary or—better yet—permanent nonforest openings, can support approximately 215 species as compared to an all-aged forest with 160 species (DeGraaf et al. 1992).

Table 20.—Potential numbers of wildlife species in northern hardwood stands by stand size-class and type of wildlife. Many species are found in several stand size-classes

Wildlife type	Stand size-class					
	Regeneration	Polestands	Sawtimber	Overmature	All-aged	All
Amphibians	8	16	19	18	18	19
Reptiles	9	12	12	12	11	12
Birds	96	72	82	90	84	131
Mammals	45	40	47	47	47	53
All	158	140	160	167	160	215

Within a northern hardwood forest, wildlife species occupy several different types of habitat conditions for purposes of breeding, feeding, or cover (Table 21). High, exposed perches are used by hawks and eagles and other birds, low perches by flycatchers and several sparrows. Many warblers are canopy feeders. Typical tree-bole users are owls and woodpeckers. Large, dead, and partially-decayed living trees are more useful than small. Many hawks, owls, and smaller birds utilize small patches of softwood trees existing with a northern hardwood stand.

Table 21.—Potential numbers of wildlife species found using certain habitat factors in northern hardwoods. Many species use more than one factor (DeGraaf et al. 1991)

Habitat factor	Number of species
High, exposed perches	7
Low, exposed perches	13
Tree canopies	89
Tree boles	40
Midstories (10-30 feet tall)	18
Shrub layers (3-10 feet tall)	81
Overstory softwood inclusions	60
Upland herbaceous vegetation	47
Wetland herbaceous vegetation	15
Decaying logs	3
Humus layers	53
Below ground	38

Upland and wetland herbaceous vegetation supports a variety of birds, amphibians and reptiles, and small mammals; these layers are best developed under low-density canopies or in openings. Decaying or hollow logs are used by amphibians and reptiles, as well as small and large mammals. Ground surface and below-ground dwellers also include a variety of amphibians and reptiles, mammals, and birds. The general message is that there is a great variety of wildlife habitat in northern hardwood stands and a myriad of opportunities to influence habitat conditions through silvicultural practice.

Regeneration of Northern Hardwoods

As outlined in the summary table of silvic characteristics (Table 1), northern hardwoods regenerate by four major approaches: new seed, buried seed, stump sprouts, and root suckers. In addition, some species depend upon advanced regeneration already present in the understory at the time of disturbance, while others depend upon new regeneration. This variety of regeneration strategies provides a means for rapid, natural revegetation of almost any type or size of disturbance. Seeding or planting seldom is required or used in northern hardwood stands.

Regeneration from Seed

Most northern hardwoods produce seed in the autumn. Only four of the species in Table 1: red maple, striped maple, aspen, and pin cherry, are spring seeders.

Seed production varies greatly with seed year, stand age, tree condition, and species composition. Examples of seed production for a range in stand age during a fair-to-good seed year indicates that seed production for most species is approaching maximum in 80-year-old stands. Variability among seed years, however, is extreme as shown by 11 years of records from an old-growth northern hardwood stand (Table 22).

Table 22.—Total seed production by species and year (thousands of seeds per acre)[a] (unpublished data, R.E. Graber, USDA Forest Service)

Year	Yellow birch	Sugar maple	Beech
1971	6,623±600	4,799±435	121±23
1972	12,982±1,171	560±85	11±1
1973	143±29	0±0	55±9
1974	25,909±3,228	2,724±314	77±13
1975	472±94	66±13	22±3
1976	2,504±203	2,482±266	22±2
1977	13,267±1,108	11±1	0±0
1978	472±78	1,263±160	176±38
1979	7,304±407	2,867±307	110±27
1980	1,109±161	428±87	88±13
1981	4,668±381	3,086±276	99±20

[a]Mean±confidence limit, f=0.95. The transformation, X+0.5, was used in computing CL.

Viability also is extremely variable, and is known to vary with seed year. Germination potential of paper birch seeds is three to six times higher during a good seed year as compared to a poor one (Table 23). Similar relationships have been shown for yellow birch, sugar maple, and beech; viability for these species varied with amount of seed fall from zero to 50-60 percent.

Before dispersal, losses of seed to birds, insects, and small mammals may reach about 40 percent. Large losses certainly must occur after dispersal as well.

Even with a fairly light-seeded species such as paper birch, dispersal by wind is limited to fairly short distances; about 90 percent or more of the seed falls within 175 feet from the source (Fig. 17). Most species disperse shorter distances. However, aspen seed may blow long distances, and birch seed, especially yellow birch, which falls throughout the winter, may travel long distances over crusty snow.

Buried Seed, Sprouts, and Suckers

Pin cherry and raspberry are the two species groups that appear to maintain viable seed in the forest floor for long periods of time or up to 200+ years (Graber and Thompson 1978) (Fig. 18). Red elderberry also showed some indication of long-term storage in the soil. Changes in temperature, and perhaps soil chemistry, following heavy disturbance apparently cause these species to germinate. Disturbance of old stands should result in less competition from these species than should disturbance of younger stands.

Table 23.—Germinative capacity of paper birch by month and annual per-acre seed fall. Penobscot Experimental Forest, Maine, 1958-60 (Bjorkbom et al. 1965)

Year	Total no. seeds per acre	Aug.	Sept.	Oct.	Nov.	Dec.-spring
	millions	percent germination				
1958	1.3	6	13	63	14	4
1959	0.8	58	25	13	3	1
1960	16.8	51	13	20	14	2

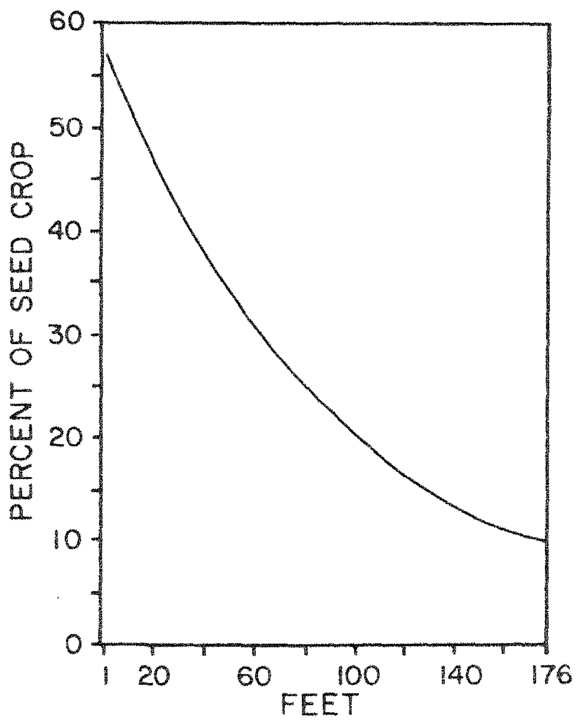

Figure 17.—Percent of seed crop dispersed into a clearcutting drops off rapidly as the distance from forest edge increases (Bjorkbom 1971).

Red maple and white ash are the two common, prolific stump sprouters in the northern hardwood forest. Red oak also sprouts vigorously. Numbers of sprouts per stump in red maple reach a maximum at approximately 10 inches stump diameter; for comparison, numbers of sugar maple sprouts (and proportion of stumps with sprouts) decline rapidly with increasing stump size (Fig. 19). Beech produces mostly weak, adventitious sprouts from the top of cut stumps; other species sprout from small stumps, but only sporadically from larger ones.

Root suckering is the primary regeneration method employed by aspen; the extent of seed production is not known. Beech regeneration from root suckering also can be substantial; over 50 percent of beech regeneration after a patch cutting at Bartlett Experimental Forest was from root suckers (Marquis 1965).

Germination and Early Growth

Moisture is the primary requirement for seed germination. Intolerant and intermediate species (birches, white ash) that

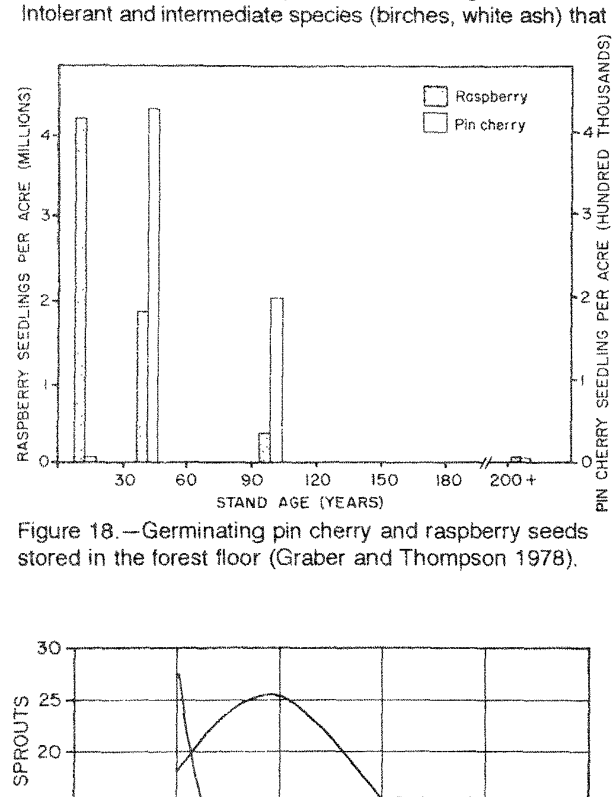

Figure 18.—Germinating pin cherry and raspberry seeds stored in the forest floor (Graber and Thompson 1978).

