A SUMMARY OF WATER YIELD EXPERIMENTS ON HARDWOOD FORESTED WATERSHEDS IN NORTHEASTERN UNITED STATES

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Abstract: This paper summarizes and compares long-term changes in annual water yield following cutting experiments at four locations in northeastern United States. Substantial increases in water yield of up to 350 mm yr^{-1} were obtained in the first year by clearfelling hardwood forest vegetation and controlling regrowth with herbicides. Commercial clearcutting of hardwoods with natural regrowth resulted in smaller initial increases in water yield of 110 to 250 mm yr^{-1}. This range in response was due to differences in precipitation and configuration of cuttings. Unless regrowth was controlled with herbicides, yield increases declined quickly after cutting, seldom persisting for more than 10 years. However, yield increases were readily extended over 20 years or more with intermediate cuttings and/or repeated control of regrowth with herbicides. Nearly all increases in water yield occur during summer and early autumn. Changes in species composition after forest cutting on several study watersheds eventually resulted in decreased water yields compared to those from uncut, control watersheds. Results are discussed in terms of implications for surface water supplies, global climate change, nutrient cycling, hydrologic modeling, and long-term research.

INTRODUCTION

Long-term paired watershed studies at four locations in the northeastern United States are analyzed in this paper: Fernow Experimental Forest in north-central West Virginia, Leading Ridge Experimental Watersheds in central Pennsylvania, Marcell Experimental Forest in north-central Minnesota, and Hubbard Brook Experimental Forest in central New Hampshire (Fig. 1). These locations span the diverse geography of the northeastern United States. At each site, one or more watersheds have been calibrated against a nearby control, then treated experimentally. Changes in water yield were then determined with results in some cases spanning up to 3 decades.

Two of the study locations, Fernow and Leading Ridge, are forested with central hardwoods. This provides an opportunity to compare streamflow responses in central hardwood forests with 2 other important forest types in the Northeast: northern hardwoods at Hubbard Brook and aspen-birch at Marcell.

Results from these studies have special significance for the northeastern United States. Forests cover >60% of the landscape, and forested watersheds serve as sources of water for more than 1,000 municipalities ranging from small, rural communities to large urban centers such as New York, Baltimore, and Boston. Although the region is well watered with 1,100 mm average annual precipitation, water shortages are not uncommon. A knowledge of how both abrupt and gradual changes in forest cover affect water yield over time periods on the order of decades is needed to manage forested watersheds for optimum water production.

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Figure 1. Northeastern United States showing study site locations.

METHODS

Results from 11 separate, treated watersheds are summarized and compared in this paper (Table 1). Record collection on many of these watersheds began in the 1950s, followed 5 to 10 years later by initial treatments of vegetation. At the time of these initial treatments, the northeastern United States was experiencing an extended period of below average precipitation and there was widespread interest in the potential for increasing water yield from forested watersheds. Also, controversies over the use of herbicides and forest clearcutting had not begun to escalate. Thus, some of the initial treatments at Fernow, Hubbard Brook, and Leading Ridge were designed to obtain benchmark information on maximum possible yield increases, and treatments included complete forest clearing and control of regrowth with herbicides. Later experiments performed in the 1970s and 1980s focused more on determining impacts of commercial harvesting operations. These treatments tended to be less drastic and did not include herbicide applications.

The longevity of the studies has in many cases allowed for determining impacts of multiple treatments on the same watershed. For example, watershed 3 on the Fernow Experimental Forest was first harvested in 1958-59 by intensive selection, a silvicultural practice that was in common use in the region and which involves cutting a relatively small fraction (in this case, 13%) of total basal area. In keeping with the silvicultural prescription, the treatment was repeated 4 years later with an additional 8% of total basal area being cut. The prescription was changed in 1968 to patch cutting, and 6% of the existing basal area was felled. Then in late 1969, to obtain information relative to a developing controversy over impacts of clearcutting (Horwitz 1974), the watershed was subjected to a commercial clearcutting during which 91% of existing basal area was cut.

