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Long-term impacts of forest treatments on water yield: a summary for northeastern USA

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Abstract

Long-term changes in annual water yield are summarized and compared for 11 catchment studies in the northeastern USA. Substantial increases in water yield of up to 350 mm year^{-1} were obtained in the first year by clearing forest vegetation and controlling regrowth with herbicides. Commercial clearcutting with natural regrowth resulted in initial increases in water yield of 110–250 mm year^{-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 the growing season as augmentation of baseflow. Changes in species composition after forest cutting on several study catchments eventually resulted in decreased water yields compared with those from uncut, control catchments. Results are discussed in terms of implications for surface water supplies, global climate change, nutrient cycling, hydrological modeling, and long-term research.

Introduction

The use of paired, gaged catchments to study impacts of forest treatments on water yield reached a zenith in the 1960s. Since then, gaged catchments have become the focus of ecosystem studies, with less emphasis on water yield (Hornbeck and Swank, 1992). Short-term results of water yield studies from many locations were summarized by Hibbert (1967) at the International Symposium on Forest Hydrology held at the Pennsylvania State University

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in 1965. An updated review of water yield studies (Bosch and Hewlett, 1982) also concentrated mostly on short-term results. Thus, data now exist on long-term changes in water yield that have not been summarized and compared between sites. Analyses of changes over two decades or more as opposed to the much shorter periods previously reported can have important implications for issues such as water shortages, global climate change, nutrient cycling, hydrological modeling, and land use planning.

Long-term paired catchment studies at four locations in the northeastern USA are analyzed in this paper: Marcell Experimental Forest in north–central Minnesota, Fernow Experimental Forest in north–central West Virginia, Leading Ridge Watershed Research Unit in central Pennsylvania, and Hubbard Brook Experimental Forest in central New Hampshire (Fig. 1). These locations span the diverse geography of the northeastern USA. At each site, one or more catchments 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 three decades.

Results from these studies have special significance for the northeastern USA. Forests cover more than 60% of the landscape, and forested catchments serve as sources of water for more than 1000 municipalities ranging from small, rural communities to large urban centers such as New York and Boston. Although the region is well watered, with 1100 mm average annual

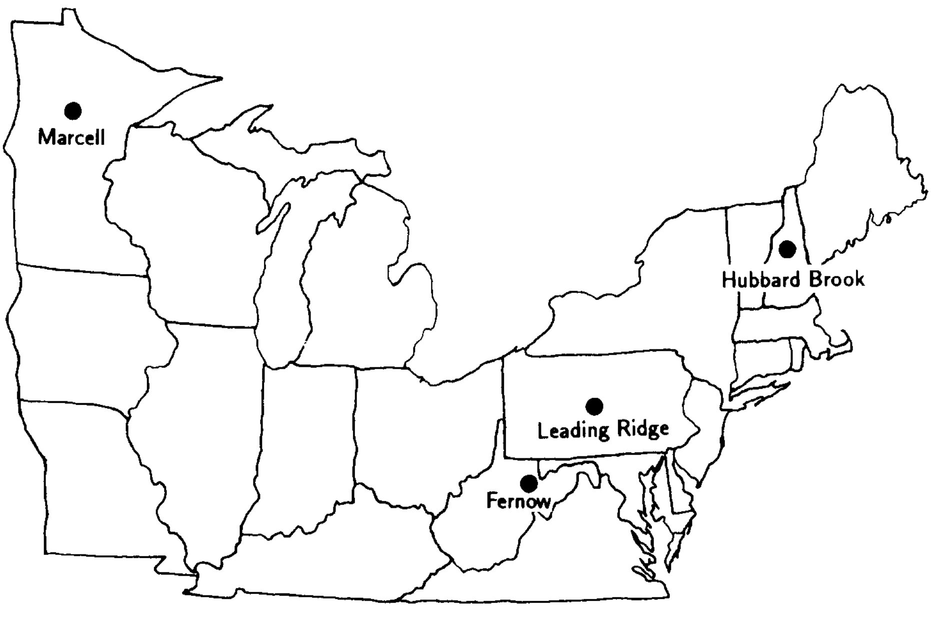

Fig. 1. Northeastern USA, showing study site locations.

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 catchments for optimum water production.