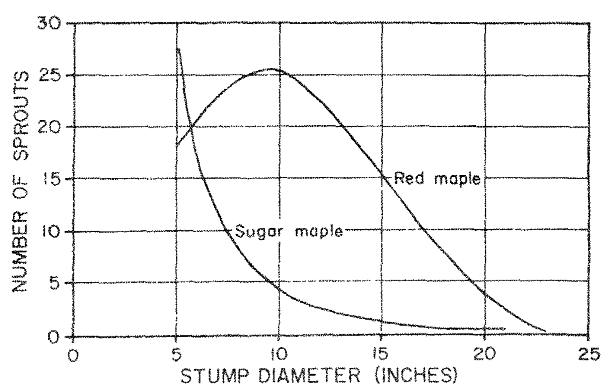

Figure 19.—Relationship of number of sprouts per stump to average stump diameter for red maple and sugar maple (Solomon and Blum 1967).

regenerate in openings generally do well on disturbed, mineral-soil seedbeds, which maintain a higher moisture level than humus or leaf-litter seedbeds (Table 24). During moist springs or under the shade of an overstory canopy, mineral soil seedbeds are not so important. Species whose regeneration is dependent upon advanced growth, buried seed, or sprouts and suckers show a minimal or negative response to mineral seedbed as compared to birches (Table 24).

Survival of regeneration is closely related to stand density and species shade tolerance. Few intolerant species (paper birch, pin cherry) will survive in any numbers under partial shade, even that provided by only 40 square feet per acre basal area. However, a moderate proportion of tolerants will persist in the open.

Another factor affecting regeneration is competition from

Table 24.—Stocking in patch cuttings at Bartlett Experimental Forest by species and seedbed condition (Marquis 1965)

	Seedbed condition							
	Skidroad		Disturbed mineral soil		Undisturbed Forest floor intact		Slashpile Forest floor intact	
Species	M stems per acre	(percent)	M stems per acre	(percent)	M stems per acre	(percent)	M stems per acre	(percent)
Paper birch	104.0	37	65.8	37	17.0	13	3.2	6
Yellow birch	63.0	23	14.8	8	9.7	8	1.6	3
Sugar maple	3.8	1	2.1	1	7.1	6	4.9	9
Beech	4.4	2	7.1	4	6.0	5	2.9	5
Red maple	7.3	3	5.3	3	4.5	4	2.3	4
White ash	3.4	1	2.2	1	1.8	1	1.3	2
Pin cherry	23.7	9	21.8	12	23.5	18	11.4	21
Striped maple	0.1	—	0.9	1	2.2	2	1.6	3
Raspberry	61.2	22	46.6	26	40.8	32	15.6	29
Aspen	1.4	1	.6	—	1.0	1	—	—
Other	5.2	1	1.9	7	13.2	10	9.6	18
Total	277.4	100	178.2	100	126.8	100	54.5	100

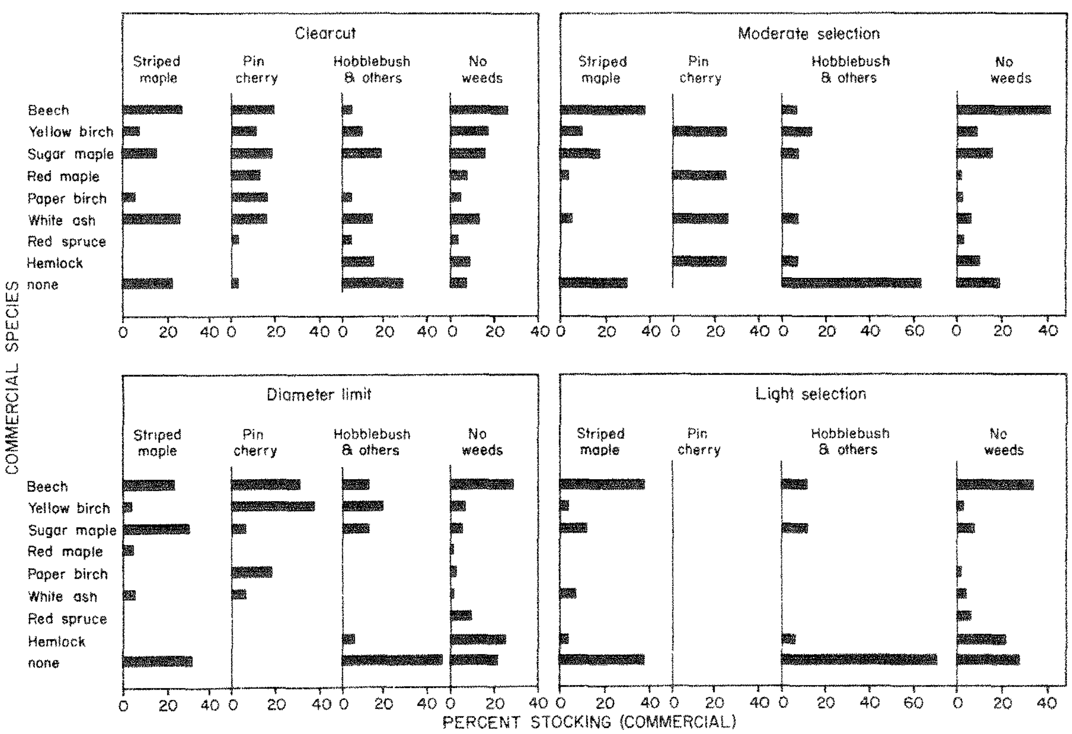

Figure 20.—Percent stocking of tallest commercial species on milacre dominated by certain noncommercial species, 8 years after cutting by four methods (Leak 1988).

other species. Preliminary information indicates that hobblebush is one of the more severe competitors, i.e. milacre plots dominated by hobblebush have a low percent stocking or complete absence of commercial species (Fig. 20). Striped maple has less effect, and pin cherry little effect at all, although other studies indicate that very dense crops of pin cherry can reduce the stocking of both paper and yellow birches. White ash and sugar maple show little negative response to any noncommercial species.

In certain areas of the Northeast, browsing and girdling from deer, rabbits, rodents, and moose can be a major obstacle to regeneration and early growth of northern hardwoods. Several management approaches, given in a later section, are available to help minimize animal damage to regeneration.

Regeneration cutting methods in northern hardwoods are designed to provide conditions of seed source, light, seedbed conditions, and competition that are conducive to the establishment of the species desired. Clearcuttings provide for maximum amounts of intolerant commercial and noncommercial species while individual-tree selection provides for maximum tolerants. Strip cuttings (wide or narrow), group selection (large or small groups or patches), and shelterwood (dense or open overstory) provide for intermediate tolerants.

Impacts of Harvest

Harvesting of northern hardwoods triggers changes in plant and animal communities, hydrologic and nutrient cycles, stream-water quality, and appearance of the landscape. The severity of change depends upon intensity of harvest and care taken in planning and carrying out logging. Thus, maximum effects usually accompany evenaged harvests such as block clearcutting, or strip cutting, a form of shelterwood harvest. Much of the following information used to illustrate expected effects of harvest relates to evenaged harvests since they have been applied widely and studied over the past three decades. Less intensive harvests, such as selection or small patch cuttings, have far less impact on hydrologic and nutrient cycles and water quality, provided logging is done with precaution, but may still trigger important changes in plant communities.

Stand Regeneration

Information on stand regeneration after harvest of northern hardwoods has been collected at the Hubbard Brook Experimental Forest as part of long-term studies of evenaged management. The studies were initiated in 1970 by performing a block clearcutting on a 30-acre watershed, and a progressive strip cutting on an 89-acre watershed. Details of the harvests and measurements of regeneration for the first 10 years after harvest have been reported by Hornbeck et al. (1987), and Martin and Hornbeck (1989, 1990).