Table 1. Descriptions of catchment studies in northeastern United States

Catchment	Area-ha	Mid elevation-m	Vegetation (before treatment) and soils	Mean annual precipitation-mm[1]	Mean annual streamflow-mm[1]	Description of treatment	Year(s) of treatment	Basal area cut - %[2]	Reference
Fernow Experimental Forest, West Virginia				1,460	640				
1	30	755	Central Appalachian hardwoods, Typic Dystrochrepts			Clearcut to 15cm dbh except culls.	1957-58	74	Kochenderfer and others 1990
2	15	780	same			Diameter limit cut to 43 cm.	1958	32	same
						Diameter limit cut to 43 cm.	1972	12	
3	34	505	same			Intensive selection.	1958-59	13	same
						Intensive selection.	1963	8	
						Patch (0.2 ha) cuttings.	1968	6	
						Clearcut.	1969-70	91	
6	22	805	same			Clearcut lower half.	1964	51	Patric & Reinhart 1971, Kochenderfer and others 1990
						Herbicides on lower half.	1965-69		
						Clearcut upper half.	1967-68	49	
						Herbicides on entire catchment	1968-69		
						Plant Norway spruce.	1973		
						Herbicides on entire catchment	1967-69		
7	24	801	same			Clearcut upper half.	1963-64	49	same
						Herbicides on upper half.	1964-69		
						Clearcut lower half.	1966-67	51	
						Herbicides on entire catchment.	1967-69		
Leading Ridge Experimental Watersheds, Pennsylvania				1,060	440				
2	43	360	Central harddwoods, Typic Dystrochrepts and Typic Hapludults			Clearcut lowest 9 ha.	1967	24	Lynch and others 1980
						Clearcut mid-slope 11 ha.	1971-72	27	
						Herbicide lower and mid-slope areas.	1974		
						Clearcut 17 ha on upper slope.	1975-76	40	
						Herbicide all clearcut areas.	1977		
3	104	340	same			Clearcut on 45 ha.	1976-77	43	Lynch and Corbett 1990
Marcell Experimental Forest, Minnesota				760	110				
4	34	433	Aspen-birch upland, black spruce peatland, Typic Glossoboralfs, interspersed with bog wetlands			Aspen-birch upland portion (26ha) clearcut (all trees >3 m height)	1970-71	100	Verry, 1987
Hubbard Brook Experimental Forest, New Hampshire				1,340	880				
2	16	595	Northern hardwoods, Typic Haplorthods			Clearfelled.	1965-66	100	Hornbeck and others 1970
						Herbicides on entire catchments.	1967-69		
4	36	606	same			Progressive strip cut, 1st 3rd harvested.	1970	33	Hornbeck and others 1987
						2nd 3rd harvested.	1972	33	
						Final 3rd harvested.	1974	33	
5	22	636	same			Whole-tree harvest.	1983-84	95	None available

[1]Long-term means for untreated, control catchments.

[2]Based on existing tree basal area on catchment at initiation of cutting.

Other forms of multiple treatments included a three-stage, progressive strip cutting on watershed 4 at Hubbard Brook, complete forest clearing in three stages on watershed 2 at Leading Ridge and in two stages on watersheds 6 and 7 at Fernow, and controlling vegetation with herbicides prior to or during species conversion or natural regrowth at Leading Ridge, Fernow, and Hubbard Brook (Table 1).

Impacts of treatment on water yield were determined using the paired watershed approach described by Reinhart (1967). Linear regression was used to develop a calibration relationship between annual water yield from a control watershed (independent variable, X) and a watershed to be treated (dependent variable, Y). At locations with multiple watershed experiments, the same control was used in developing all regressions. The calibrations are based on 5 or more water years of record, and although most of the calibration periods ended at least 2 decades ago, we assume the relationships still apply. Forests on all control watersheds are mature and reasonably steady-state with regard to biomass and leaf area (Bormann and Likens 1979) and annual evapotranspiration (Federer and others 1990). Thus, water yield relationships for control watersheds should be unchanging, except during a 2-year period of severe insect defoliation at Leading Ridge (Corbett and Heilman 1975).

After treatment, deviations from the calibration regressions were considered to be statistically significant and attributed to treatment if they exceeded 95% confidence intervals about the regressions. The deviations, which indicate increases and decreases in annual water yield from the treated watersheds, are presented in both graphical and tabular form in this paper. Statistical significance is not indicated when using graphs. However, on average for all sites, deviations greater than $\pm$ 30mm yr^{-1} from the calibration regressions were statistically significant.

RESULTS

The array of forest treatments across the four study locations caused a variety of responses in water yield (Fig. 2, Table 2). However, three generalizations can be used as a framework for discussing results: (1) initial increases in water yield occur promptly after forest cutting, with the magnitude being roughly proportional to percentage reduction in basal area, (2) the increases can be prolonged for an undetermined length of time by controlling natural regrowth; otherwise increased streamflow diminishes rapidly, usually within 3 to 10 years, and (3) small increases or decreases in water yield may persist for at least a decade, and probably much longer, in response to changes in species composition and climate.

Initial Increases in Water Yield

Only Hubbard Brook and Marcell Experimental Forests normally have continuous winter snowpacks. Snowmelt runoff occurred earlier at both sites, but volume of snowmelt runoff was unchanged (Hornbeck 1975, Verry and others 1983). Thus, increases in annual yield at all four study sites resulted primarily from reductions in transpiration and canopy interception. Simply stated, soils were wetter on recently treated watersheds and more water was available for streamflow. Flow-duration curves for posttreatment periods at each site show that nearly all changes in water yield result from increases at low flow levels, or as augmented baseflow or delayed flow, and that flood flows were not greatly affected (Hornbeck and others 1970, Lynch and others 1980, Patric and Reinhart 1971, Verry 1972). Further, the yield increases occurred primarily in the growing season. Complete recharge of soil moisture on both forested and treated watersheds usually occurs soon after the start of the dormant season, thus limiting further opportunities for treatment effects until the start of the next growing season.

As found in previous summaries (Bosch and Hewlett 1982, Douglass and Swank 1972), increases in yield for the first water year after treatment were roughly proportional to percentage reductions in stand basal area. Moreover, a comparison for all sites (Fig. 3) supports previous findings that reductions in basal area must approach 25% to obtain measurable responses in annual water yield (Douglass and Swank 1972). Above this threshold, there is some variability in first-year responses among watershedss with similar basal areas cut, but differences usually can be explained by factors such as configuration and timing of the cutting, and whether regrowth was controlled with herbicides.