Progressive strip cutting evolved from block clearcutting as an attempt to further favor regeneration of birches by more closely controlling variables such as distance to seed sources, light, moisture, and scarification of the seed bed. The method of strip cutting applied at Hubbard Brook is recommended by Marquis (1966) and Safford (1983) and entails cutting strips about 80 feet wide oriented along the

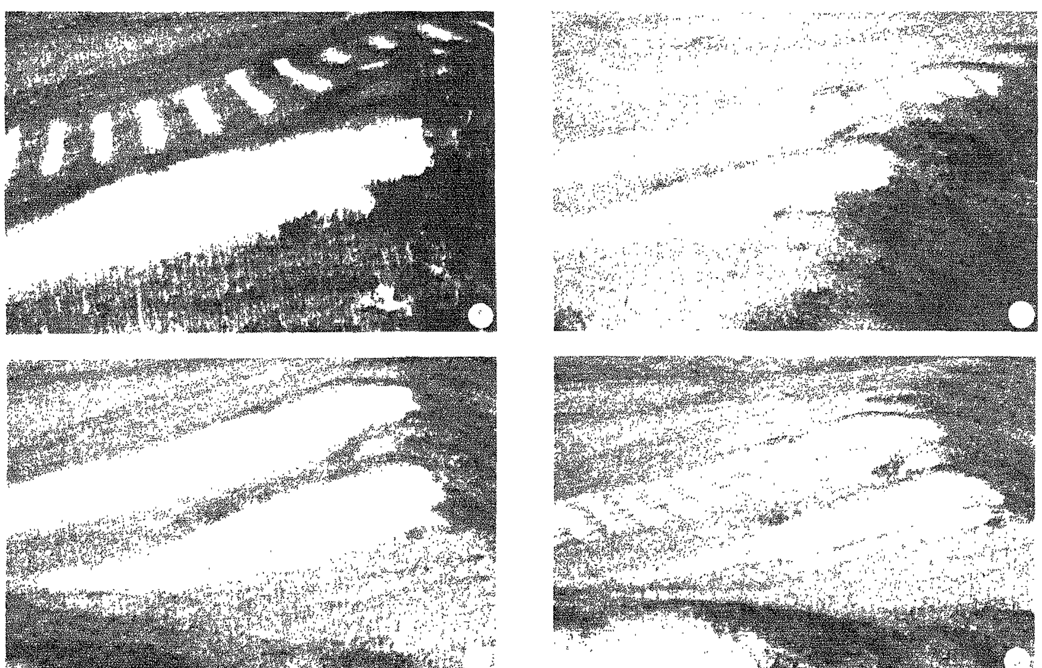

Figure 21.—East-to-west views across strip-cut watershed. Cleared area in foreground is an earlier deforestation experiment.

Table 25.—**Number of tree, shrub, and herbaceous stems at 2 and 10 years after individual harvests (elevation ranges are low, 1,440 to 1,805 ft; mid, 1,805 to 2,130 ft; and upper, 2,130 to 2,460 ft; block-cut spanned elevations 1,540 to 1,970 ft, or closest to mid-elevation range on strip cut)**

	First strip						Second strip						Third strip						Block cut	
	Low		Mid		Upper		Low		Mid		Upper		Low		Mid		Upper		Mid	
Year	2	10	2	10	2	10	2	10	2	10	2	10	2	10	2	10	2	10	2	10
Species	Thousands of stems/acre																			
Tree[a]	240	53	211	40	89	36	102	22	114	20	63	16	173	30	125	20	80	27	267	94
Shrub[b]	67	21	13	37	38	89	45	7	53	11	31	22	83	4	87	8	47	27	21	13
Herbaceous[c]	138	114	297	91	217	252	203	52	187	36	137	92	337	79	469	44	312	219	120	74
All species	445	188	521	168	344	377	350	81	354	67	231	130	593	113	681	72	439	273	408	181

[a]Major tree species include: Balsam fir, striped maple, red maple, sugar maple, mountain maple, yellow birch, paper birch, American beech, white ash, red spruce, aspen, and pin cherry.

[b]Major shrub species include: raspberry, common elderberry, and hobblebush.

[c]Major herbaceous species include: whorled aster, hay-scented fern, spinulose wood-fern, shining club moss, Canada mayflower, wood sorrel, wild oats (sessile bellwort), and species of violet and trillium.

contour with 160-foot-wide uncut strips between them (Fig. 21A). After a 2-year period for establishment of regeneration, a second series of 80-foot-wide strips is cut on the southernmost or westernmost side of the original cut (Fig. 21B). The remaining set of strips is then cut after a second establishment period of 2 years (Fig. 21C). On both the block clearcut and stripcut watersheds, all merchantable stems were removed using logging practices common to the White Mountain region. Soil scarification to provide a favorable seedbed for yellow birch was encouraged during logging, with appropriate measures to avoid erosion (Marquis 1969; Filip 1969).

Natural regeneration flourished after both block clearcut and strip cutting, with the density and mix of species changing dynamically in the postharvest periods (Table 25). Total numbers of all stems increased rapidly after harvest and peaked between years 2 and 4 at about 400,000 stems per acre. In terms of ground cover, the vegetation at year 2 after block cutting and each of the strip cuttings formed a dense tangle, averaging approximately 3 feet in height. The only areas not revegetated were those under dense slash or those severely gouged and rutted during logging. Such areas amounted to less than 3 percent of the total watershed area.

Between years 2 and 10, the canopy closed and tree species gained dominance in both height and biomass (Fig. 22). By year 10 competition had drastically reduced the number of stems approximately to precutting levels, and some tree species had obtained sufficient size to move into lower diameter classes (Table 26). The three most common northern hardwood species, beech, yellow birch, and sugar maple, became prominent in terms of

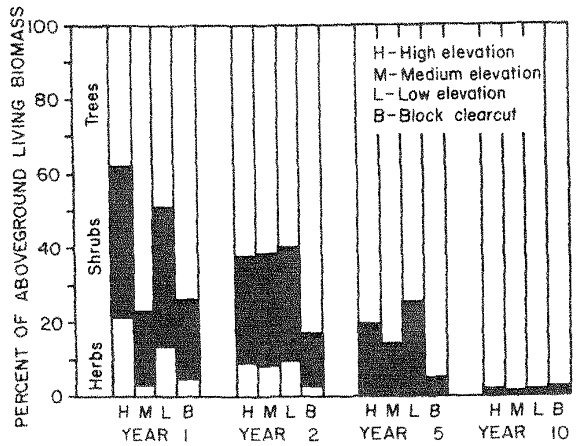

Figure 22.—Percentages of biomass occupied by trees, shrubs, and herbs on the second strip. Percentages of trees represented by the top portions of the bars; herbs by the lower portions. (Hornbeck et al. 1981).

Table 26.—Stems per acre, by diameter class in inches, for six major tree species occurring at year 10 after harvest

Species	Elevation	First strip				Second strip				Third strip				Block clearcut			
		<1.0	1.0-1.9	2.0-2.9	3.0-3.9	<1.0	1.0-1.9	2.0-2.9	3.0-3.9	<1.0	1.0-1.9	2.0-2.9	3.0-3.9	<1.0	1.0-1.9	2.0-2.9	3.0-3.9
Yellow birch	Low[a]	10,238	301	23	0	1,538	594	81	27	3,561	837	189	0				
	Mid[b]	7,689	227	32	0	486	998	108	0	728	648	301	46	58,274	587	17	3
	Upper[c]	9,510	255	69	23	2,023	1,318	93	0	5,544	944	108	0				
Sugar maple	Low	14,892	23	0	0	11,129	1,025	135	27	15,176	486	27	0				
	Mid	18,413	97	32	0	9,955	620	108	0	10,117	740	93	0	6,799	138	7	0
	Upper	7,649	139	0	0	5,180	0	0	0	4,209	27	0	0				
American beech	Low	2,185	139	23	0	1,700	432	27	0	3,035	377	0	0				
	Mid	3,642	65	0	0	2,185	1,025	0	0	1,862	255	23	23	5,787	176	0	3
	Upper	3,076	231	0	0	1,012	370	69	23	3,885	486	27	0				
Pin cherry	Low	3,885	786	416	116	0	61	243	135	0	377	243	189				
	Mid	405	809	583	130	1,012	594	450	23	0	162	162	69	7,244	2,580	479	27
	Upper	728	347	69	69	1,133	416	208	23	688	81	54	0				
Striped maple	Low	1,902	278	162	0	850	351	0	0	1,862	297	54	0				
	Mid	3,237	227	32	0	526	675	54	0	2,023	440	23	0	3,845	101	0	0
	Upper	2,023	0	0	0	2,185	93	23	0	4,047	54	0	0				
Mountain maple	Low	2,023	93	0	0	850	837	108	0	0	54	0	0				
	Mid	0	0	0	0	0	162	0	0	1,295	93	0	0	121	3	0	0
	Upper	4,937	0	0	0	728	139	0	0	2,873	0	0	0				

[a]Low elevations are 1,440 to 1,805 ft
[b]Mid elevations are 1,805 to 2,130 ft
[c]High elevations are 2,130 to 2,460 ft

total number of stems. Pin cherry, an exploitive or pioneer species (Bormann and Likens 1979), occurred in moderate numbers on the strip cutting, and in large numbers on the block cutting, and usually dominated in terms of biomass as a result of having far more stems in the larger diameter classes (Table 26). Pin cherry is shortlived, and should no longer be an important competitor by year 20. At 10 years after cutting, total biomass was between 37 and 58 tons per acre, or 25 to 40 percent of the aboveground biomass before harvest.

Cutting of the early strips increased the density and biomass of the advance regeneration in the uncut strips, but this advance regeneration was mostly destroyed during subsequent logging and was not an overriding factor to regeneration of the watershed. Likewise, stump sprouts were of only minor importance as a source for regeneration on both watersheds.

Little is known about the species composition and stocking levels necessary at year 10 to produce a commercially valuable northern hardwood stand. Solomon and Leak (1969) indicated that stocking ultimately should be approximately 400 stems per acre of commercial species having minimum diameters of 5 inches. Data from Hubbard Brook watersheds suggests that regeneration at year 10 after harvest is adequate to evenly produce such a stand, especially in light of the high counts of yellow birches and sugar maples (Table 26).

Other studies from the region show that regeneration following group selection and single-tree selection will have a much higher percentage of tolerant species compared to clearcutting (Table 27). Also, contrary to expectations, a study at 5 years after logging of 66 northern hardwood stands in Vermont showed no compelling evidence that summer cuttings might provide more scarification and birch regeneration than winter cuttings (Table 28).

Logging Damage to Residual Trees

Damage from skidded trees, logging equipment, or from felling of adjacent trees commonly occurs on 20 to 40 percent of the trees left behind during partial cuts and thinnings of northern hardwoods (Ostrofsky 1988). The injuries, which include breakage and abrasion of roots and root crowns, scuffing and bruising of the bole, and breakage of tops and branches, serve as entry points for a variety of pathogens. Common diseases that take advantage of logging wounds include *Armillaria* root rot, sapstreak disease of maple, *Nectria* canker, and internal discolorations and decay caused by fungi (Ostrofsky 1989; Houston 1986).

Frequency and severity of logging wounds are related to soil, stand, and tree factors (Table 29), and also to the season. Logging damage can be minimized by restricting logging to winter and dry season conditions, matching logging equipment and skid-trail layout to tree size and site conditions, and minimizing the number of entries into a stand over a rotation (Ostrofsky 1988).

Table 27.—Species composition of stocked milacres, 10 to 15 years after cutting in beech-birch-maple stands, by tolerance group and cutting method (Leak and Wilson 1958)

Tolerance group[a]	Clearcutting	Group selection	Single-tree selection
	Percent		
Tolerant	43	62	92
Intermediate	19	34	7
Intolerant	38	4	1

[a]Tolerant: beech, sugar maple, eastern hemlock, and red spruce (also balsam-fir if present); Intermediate: yellow birch, white ash, and red maple; Intolerant: paper birch and aspen.

Table 28.—Average 5-year stocking (percent) of stocked plots after logging northern hardwood stands in Vermont, 1973-82 (Tubbs and Reid 1984)

Season or kind of cut	Stands (N)	Tree species: Yellow birch	Sugar maple	Am. beech	Red spruce	Other	All commercial species
Summer	15	40	26	14	5	15	88
Winter	21	48	32	11	4	6	91
Shelterwood	9	29	48	15	1	7	—
Clearcut	21	49	17	14	5	15	—

Table 29.—Natural factors affecting frequency and severity of injuries to residual trees during harvesting operations (Ostrofsky 1988)

Factors	Injuries more frequent and/or more severe		Injuries less frequent and/or less severe
Soil			
Texture	Clay	Loam	Sand
Drainage	Wet	Moderate	Dry
Depth	Shallow	Moderate	Deep
Rockiness	Rocky	Moderate	Not rocky
Stand			
Density	High	Moderate	Low
Age	Old (50+)	Moderate	Young (25-)
Structure	Uneven	2-3 Classes sized	Even sized
Tree			
Size	Large (8"+)	Medium	Small (6"-)[a]
Rooting habit	Shallow	Intermediate	Deep
Species	Intolerant[b]	Intermediate	Tolerant
Vigor	Low	Moderate	High

[a]Survival of small trees is threatened by major injuries, but if the tree survives, loss in quality will be less than from a similar injury on a large tree.
[b]One exception is beech.

Impacts on Stream Water Quality and Biota

Turbidity. Northern hardwood forests have an inherent resistance to erosion and subsequent production of stream sediment and turbidity that can withstand disturbances such as harvesting so long as the forest floor is not abused. This was clearly demonstrated on the strip-cut and block clearcut watersheds at Hubbard Brook. To protect the forest floor, all known precautions were taken during logging. For example, logging was conducted in early autumn when chances for erosion and turbidity are least. A buffer strip of trees was left along the stream channel in the strip cut, and efforts were made to avoid streamside zones in both the clearcut and strip cut. Skidroads were kept at lowest possible grades, and water bars were installed. These efforts, combined with the occurrence of rapid revegetation, resulted in minimal changes in stream turbidity. Of more than 450 water samples collected during, and 3 years after, harvest, only 11 had turbidities exceeding the drinking water standard of 10 JTU, and none exceeded 40 JTU (Hornbeck et al. 1987). In contrast, after clearcutting another area in northern New Hampshire, plugging and overtopping of a skidroad culvert during a summer thunderstorm resulted in turbidity values of 2,200 and 3,300 JTU (Hornbeck et al. 1986).

Stream temperature. Leaving a buffer strip of unharvested trees approximately one-half to one tree height on both sides of the stream channel will prevent any significant changes in stream temperature (Hornbeck et al. 1986). Cutting of all trees around the channel can increase peak stream temperatures by 10 to 25 °F in July and August, and reduce winter stream temperatures to freezing. In most cases, streams draining harvested sites are of relatively small volume, and changes in temperature caused by harvests are likely to disappear quickly once the streams pass into uncut forests.

Stream chemistry. Concentrations of most stream-water ions are affected by harvest. Maximum changes occur after intensive harvests such as clearcutting, and the ion showing the greatest change—an increase—usually is nitrate (NO_3^-), an oxidized form of nitrogen. Nitrate in streams draining northern hardwoods can increase from an average of <1 ppm before harvest to as high as 28 ppm in the second year after clearcutting (Martin et al. 1986). The increases generally are short-lived and disappear by the third or fourth year after harvest. Post-harvest concentrations of nitrate seldom exceed the EPA standard of 45 ppm for drinking water, but may stimulate increased numbers and production of aquatic organisms, and also represent an additional loss of nitrogen from the harvest site. At Hubbard Brook, increases in nitrate in streams were as high as 23 ppm after block clearcutting, but only 2-4 ppm after strip cutting. Small increases on the order of 1 to 4 ppm occur in nutrient ions such as calcium, potassium, and sodium during the first 3 to 4 years after clearcutting (Martin et al. 1986; Hornbeck et al. 1987).

Stream biota. Forest harvest may affect stream biota by changing nutrients, light, temperature, and sediment in streams. Following clearcuttings in northern New England, densities of algal cells in streams were increased six-fold, and densities of stream insects were 2-4 times greater (Noel et al. 1986). The increases apparently were caused by higher light levels and stream temperatures after clearcutting. Thus, buffer strips left along the stream channel should minimize changes in stream biota associated with clearcutting.

Changes in Volume of Streamflow

Harvesting of northern hardwoods reduces water lost to the atmosphere through canopy interception and transpiration, resulting in wetter soils and increased streamflow. A second major impact is that reduction in shading leads to more rapid melt of the spring snowpack and the earlier snowmelt runoff compared to uncut forests.

These changes have been demonstrated using experimental treatments on three gauged watersheds at Hubbard Brook. The first experiment was a clearfelling and herbiciding experiment performed to determine maximum possible changes in streamflow. The experiment involved cutting all trees in the winter of 1965-66, leaving them where they fell, then spraying the watershed with herbicides for the next three summers to prevent regrowth (Fig. 21). After the third summer the watershed was allowed to regenerate naturally. The second experiment was the stripcutting performed between 1970-74 and described in the previous section (Fig. 21). The third experiment was a whole-tree clearcutting carried out in the dormant season of 1983-84.