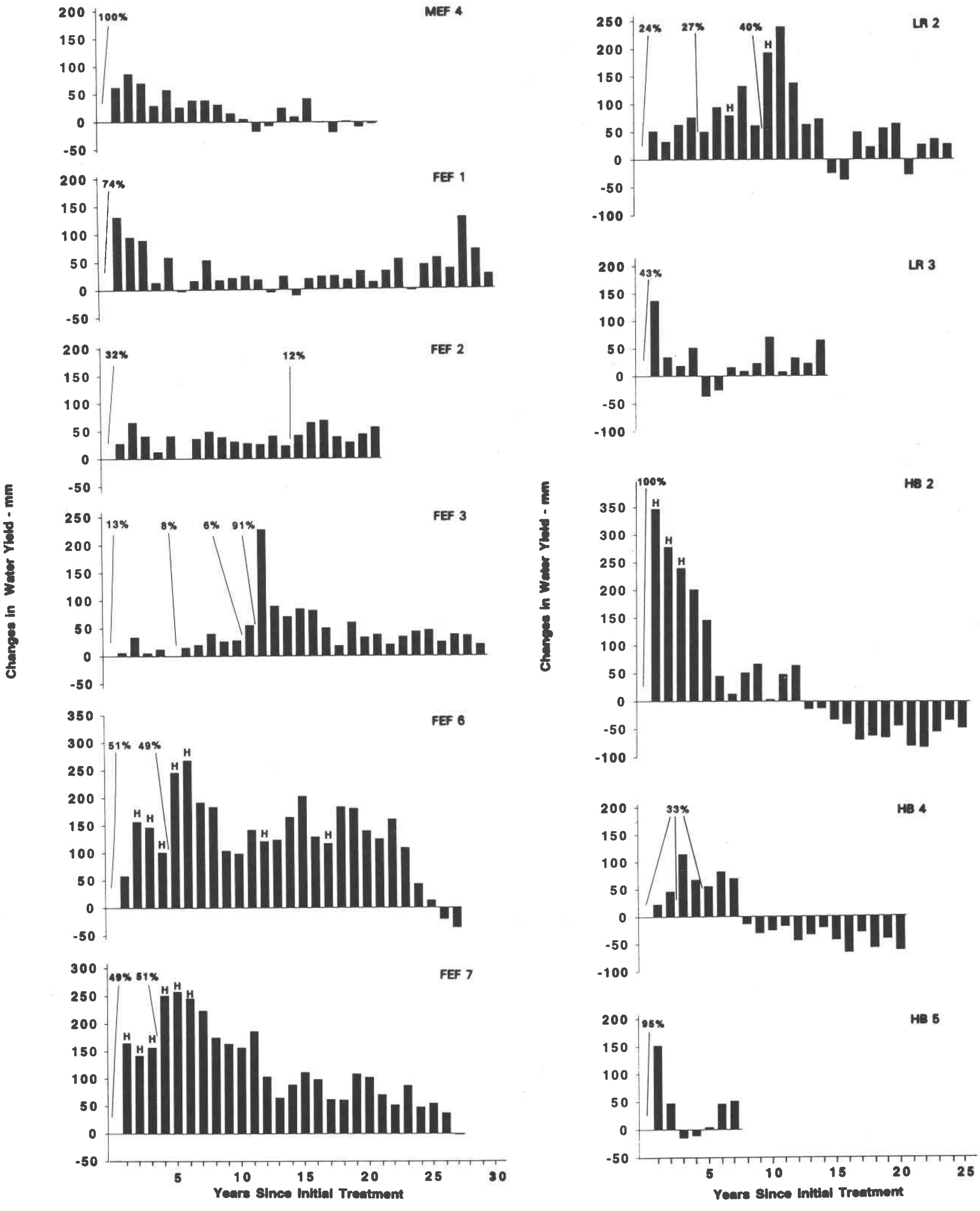

Figure 2. Changes in water yield for 11 experimental watersheds studies. MEF is Marcell Experimental Forest, FEF is Fernow Experimental Forest, LR is Leading Ridge Experimental Watersheds, and HB is Hubbard Brook Experimental Forest. Percentage values denote existing basal area cut during experimental treatments and H signifies herbicide application to cut portions of watersheds.

Table 2. Changes in annual water yield for selected watersheds

	Marcell Experimental Forest #4				Fernow Experimental Forest #7			
Year after initial treatment	Estimated streamflow if untreated[1]	Change due to treatment[2]		Precipitation	Estimated streamflow if untreated[1]	Change due to treatment[2]		Precipitation
	mm	mm	%	mm	mm	mm	%	mm
1	209	81*	39	871	715	165*	23	1,316
2	195	114*	58	817	390	142*	36	1,057
3	130	92*	70	779	669	157*	23	1,231
4	188	38*	20	862	658	251*	38	1,215
5	227	77*	34	780	637	258*	40	1,217
6	76	34*	45	458	738	246*	33	1,332
7	152	51*	34	935	675	224*	33	1,268
8	246	52*	21	882	869	175*	20	1,481
9	276	40*	15	786	1,030	164*	16	1,557
10	108	19	18	662	919	157*	17	1,553
11	198	6	3	821	944	187*	20	1,551
12	282	-22	-8	799	628	104*	17	1,243
13	100	-9	-9	748	607	65	11	1,170
14	202	33*	16	744	755	89*	12	1,328
15	286	12	4	920	988	112*	11	1,628
16	217	56*	26	796	828	99*	12	1,451
17	178	-1	0	744	755	62*	8	1,397
18	296	-25*	-8	995	987	61	6	1,587
19	281	1	0	839	801	109*	14	1,470
20	125	-12	-10	587	852	103*	12	1,529
21	89	-4	-4	711	842	71*	8	1,487
22					1,073	52	5	1,745
23					694	88*	13	1,389
24					516	48	9	1,191
25					766	55*	7	1,435
26					958	37	4	1,561
27					936	-2	0	1,583

Continued on next page

Table 2. (continued) Changes in annual water yield for selected watersheds

Year after initial treatment	Leading Ridge Experimental Watershed #2				Hubbard Brook Experimental Forest #2			
	Estimated streamflow if untreated[1]	Change due to treatment[2]		Precipitation	Estimated strreamflow if untreated[1]	Change due to treatment[2]		Precipitation
	mm	mm	%	mm	mm	mm	%	mm
1	433	51*	12	967	851	347*	41	1,279
2	302	32*	11	897	954	278*	29	1,394
3	401	63*	16	1,008	919	240*	26	1,271
4	562	76*	14	1.167	902	200*	22	1,294
5	507	50*	10	1,061	840	146*	17	1,225
6	940	94*	10	1,435	787	44	6	1,221
7	462	79*	17	1,018	1,059	12	1	1,504
8	529	132*	25	1,104	1,469	52	4	1,832
9	658	61*	9	1,210	832	67*	8	1,240
10	606	193*	32	1,214	1,305	3	0	1,659
11	682	239*	35	1,285	884	48	5	1,323
12	648	138*	21	1,220	996	64*	6	1,431
13	687	63*	9	1,255	902	-13	-1	1,287
14	260	73*	28	877	764	-13	-2	1,139
15	570	-25	-4	1,089	807	-34	-4	1,261
16	528	-37	-7	1,060	1,179	-41*	-3	1,530
17	570	49*	9	1,091	885	-70*	-8	1,328
18	559	22	4	1,121	1,099	-62*	-6	1,522
19	500	56*	11	1,106	715	-64*	-9	1,087
20	558	64*	11	1,178	958	-44*	-5	1,310
21	422	-28	-7	964	872	-80*	-9	1,210
22	410	26	6	964	790	-82*	-10	1,190
23	584	36*	6	1,163	708	-56*	-8	1,149
24	777	27	3	1,139	1,109	-34	-3	1,468
25					1,194	-48*	-4	1,590

[1]Determined form calibration regression
[2]Determined by subtracting estimated streamflow from actual streamflow
[3]Change exceeded 95% confidence interval about the calibration regression

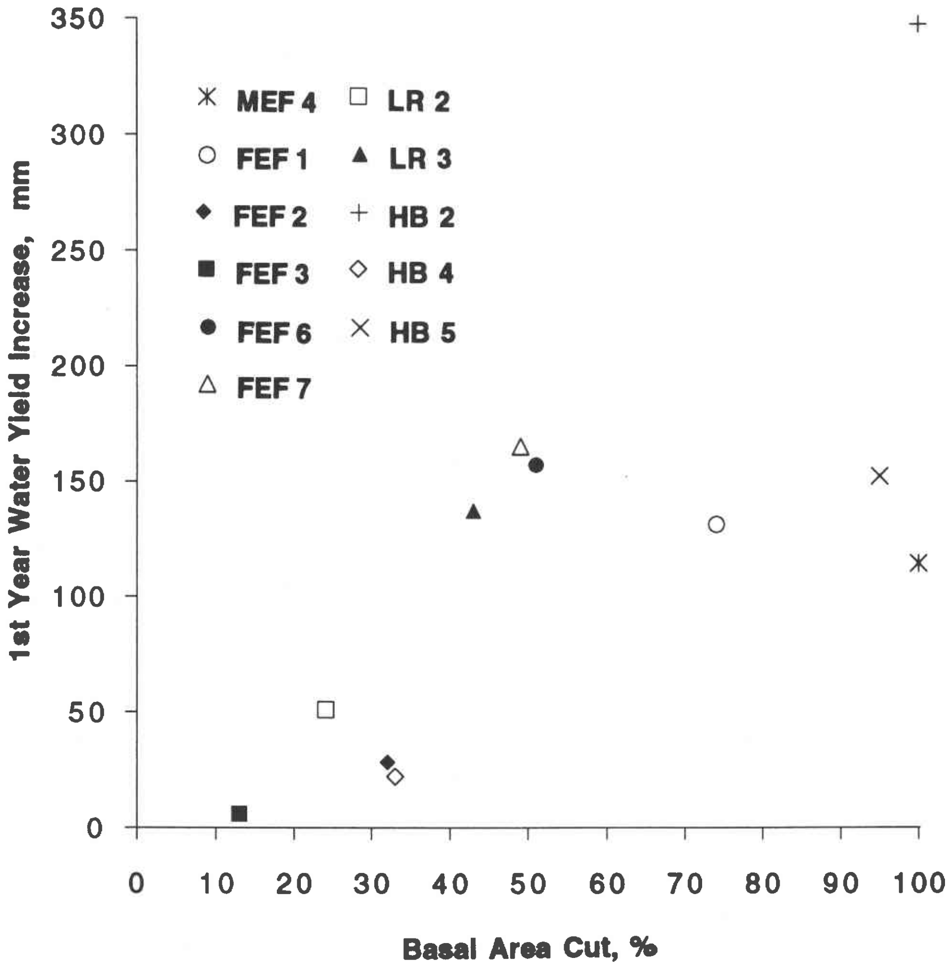

Figure 3. First-year increases in water yield in response to forest cutting.