Changes in annual streamflow, by year, after each of the experiments are shown in Table 30. For the clearfelling-herbicide experiment, annual increases in streamflow for the 3-year period with no regrowth ranged from 9.5 to 13.7 inches, or 26 to 41 percent greater streamflow than if the forest had been left undisturbed. Once natural regrowth was allowed, the increases rapidly diminished, and from the fourth through twelfth years of regrowth, annual streamflow was only slightly greater than before the experimental treatment. In the following years, 13 through 23, the regrowing forest actually returned more water to the atmosphere than mature forests, resulting in decreases in annual streamflow (Table 30).

On a monthly basis the timing of streamflow changes showed a consistent pattern (Fig. 23). During the 3 years when there was no vegetation, sizable streamflow increases occurred in the growing season months of June through September. These increases tapered off in October and November with annual soil moisture recharge. Streamflow changes through the winter months were small until the start of snowmelt in March or April when the effect of forest clearing was to advance snowmelt runoff. In the monthly analyses this effect shows up as a streamflow increase for the first month of major snowmelt (Fig. 23). Decreases in snowmelt then occur in 1 or 2 following months, compared to undisturbed watersheds where snowmelt runoff progresses at the regular speed. The forest cutting affects

Table 30.—Changes in annual streamflow due to treatments on three watersheds at Hubbard Brook Experimental Forest. All values are inches depth over the watersheds

Year after treatment/harvest	Treatment/harvest Clearfelling	Strip cutting	Whole-tree harvest
1	13.7[a]	0.9[b]	6.0
2	11.0[a]	1.8[b]	1.9
3	9.5[a]	4.5[c]	-0.6
4	7.9	2.7[c]	-0.4
5	5.7	2.2[d]	0.2
6	1.7	3.2[d]	
7	0.5	2.7[d]	
8	2.0	-0.6[d]	
9	2.6	-1.2[d]	
10	0.1	-1.0[d]	
11	1.9	-0.7[d]	
12	2.5	-1.8[d]	
13	-0.5	-1.3[d]	
14	-0.5	-0.8[d]	
15	-1.3	-0.6[d]	
16	-1.6	-2.6[d]	
17	-2.7	-1.2[d]	
18	-2.5	-2.3[d]	
19	-2.5		
20	-1.7		
21	-3.2		
22	-3.2		
23	-2.2		

[a]Regrowth suppressed with herbicides.
[b]One-third of strip-cut watershed harvested.
[c]Two-thirds of strip-cut watershed harvested.
[d]Entire strip-cut watershed harvested.

only the timing during the snowmelt period; total volume of snowmelt runoff was not changed. Revegetation of the watershed changed the pattern by rapidly eliminating the summer increase in streamflow (Fig. 23). The advance in snowmelt runoff, however, persists for 10 to 15 years, or until canopy and boles of the regrowth begin to provide shade equivalent to that of undisturbed forest.

Commercial harvesting by strip-cutting and whole-tree harvesting caused similar patterns in streamflow changes, although magnitudes were less (Table 30). Maximum increase in streamflow after the strip-cutting occurred in the third year with two-thirds of the watershed harvested, and was just over 4.5 inches. Maximum annual increase after the whole-tree harvest was 6.0 inches in the first year after harvest.

Storm runoff. Under certain combinations of soil moisture and rainfall, forest cutting may increase the volume of runoff from individual storms. The changes are most pronounced in summer when reductions in transpiration and interception mean wetter soils on the cutover watershed, and more precipitation becoming streamflow. A situation in which a major storm of several inches has been preceded by a prolonged dry period would result in less soil drying and a maximum increase in storm runoff from a cutover watershed when compared to uncut areas. In the 4 years after the clearfelling and herbicide treatment at Hubbard Brook, volume of summer storm runoff was increased by an average of approximately only 20 percent (Hornbeck 1973). Since relatively small portions of the landscape are freshly cut over, such changes are unimportant to regional flooding, but should be a consideration when determining

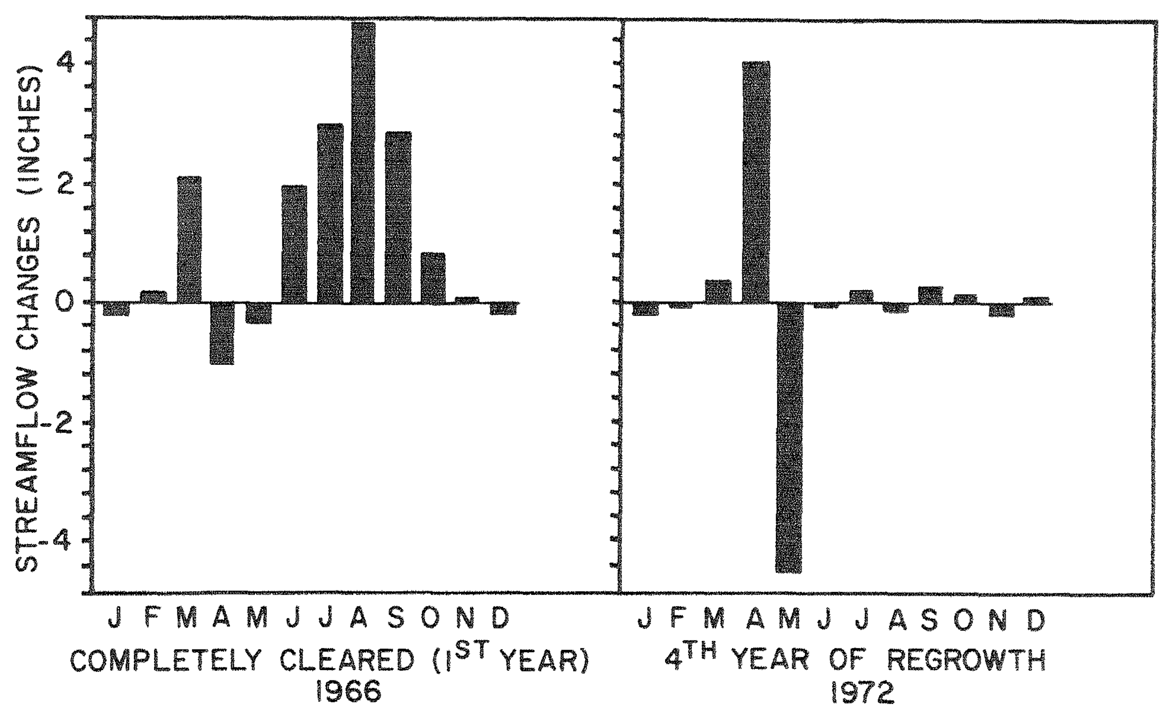

Figure 23. —Changes in streamflow, by months, for 2 selected years after the clearfelling experiment.

sizes of culverts to install on skidroads of harvested watersheds (Helvey and Kochenderfer 1988).

Impacts on Nutrient Cycling

Harvesting of the forest reduces pools of plant nutrients through removal of nutrients in harvested products, and by triggering a temporary increase in nutrient leaching to streams and groundwater. Intensity of harvest is a primary factor with selection and small-patch cuttings having far less influence than practices such as bole-only and whole-tree clearcuttings.

Nutrient removal in harvested biomass. The Hubbard Brook bole-only harvests (by strip cutting or block clearcutting) removed a range of nutrients from 7 lb/acre of phosphorus to 156 lb/acre of calcium (Table 31). The removals represented less than 2 percent of total site capital for any plant nutrient. In contrast, by harvesting the more nutrient-rich foliage and branchwood, a whole-tree clearcutting at a site in northern New Hampshire removed 2 to 3 times more nutrients, to a maximum of 386 lb/acre for calcium (Table 31). However, even with this intensive harvest, the removals were only 4 percent or less of total nutrient capitals.

The nutrient removals are not of themselves a concern for northern hardwood forests, provided site nutrient capitals have not been depleted by previous land use (Hornbeck 1990). However, the harvest removals must become a consideration in management decisions if whole-tree harvesting continues to increase in popularity, if rotation times are significantly reduced, and if forest ecosystems continue to experience accelerated nutrient leaching losses caused by atmospheric deposition. These factors could combine over a 120-year period to remove as much as 50 percent of the soil-calcium capital of northern hardwood sites (Federer et al. 1989).

Nutrient leaching losses. Several processes combine after harvest to increase nutrient content of soil water and subsequent leaching to streams and groundwater: 1) accelerated decomposition of soil materials as a result of increased exposure to light, heat, and moisture, 2) accelerated nitrification, 3) temporary reduction in uptake by vegetation, and 4) small acceleration of chemical weathering of inorganic minerals in soils and rocks.