As an example of the role of configuration, the cutting of 24% of the basal area on watershed 2 at Leading Ridge produced a nearly twofold larger increase than cutting one-third of the basal area on watershed 4 at Hubbard Brook and watershed 2 at Fernow (Fig. 3). The cutting at Leading Ridge was in a single block on the lowest portion of the watershed, the cutting at Hubbard Brook was in a series of strips spaced equidistant from bottom to top of the watershed, and the cutting on the Fernow involved harvesting individual trees scattered about the watershed. The cutting of strips and individual trees increases crown exposure and transpiration rate of residual trees, especially those bordering openings (Federer and Gee 1974). A portion of the added transpiration may be drawn from the extra water available in the cut strips or individual tree openings, or from soil water moving downslope from cut to uncut areas. As a result, increases in streamflow were smaller than had the areas been cut like the single, low-elevation block at Leading Ridge. Larger increases for the first water years after cutting the second and third sets of strips at Hubbard Brook watershed 4 (Fig. 2) support this explanation.

The importance of timing of cutting and control of regrowth are demonstrated by comparing Hubbard Brook watersheds 2 and 5. On watershed 2, 100% of the basal area was clearfelled during the dormant season, and herbicides were applied early in the next growing season. This combination proved optimum for increasing water yield and resulted in a first-year increase of 347 mm, the maximum for all experimental treatments (Figs. 2, 3). By contrast, 95% of the basal area on watershed 5 was felled during a whole-tree harvest that spanned nearly a full year, and natural regrowth was uncontrolled. The first-year increase in water yield from watershed 5 was only 152 mm, or 44% of that from watershed 2. The difference in first-year increases from the watersheds is due largely to greater transpiration and interception by regrowth on watershed 5.

Impacts of Controlled Versus Natural Regrowth

Herbicides were used to control regrowth on watersheds 6 and 7 at Fernow, watershed 2 at Leading Ridge, and watershed 2 at Hubbard Brook (Table 1). In all cases, the effect was to prolong and substantially increase annual water yields compared to treated watersheds on which natural regrowth was uncontrolled. The use of herbicides for 3 successive growing seasons after felling all trees on watershed 2 at Hubbard Brook resulted in average annual yield increases of 288 mm for the 3-year period (Table 2). Herbicide applications to completely cleared watersheds at Fernow and Leading Ridge resulted in maximum annual increases of about 250 mm (Fig. 2, Table 2). Upon cessation of herbicide applications, sizable increases in water yield persisted for about 7 years at Fernow. However, natural regrowth quickly cut into increases in water yield at Hubbard Brook and Leading Ridge (Fig. 2).

Transpiration and interception by natural regrowth also quickly reduced increases in water yield in experiments where herbicides were not used. This was especially true for Hubbard Brook watersheds 4 and 5 where increases in water yield either disappeared or were greatly reduced within 3 or 4 years after cessation of intensive harvests (Fig. 2).

The increases appeared to decline equally rapidly on watershed 3 at Leading Ridge. Small decreases in water yield occurred by years 5 and 6 after harvest (Fig. 2). However, these decreases were anomalies resulting from a natural disturbance. During both of these years the mature forest on the control watershed was defoliated for part of the growing season by gypsy moth (*Porthetria dispar*). Such defoliations reduce transpiration and cause small increases in water yield (Corbett and Heilman 1975). Regeneration on the harvested watershed was not defoliated, resulting in greater transpiration from the harvested watershed and decreases in water yields compared to the control.

The decline with regrowth was less rapid on Fernow and Marcell watersheds (Fig. 2, Table 2). Yield increases persisted for two decades on watershed 2 at Fernow, but these were partly due to a follow-up diameter limit cut that was part of the prescribed treatment. Small increases of <50 mm yr^{-1} persisted for up to a decade or more after clearcuttings on watershed 4 at Marcell (Fig. 2). For years 12 through 21 since harvest at Marcell, the relatively small and inconsistent changes in water yield have been closely related to amount and distribution of spring and summer precipitation; increases in water yield occurred with above average precipitation and decreases occurred with drier weather conditions (Verry 1987). The same response was found for watershed 3 at Leading Ridge. The larger increases that occurred in years 10 and 14 after harvest (Fig. 2) were accompanied by growing season precipitation values that exceeded long-term means by more than 100 mm. Such findings reinforce an axiom expressed by Hewlett (1967) regarding forest cutting and increases in water yield: "It takes water to fetch water."