The accelerated decomposition of organic matter releases all plant nutrients, but most importantly, nitrogen in the form of ammonium (NH_4^+). Normally the NH_4^+ would be taken up by living trees, but in the absence of trees, soil microbes convert the surplus NH_4^+ to nitrate (NO_3^-) by nitrification. The result is a flush of available NO_3^- and hydrogen (H^+). The H^+ replaces cations such as calcium, potassium, and magnesium on soil particles, and soil water becomes enriched in these cations and NO_3^-. As soil water becomes streamflow or groundwater, these cations plus nitrogen as NO_3^- are lost from the ecosystem. The nutrient leaching losses continue at increased levels for 3 or 4 years after harvest until rates of decomposition slow and uptake is renewed.

Losses of nutrients due to increased leaching are much smaller than removals in biomass. For example, increased leaching of nitrogen after the block clearcut at Hubbard Brook totaled 65 lb/acre compared to removals of 109 lb/acre in harvested biomass (Table 31). The leaching losses, however, may be of greater immediate importance since they occur primarily from the pool of nutrients readily available for plant growth (Hornbeck and Kropelin 1982; Hornbeck et al. 1990).

Table 31.—Nutrient removals, leaching losses, and soil capitals for three harvested sites in New Hampshire

	Calcium			Potassium			Magnesium			Nitrogen			Phosphorus		
	SC[a]	BC[b]	WTH[c]	SC	BC	WTH	SC	BC	WTH	SC	BC	WTH	SC	BC	WTH
	b/acre														
Removal by harvest	120	156	386	45	58	145	12	16	43	83	109	271	7	8	21
Dissolved ion losses in streamflow due to harvest[d]	30	54	34	34	54	7	3	8	13	25	65	7	0	0	0
Total losses due to harvest	150	210	420	79	112	152	15	24	56	108	174	278	7	8	21
Total soil capital	11,720	11,720	9,560	5,700	5,700	6,020	8,680	8,680	8,790	5,860	5,860	7,820	2,960	2,960	1,420

[a]Strip-cut, bole-only harvest at Hubbard Brook Experimental Forest (Hornbeck et al. 1987).
[b]Block clearcut, bole-only harvest at Hubbard Brook Experimental Forest (Hornbeck et al. 1987).
[c]Block clearcut, whole-tree harvest at Success, NewHampshire (Hornbeck and Kropelin 1982).

Impacts on Site Productivity

Harvesting can reduce productivity of subsequent rotations by compacting soils to the extent that germination and root growth are inhibited, or by creating nutrient deficiencies. Aside from skidroads, compaction is seldom a problem on properly conducted logging operations. However, today's more intensive, mechanized harvesting causes significant soil disturbance (Martin 1988), and managers must remain alert to possibilities of increased compaction.

Regarding nutrient deficiencies, a study of a series of clearcut, northern hardwood stands suggested that a decline in leaf production of pin cherry at years 6 to 11 after cutting may be due to a temporary shortage of nitrogen (Covington and Aber 1980). At 5 to 6 years after the harvests at Hubbard Brook nitrogen in streamwater fell below levels from uncut forests, again suggesting heavy demands and possible shortages of nitrogen (Hornbeck et al. 1987). Also, depletion of calcium due to a combination of intensive harvesting and atmospheric deposition may pose a threat to future site productivity (Federer et al. 1989).

Defining potential nutrient shortages is only a beginning step in determining the effects of harvesting. The difficult task of evaluating how temporary shortages and deficiencies actually affect site productivity still lies ahead.

Impacts on Wildlife

Numbers of wildlife species associated with different harvesting practices have been estimated for the northern hardwood and subtypes in New England (DeGraaf et al. 1992). In general, management practices that produce habitat diversity will promote increased numbers of wildlife species. Diversity means a range in forest types (deciduous and coniferous), species, age classes (including both large and small openings), and tree condition (including a component of dead and defective trees).

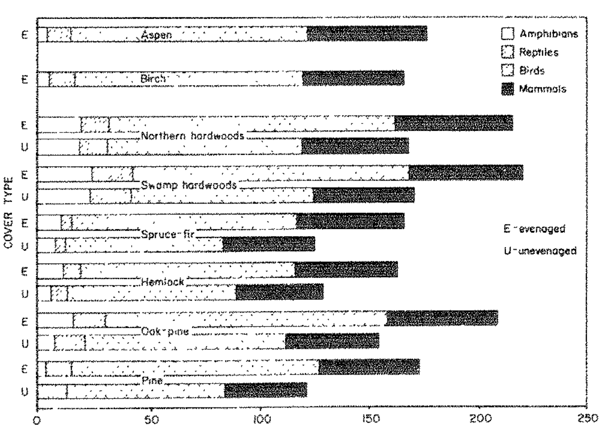

Figure 24.—Potential numbers of wildlife species by timber management regime and selected cover type group (DeGraaf et al. 1992).

Table 32.—Year in which breeding bird species first appear, become common, and decline in seedling and sapling stands of northern hardwoods in New England (DeGraaf et al. 1991)

Bird species	First appear	Become common	Decline
Eastern bluebird	1	1	2
Northern flicker	1	1	7-10
Willow flycatcher	1	4	7-10
Winter wren	1		2
Swainson's thrush	2	4	15[a]
Chestnut-sided warbler	2	4	10
Mourning warbler	2	5	7-10
Common yellowthroat	2	6	10
American goldfinch	2	6	7-10
Cedar waxwing	2	4	7-10
Veery	3	6	a
Black-and-white warbler	3	4	15[a]
Rose-breasted grosbeak	3	15	a
Canada warbler	5	15	a
Ruffed grouse	10	15	a
Wood thrush	10	15	a
Ovenbird	10	15	a
Black-throated blue warbler	15	a	a
Black-throated green warbler	15	a	a

[a]Present throughout remainder of developing stand.

Wetlands and grassy or shrubby openings also are important habitat features that can be maintained or created through harvesting.

Evenaged management systems tend to support larger numbers of wildlife species than unevenaged (Fig. 24). Group selection tends to be intermediate in numbers of species. Note in Fig. 24 that northern hardwoods, spruce-hardwoods, and oak-pine tend to be richest in numbers of wildlife species. Large-scale conversions to spruce-fir or some of the other forest types would lead to some losses in species numbers. Maintenance of maximum numbers of wildlife species under even-aged management requires fairly regular cutting activity since certain species occupy regenerating areas for only a short period of time—from 2 to 15 years, for example (Table 32).

Esthetics

New England's northern hardwood forests are easily accessible to large numbers of people, and recreational use is heavy. These users find mature northern hardwood forests esthetically pleasing, and sometimes are upset when they encounter recently harvested sites, whether up close or from a vista. Complaints most often focus on clearcutting. Piles of slash, scraggly small trees and large, deformed ones left standing, sharp borders around the cutover area, and the network of skidroads, skidtrails, and landings are listed by viewers as contributing to a sense of "devastation." The problem is mitigated somewhat by quick regrowth in the years immediately after harvest. But early regrowth does not help much in the leafless season, or with the problem of highly visible, sharp borders.

Guides to Managing and Harvesting Northern Hardwoods

Owners and managers of northern hardwood forests face the decision of whether to manage for multiple uses including commercial products, or to allow their stand to develop free of human intervention. The latter is sometimes chosen by those who enjoy the esthetics and ecological values of a maturing forest, or who simply may not want to be involved with the myriad of management and harvest activities. For those choosing to manage their forests, the responsibilities and decisions are considerable. The task of matching management objectives with site and stand characteristics can be difficult. There are strict regulations governing logging and protection of water quality. And consideration must be given to the public which expects to share forests for viewing, recreation, and watershed and wildlife protection. This section provides guidelines for the balancing act necessary to successfully manage and harvest northern hardwood forests.

Choice of Commercial Products

The choice of products to be removed during harvest depends primarily upon available markets. However, opportunities for more complete utilization have increased in recent years due to stronger demands for firewood, use of more mechanized logging, and chipping of tops and poor quality trees at the landing (for pulp and energy use). The firewood and chip markets can add value to pulp and timber harvests, and can help support silvicultural activities such as thinning and species conversion that might otherwise be uneconomical.

More complete utilization, usually accomplished by whole-tree harvesting, again raises the question of nutrient depletion. The concern is not so much for sites being thinned as for those being clearcut. To date, there are few guidelines whether whole-tree clearcutting should or should not be practiced. Research is in progress, but until more is known, whole-tree clearcutting should be avoided on shallow (<2-ft deep) and coarse-textured soils, and on sites that may previously have been depleted of nutrients by agricultural use, erosion, or fire.

Harvesting for sawtimber or veneer necessitates a rotation of 100 or more years in northern hardwoods, and usually requires one or more intermediate cuttings to improve stand quality (Table 11). Managing for sawtimber and veneer obviously requires a long-term commitment with no guarantees on economic returns. Compound annual rates of value change can be around 15 percent (Arner et al. 1990), although long-term real rates of return may be lower, probably more like 5-7 percent (Leak et al. 1987).

Selecting a Harvesting Method

A variety of silvicultural and ecological factors enters into choosing a harvest method, including: current stand condition, size-class distribution, desired regeneration, operational constraints, esthetics, ecological objectives (wildlife, biodiversity), and environmental effects (air and water quality, nutrient depletion, erosion). Each factor is briefly discussed below, and the attributes of each practice are summarized in Table 33.

The current stand condition may be immature, mature, or overmature. An immature stand is not old enough, from the timber-management point of view, to be harvested, although it might be cultured by precommercial or commercial thinning to improve growth, species mix, or quality. A mature stand is one where growth and quality have peaked. Northern hardwoods commonly are considered mature at about 120 years or when half or more of the basal area is in trees that have reached the diameters such as illustrated in Table 5. Stands of aspen and paper birch mature in 50-70 years. A mature stand generally is vigorous enough so that it can be harvested in any of several ways. An overmature (low vigor or poor risk) stand, on the other hand, contains a significant proportion of trees that must be harvested or they will be lost to mortality.

The size-class distribution of most northern hardwoods is inverse J-shaped, meaning that numbers of trees by d.b.h. class increase as the d.b.h. class gets smaller. However, if the best trees (desirable species with well-formed boles) occur across a range of size-classes, some form of partial cutting may be best; a heavier cutting would remove immature trees. On the other hand, if the best trees occur in the large size-classes, clearcutting or shelterwood cutting would be a reasonable alternative.

Desired regeneration is one of the most important determinants of the harvesting method. Systems that maintain a dense canopy, such as single-tree selection and dense shelterwoods, will generate shade-tolerant species (sugar maple, beech, hemlock, and red spruce) almost exclusively. Systems providing abundant sunlight, such as complete clearcutting, will encourage intermediate to intolerant species such as yellow and paper birch and red maple. Methods such as group selection, low density shelterwoods, and narrow strip cuts will favor intermediately tolerant species or a mix of tolerance classes.

Some operational constraints tend to dictate a certain type of harvest method. On steep slopes, individual-tree selection is difficult without damaging the residual trees. Inaccessible stands that might require road building or long skidding distances make light cutting uneconomic. In general, operational constraints lead the forest manager toward recommending heavier cutting systems that remove more volume per acre.

Esthetic values are becoming more important in most parts of the northern hardwood region. The maintenance of esthetic values is complex because the subject involves close-up views, form, color, and texture. And there is some disagreement on good versus poor appearance.

Table 33.—Choices of harvesting methods and appropriate conditions for using each method (Y=yes, N=no or none)

Harvest method[a]	Current stand condition	Size class distribution	Desired regeneration	Operational constraints	Esthetic values	Biodiversity goals	Environmental goals
Clearcut	Mature, overmature	One main class	Nontolerant	Y/N	N	Y, Large scale	N
Stripcut	Mature, overmature	One main class	Nontolerant	N	N	Y, large scale	Y/N
Dense shelterwood	Mature	One main class	Tolerant	N	Y	Some large scale	Y/N
Open shelterwood	Mature, overmature	One main class	Nontolerant	Y/N	Some/N	Y, large scale	Some/N
Reserve tree shelterwood	Mature, overmature	One main class	Nontolerant	Y/N	Some/N	Y, large scale	Some/N
Two-cut system	Mature, overmature	Two or more	Mostly tolerant	Y/N	Some/N	Some small scale	Y/N
Group selection	Mature, some overmature	Several	Tolerant/nontolerant	Some/N	Y/N	Small scale	Y/N
Individual tree selection	Mature	Several	Tolerant	N	Y	N	Y/N

[a]Definitions:

Clearcut—Harvesting all merchantable trees and elimination of nonmerchantable down to some threshold—e.g. 2 inches d.b.h. May leave some reserve wildlife trees. As in all evenaged methods, harvesting is scheduled at rotation age, which is approximately 120 years for northern hardwood sawtimber, 50-60 years for biomass, and 50-70 years for paper birch or aspen.

Strip cut—Removal of an entire stand in a series of approximately three strip cuttings spaced about 3 years apart. Wide or narrow strips are laid out in groups of three. The first operation removes one strip from each group; the second operation, a second strip from each group, and so on.

Dense shelterwood—Removal of a stand in two or three cuttings from below, maintaining 60-80 percent cover, or more, in all but the last cut.

Open shelterwood—Removal of a stand in two-three cuttings from below, maintaining 30-40 percent crown cover in all but the last cut.

Reserve shelterwood—Reserved trees are left standing in the last shelterwood cut until thinnings begin in the new stands.

Two-cut system—Two storied stands are maintained by removing the entire overstory at intervals equal to one-half the rotation.

Group selection—An uneven-aged system where trees are removed in small groups, often about one-quarter to one-half acre in size, but sometimes larger or smaller. The purpose is to remove clumps of mature and overmature trees and provide for regeneration of some nontolerant species. Often, individual tree selection is carried out among the groups.

Individual tree selection— Removal of mature, over-mature, and less desirable trees to create one-tree openings in the stand. Commonly one-quarter to one-third of the stand is cut at each entry.

However, in many situations, protection of esthetic values leads toward lighter cutting methods or creation of indistinct cutting boundaries.

The principal ecological values related to the choice of harvest method are the maintenance of biodiversity goals—a wide range of plant and animal species and variety in vertical-horizontal stand structure—or the maintenance of certain species of wildlife such as deer or grouse. The latter subject is species-specific, requiring specifically designed management practices. The former—the maintenance of biodiversity—can be achieved best on a small scale by group selection approaches; or on a large scale by clearcutting or shelterwood methods, provided that the latter two are applied in a managed forest where a range of age classes is maintained in surrounding areas.

The various environmental goals of harvest range from being clearly known and generally controllable to ones that are less understood and being less studied. As an example of the latter, some information and theories suggest the possibility of nutrient depletion due to product removals and increased leaching losses stemming from both harvest and acid deposition. The potential is greatest on sites with coarse-textured or shallow soils, and for intensive harvests and short rotations (Hornbeck 1986). Soil compaction and rutting can be problems, especially on wet or fine-textured soils, but the full impacts on roots, soils, and productivity are not well understood. Erosion from skid trails, roads, and landings is always a potential problem, but one that is controllable by following guidelines discussed in a later section. Where environmental impacts are considered a hazard, the first approach is to minimize the adverse effects through season, layout, and control of the harvesting operation, including limitations on utilization, such as removing only tree boles and leaving tops on site. If such measures are deemed inadequate, a change in the method of harvesting may be warranted, usually in the direction of lighter or less frequent cutting.

Marking Harvest Trees

If the selected harvest method is other than clearcutting or stripcutting, the next step is to decide which trees to cut and which to leave. Tubbs (1977) has suggested the following guides if the objectives are to upgrade stand quality, minimize loss from cull and mortality, and enhance the potential for future production:

1. Remove trees that will not live and grow until the next cut.

2. Remove cull and highly defective trees that will not increase in value during the cutting cycle.

3. Remove crooked or leaning trees, those with an acute angle between limbs and bole, and those with short, clear length or large limb diameter.

4. Low quality timber has about the same value regardless of species, and high quality logs of any of the major species are usually salable. Nevertheless, determine local preference for species.

5. Consider the position of a tree in relation to other trees to be left in a stand. Mark for removal trees that are interfering with the full development of other trees of higher quality, those providing the better trees freedom for crown development in all directions.

6. Consider an upper size limit. Generally, most tree species within the northern hardwood type become economically mature when they reach 20 to 24 inches d.b.h. Trees that have reached or grown beyond economic maturity do not pay their way in comparison to smaller trees.

If stand quality is already acceptable, species, tree age, and stand basal area can be used to establish marking guides based on the stocking guidelines in Figures 11 and 13.

Wildlife Considerations

There are two considerations regarding wildlife: the first involves changes in species diversity due to harvesting, the second concerns damaging effects on residual trees and regeneration. Examples of the latter include a post-harvest increase in browsing by deer and rabbit populations, or a switch by sapsuckers in feeding from a removed tree to a more valuable tree left behind.

The combination of tree species, size classes, and habitats found in most northern hardwood forests is conducive to substantial numbers of game and nongame wildlife species (DeGraaf and Rudis 1987; Tubbs et al. 1987). Some guidelines for maintaining this diversity and for protecting the stand against damage from shifts in population and habitats include:

1. As a general rule, selection cuttings will produce smaller amounts of browse and fewer plant species than even-aged harvests.

2. Keep clearcuts small enough to provide good access and forage for birds and mammals, but large enough to minimize the effects of heavy browsing. A harvest area between 20 and 100 acres probably is optimum.

3. Consider strip cutting or shelterwood to increase the length of time that browse is available.

4. Protect wetlands, seeps, old orchards, and pockets of conifers favored for cover and food by deer, moose, rabbits, and others.