While above-average precipitation stimulates increases in water yield from cutting, excessive amounts can create problems with statistical procedures used in paired watershed studies. When precipitation and streamflow are well above the range normally encountered, calibration statistics must be extrapolated to accomodate resulting extremes in streamflow, providing a potential source of error in determining treatment effects (Hornbeck 1973). A case in point may be the 28th and 29th years after harvest on Fernow watershed 1. The increases in water yield were about the same magnitude as those for the 1st and 2nd years after cutting (Fig. 2). Since the regrowing forest on watershed 1 is similar in species composition to that before harvest and there have been no recent changes in forest condition, there is no reason to expect such increases to suddenly occur late in the postcutting period. As it turns out, both the 28th and 29th years after harvest had extreme precipitation values. The calibration regressions had to be extrapolated substantially to test the resulting extremes in streamflow, and probably gave erroneous results. Obviously, the evaluation and interpretation of extreme events must be handled with caution.

Long-term Changes Related to Species Composition

Long-term changes of some consequence occurred on Fernow watersheds 6 and 7 and Hubbard Brook watersheds 2 and 4. The Fernow watersheds are recovering from clearcutting and several years of herbiciding. Watershed 6 also was planted to Norway spruce 9 years after the initiation of clearcutting, and herbicides subsequently were applied on 2 occasions to reduce competition to spruce (Table 1). Water yields had remained at elevated levels on both watersheds 6 and 7, with slightly higher values on watershed 6 (Fig. 2). In recent years, however, the spruce canopy on watershed 6 has begun to close, and water yield is showing strong indications of returning to and probably dropping below pretreatment levels (Fig. 2). This would not be unexpected for a hardwood to conifer conversion. Swank and others (1988) pointed out that transpiration and interception losses are greater from young conifers than mature hardwoods, particularly during the dormant season.

On Fernow watershed 7, a final herbicide application to kill back all regrowth took place 6 years after the initial cutting. The substantial increases in water yield (>250 mm yr^{-1}) declined over a 6-year period in relation to increasing dry-matter production of regrowth (Kochenderfer and Wendel 1983) to between 50 and 100 mm, where they persisted for 14 years (Fig. 2). Comparisons with Fernow watershed 3 suggest a possible explanation for this extended period of increases of 50 to 100 mm. After a series of selection and patch cuttings, watershed 3 was clearcut but not herbicided. Increases in water yield declined much more rapidly than on watershed 7 (Fig. 2). Species composition of regrowth is similar on both watersheds, but regrowth on watershed 3 consisted almost exclusively of sprouts. By contrast, herbicide applications on watershed 7 eliminated sprouts, and regrowth originated from seeds. By utilizing the rooting network from the previous forest, the regrowth composed of sprouts may have better access to soil moisture, and transpiration may be greater, at least during the first 15 to 20 years of stand establishment, than for regrowth originating from seeds. The final 2 years of water yield data from watershed 7 suggest a shift more in line with watershed 3, but additional data are needed to draw conclusions.

The long-term trends at Hubbard Brook are different from those at the other three study locations. Decreases in water yield were evident early in the regrowth phase on watersheds 2 and 4, and persist through the remaining 13 years of record on both watersheds (Fig. 2). The explanation may lie with a posttreatment change in species composition. Before treatment, basal area was distributed about evenly among beech, birch, and maple species. During regrowth, nearly 80% of the basal area has been in birch and pin cherry (a common pioneer species in northern hardwood forests) with the remainder divided between beech and maple. Federer (1977) showed that birch and pin cherry have significantly lower leaf resistances (3.2 s cm^{-1}) than beech and maple species (4.0 to 4.5 s cm^{-1}). Thus, transpiration may be greater from the regrowing stand dominated by birch and pin cherry than from the mature, undisturbed forest, the end result being less water available for streamflow.

DISCUSSION

Surface Water Supplies

Results from the four study sites indicate the potential to increase water yield from forested watersheds in the northeastern United States. Based on experiments at Hubbard Brook, Fernow, and Leading Ridge, in which watersheds were clearcut and then herbicided, the maximum possible increase is in the range of 250 to 300 mm yr^{-1}. However, in light of controversy over the use of herbicides, it is likely that attempts to increase water yield will be confined to cutting. Even then, the studies indicate that various sizes of clearcuts, without control of regrowth, can provide immediate increases in annual yields ranging from about 110 mm (at Marcell) to 150 mm (at Hubbard Brook and Leading Ridge) to 250 mm (at Fernow). However, such increases diminish fairly rapidly, more so in some areas (Hubbard Brook and Leading Ridge) than others (Fernow and Marcell).