5. Manage areas around ponds and wetlands to favor natural ecosystems and indigenous species.

6. Plan cuttings to provide a patchwork of age classes and species within one-half mile of any site.

7. Tops left during winter harvests serve as convenient deer browse as well as cover for small game and non-game animals.

8. Protect or reserve mast producers (beech and oak), snags, and den trees for food and cover.

9. Develop landings and skidroads as feeding sites by fertilizing and seeding to perennial grasses and legumes or, in certain cases, by leaving exposed subsoil to regenerate naturally to local grasses and herbs.

Protecting Esthetic Quality

Esthetics can be a frustrating problem for forest managers and loggers. What is or is not esthetically pleasing varies widely among viewers, depending upon a variety of sociologic and economic factors (Rader and Hamilton 1974). Concerns are sometimes eased if viewers can be educated about various cutting practices and logging techniques. However, for the most part, landowners and loggers must assume responsibility for esthetics, starting with initial planning of the harvest and continuing through completion of logging. The following guides help soften esthetic impacts of harvests:

1. Shield harvest sites and log standings from highways, scenic vistas, water bodies, trails, and buildings by using topography and standing trees as buffers.

2. Blend clearcuts and stripcuts to landscape by using uneven edges, leaving large, attractive border trees, and by avoiding cutting along skylines and terrain ridges.

3. Leave a buffer strip of one tree height or more on both sides of perennial streams. Removal of mature and poor quality trees from these strips is permissible, but consideration should be given to leaving snag and den trees for wildlife.

4. Locate log landings so they are screened from view, and keep landing areas neat in appearance by minimizing piles of waste wood, disposal of trash, and grading and seeding upon completion of the operation.

5. Minimize mud and erosion during and after logging by following the guidelines given in the next section, Protecting Water Quality and Soils.

Protecting Water Quality and Soils

Silvicultural activities, including harvesting and logging, are considered as nonpoint sources of pollution to surface water or ground water. Nonpoint-source pollution comes from diffuse sources such as an area of land as opposed to point-source pollution from a local factory or waste-treatment plant. Effluent control is not feasible for nonpoint sources, so regulation is achieved by dealing with the activity rather than its result. To regulate nonpoint sources of pollution from silvicultural activities, the U.S. Environmental Protection Agency has implemented the concept of Best Management Practices (BMP's)—the mix of controls and activities that accomplish the forest management objective while protecting stream and ground water quality. BMP's are designed and regulated by each state and vary considerably from state to state. Thus, it is the responsibility of forest managers, landowners, and loggers to determine and adhere to BMP's for the state in which the silvicultural activity is taking place.

For northern hardwood forests, BMP's focus primarily on activities that affect the amount of turbidity in streams. BMP's specific to protection of stream temperature, nutrient concentrations, and water color usually are not available. Fortunately, the BMP's for protecting turbidity also will help guard against changes in the other parameters. The same holds for the impact of logging on soils. The main concerns about soils are the potential for increased erosion due to disturbance of the forest floor and exposure of mineral soil, and possible impairment in establishment and growth of regeneration due to excessive soil compaction. The BMP's for protecting streams against turbidity will minimize impacts on soil erosion and compaction.

The BMP's listed below are a composite for several New England states. They illustrate the kinds of guidelines that can be anticipated. Before any logging operation, BMP's for the particular state in which the operation is located should be obtained from sources given in Table 34.

BMP's for the streamside zone. The moist areas close to stream channels are critical in protecting water quality. Leaving a strip of trees—buffer strips—so that streams are separated from roads and harvest areas is a recommended way to protect against changes in turbidity and stream temperature. Buffer strips protect stream banks and channels, provide shade, and prevent logging slash and eroding soil from entering streams. Some suggested BMP's for locating and maintaining buffer strips are as follows:

1. Buffer strips usually are required along perennial streams. However, state and local regulations vary widely from no recommendations to requirements that buffers be left along all intermittent and perennial streams. If buffer strips are not mandated by law, it is necessary to determine whether buffer strips are suitable for the location in question. In some locations exposure of a thin strip of trees may make the strip susceptible to windthrow, sometimes creating more water quality problems than if the strip were removed.

2. The width of the strip can vary depending upon slope, climatic factors, and soil erodibility. A variable width of at least 50-100 feet on each side of the stream channel (more in steeply sloping terrain) is recommended.

Table 34.—Addresses and phone numbers of state agencies responsible for administering Best Management Practices

State	Agency address and phone
Maine	Maine Forest Service Station 22 Augusta, ME 04333 (207) 289-2791
New Hampshire	Department of Resources and Economic Development Division of Forest and Lands P.O. Box 856-172 Pembrook Road Concord, NH 03302-0856 (603) 221-2214
Connecticut	Department of Environmental Protection Division of Forestry 165 Capitol Ave., Room 260 Hartford, CT 06106 (203) 566-5348
Massachusetts	Division of Forest and Parks 100 Cambridge Street Boston, MA 02202 (617) 727-8893
Rhode Island	Division of Forest Environment 1037 Hartford Pike North Scituate, RI 02857 (401) 644-3367
Vermont[a]	Department of Forests, Parks, and Recreation 103 South Main Street 10 South Building Waterbury, VT 05676 (802) 244-8716

[a]Guidelines for the state of Vermont are termed "Acceptable Management Practices."

3. Truck roads and skid trails through buffer strips should be kept to a minimum.

4. Crossing of stream channels, including intermittent ones, should be on bridges or closed culverts. Bridges usually are preferred because culvert installation and removal causes channel disturbance and produces sediment and turbidity. When culverts are used, guides to sizes are given in Helvey and Kochenderfer (1988). 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.

5. It may be desirable to make a light selection-cutting in the buffer strip to remove larger trees or those susceptible to windthrow. In such instances, care should be taken to avoid soil disturbance and to prevent logging debris and slash from plugging the channel and causing bank-cutting.

BMP's to prevent stream sedimentation and turbidity. About 80 percent of the deterioration in quality of forest streams is caused by suspended sediment or turbidity from soil erosion. Logging roads and skid trails cause a disproportionate share of this problem, probably greater than 90 percent in most areas. With this in mind, some general BMP's for minimizing erosion and turbidity problems from transport systems are:

1. Consider the use of buffer strips as discussed in the previous section. In addition to stream channels, avoid, or treat with caution, other sensitive areas such as seeps and swamps, leaving buffer strips as needed (see *BMP's to protect wetlands*).

2. Carefully select logging methods and equipment to minimize roads and reduce serious disturbance to soils and stream channels. On steep slopes, cable systems may cause considerably less damage than skidders.

3. Locate roads far enough from stream channels for runoff from the roads to spread out and infiltrate the forest floor. Trimble and Sartz (1957) developed a rule-of-thumb for northern hardwoods that roads should be 25 feet from the stream channel, plus 2 feet for each 1 percent increase in slope between the road and stream. For sensitive situations, such as on municipal watersheds, the numbers in the rule-of-thumb should be doubled.

4. Except for short stretches, maximum grade on truck roads and skidtrails should not exceed 10 percent. A minimum grade of 3 percent is desirable to obtain adequate drainage and prevent ponding.

5. Install cross drains and broad-based dips to channel moving water from roads and trails. The placement interval in feet can be calculated as 1,000 divided by percent grade.

6. During logging, minimize deep disturbances, such as rubber-tired skidder ruts, which favor concentration of drainage waters.

7. Require care and flexibility in operation. For example, as far as possible, skid trails and roads should be built in dry weather. During wet periods, skidding should be discontinued on easily compacted soils.

8. Divide the harvest area into blocks and require that each completed block be inspected before moving to another. This helps assure that a satisfactory job is done as the operation progresses.

9. Finish the operation as soon as possible without increasing the potential for erosion.

10. Upon completion of logging, remove temporary bridges and culverts and fertilize and seed problem areas on logging roads, skid trails, and landings.

BMP's to protect wetlands. Wetlands are defined as land areas saturated or inundated with water for varying periods during the growing season. Examples are bogs, swamps, marshes, fens, and some floodplains. In the past, such areas often have been considered as low value or wasteland, but in recent years they have become better recognized for their unique habitats for plants and wildlife, for recreation opportunities, and for roles in protecting water quality and reducing flood flows.

BMP's for wetlands are not as clearcut as those for soils and streams. A recurring problem is that wetlands are not always easy to recognize. For example, during some periods of the growing season, wetlands actually may be dry. Individual states have different methods and criteria for defining wetlands, and also differing BMP's for protecting wetlands. When logging and road construction are permitted, there usually are severe restrictions and precautions. When in doubt about whether an area is a wetland, and what precautions are needed, state agencies listed in Table 34 should be contacted.

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