When cutting forests with an objective of increasing water yields, one must consider the possible impacts of a change in species during regrowth. The long-term results from Fernow and Hubbard Brook show that desired increases in water yield occurring immediately after cutting may be compensated in later years if hardwoods are converted to softwoods, or if there is a major shift in composition of hardwood species.

It is clear that the prolonged increases in water yield that occur after cutting in other regions of United States, such as from deeper soils of the southeast (Swank and others 1988) or from slowly regenerating forests of the west (Troendle and King 1985), cannot be expected in the Northeast. Shallow soils and rooting depths, shorter growing seasons, rapid root occupancy and leaf-area development by natural regeneration, lower evapotranspiration, and complete recharge of soil moisture during every dormant season all act to limit the magnitude and duration of increases in water yield in the Northeast.

Global Climate Change

The potential for a gradual change in species composition of forests is a major concern related to global climate change (Roberts 1989). The Hubbard Brook findings have implications regarding this concern. If one or two species were to drop out of the current hardwood forest, there could be detectable impacts on water yield. For example, the replacement of beech and maple at Hubbard Brook with birch and cherry resulted in decreases in water yield that averaged about 50 mm yr^{-1}. Although these decreases are small, they could become important if global climate change included a decrease in precipitation or conditions that favor increased evapotranspiration.

Nutrient Cycling

Forest cutting affects many processes involved in nutrient cycles and can lead to mobilization and increased leaching of nutrients (Hornbeck and others 1987). The mobilization and leaching of nutrients usually coincide with maximum increases in water yield. Thus, the larger the increases in water yield, the greater the potential to transport an additional mass of nutrients from cutover watersheds.

Forest cutting had negligible effects on nutrient leaching to streams at Marcell (Verry 1972), Fernow (Aubertin and Patric 1974), and Leading Ridge (Lynch and Corbett 1990), but caused significant increases at Hubbard Brook (Bormann and others 1968, Hornbeck and others 1987). In the 7 years after the clearfelling and herbicide experiment on watershed 2 at Hubbard Brook, increased leaching losses of nitrogen in streams represented a loss of nearly one-fourth of the total nitrogen capital of the watershed. A significant portion of this nitrogen loss was transported by the increased water yields that occurred in response to cutting and herbicide applications. By contrast, leaching losses of nitrogen after the less drastic strip cutting of watershed 4 represented <1% of total capital (Hornbeck and others 1987). Part of the explanation for this reduced loss lies with the much smaller increases in water yield, and less opportunity for nitrogen to be transported from the watersheds. Before recommendations are made to increase water yields from forests where nutrient leaching may be a problem, the potential impacts of added nutrient losses on site productivity and water quality must be considered.

Hydrologic Modeling

A primary objective of watershed studies is to provide data for developing and testing hydrologic models. The variety of responses to treatments in the northeastern United States suggests why it has been difficult to obtain good simulations of changes in water yield, especially those that are long term and more subtle.

The role of changes in species composition may have to be simulated more carefully. At present, some forest hydrology models use leaf area as the primary parameter for governing transpiration rates and water yield responses after treatment. As leaf area increases to an established level (e.g., 4 ha ha^{-1}), water yields gradually are returned to pretreatment levels. However, as suggested by long-term results at Fernow and Hubbard Brook, the changes in water yield might be more appropriately modeled with parameters such as leaf resistance, sapwood area, or indicators of leaf and needle geometry. Such parameters might allow better simulation of the processes that eventually resulted in long-term decreases in water yield at Fernow and Hubbard Brook.

Long-Term Research.

The knowledge summarized in this paper was obtained as a result of a continuing commitment to long-term research. Counting calibration periods, the studies have spanned at least 3 decades at Marcell, Leading Ridge, and Hubbard Brook, and 4 decades at Fernow. The reward for this long-term commitment is a more complete understanding of the impacts of forests and associated treatments on the hydrologic cycle. Watershed studies have taken on an added dimension over the past 2 decades as they have been expanded into ecosystem studies (Hornbeck and Swank 1992). The merging of forest hydrology with ecosystem studies ensures that watershed studies will continue as a primary source of knowledge about the role of forests in the hydrologic cycle.

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