Study areas, treatments, and methods

Results from 11 separate, treated catchments are summarized and compared in this paper (Table 1). Measurements on many of these catchments began in the 1950s, followed 5–10 years later by initial treatments of vegetation. At the time of these initial treatments, the northeastern USA was experiencing an extended period of below-average precipitation and there was widespread interest in the potential for increasing water yield from forested catchments. 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 the determination of impacts of multiple treatments on the same catchment. For example, Catchment 3 of the Fernow Experimental Forest was first harvested in 1958–1959 by intensive selection, a silvicultural practice that was in common use in the region and which involved 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 catchment was subjected to a commercial clearcutting during which 91% of existing basal area was cut.

Other forms of multiple treatments included a three-stage, progressive strip cutting on Catchment 4 at Hubbard Brook, complete forest clearing in three stages on Catchment 2 at Leading Ridge and in two stages on Catchments 6 and 7 at Fernow, and controlling vegetation with herbicides before 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

Table 1
Descriptions of catchment studies in northeastern USA

Catchment	Area (ha)	Mid-elevation (m)	Vegetation (before treatment) and soils	Mean annual precipitation (mm)[a]	Mean annual streamflow (mm)[a]	Description of treatment	Year(s) of treatment	Basal area cut (%)[b]	Reference
Marcell Experimental Forest, MN				760	110				
4	34	433	Aspen–birch upland, black spruce peatland, Typic Glossoboralfs, interspersed with bog wetlands			Aspen–birch upland portion (26 ha) clear-cut (all trees > 3 m height)	1970–1971	100	Verry (1987)
Fernow Experimental Forest, WV				1480	640				
1	30	755	Central Appalachian hardwoods, Typic Dystrochrepts			Clearcut to 15 cm dbh except culls	1957–1958	74	Kochenderfer et al. (1990)
2	15	780				Diameter limit cut to 43 cm	1958	32	Kochenderfer et al. (1990)
						Diameter limit cut to 43 cm	1972	12	
3	34	505				Intensive selection	1958–1959	13	Kochenderfer et al. (1990)
						Intensive selection	1963	8	
						Patch (0.2 ha) cuttings	1968	6	
						Clearcut	1969–1970	91	
6	22	805				Clearcut lower half	1964	51	Patric & Reinhart (1971)
						Herbicides on lower half	1965–1969		Kochenderfer et al. (1990)
						Clearcut upper half	1967–1968	49	
						Herbicides on entire catchment	1968–1969		

						Plant Norway spruce	1973		
						Herbicides on entire catchment	1975, 1980		
7	24	801				Clearcut upper half	1963–1964	49	Kochenderfer et al. (1990)
						Herbicides on upper half	1964–1969		
						Clearcut lower half	1966–1967	51	
						Herbicides on entire catchment	1967–1969		
Leading Ridge Watershed Research Unit, PA				1060	440				
2	43	360	Central hardwoods, Typic Dystrochrepts and Typic Hapludults			Clearcut lowest 9 ha	1967	24	Lynch et al. (1990)
						Clearcut mid-slope 11 ha	1971–1972	27	
						Herbicide lower and mid-slope areas	1974		
						Clearcut 17 ha on upper slope	1975–1976	40	
						Herbicide all clearcut areas	1977		
3	104	340				Clearcut on 45 ha	1976 1977	43	Lynch and Corbett (1990)
Hubbard Brook Experimental Forest, NH				1340	860				
2	16	595	Northern hardwoods, Typic Haplorthods			Clearfelled	1965–1966	100	Hornbeck et al. (1970)
						Herbicides on entire catchment	1967–1969		

Table 1 (continued)

Catchment	Area (ha)	Mid-elevation (m)	Vegetation (before treatment) and soils	Mean annual precipitation (mm)[a]	Mean annual streamflow (mm)[a]	Description of treatment	Year(s) of treatment	Basal area cut (%)[b]	Reference
4	36	606				Progressive strip cut, first third harvested	1970	33	Hornbeck et al. (1987)
						Second third harvested	1972	33	
						Final third harvested	1974	33	
5	22	636				Whole-tree harvest	1983–1984	95	None available

[a] Long-term means for untreated, control catchments.
[b] Based on existing tree basal area on catchment at initiation of cutting.

catchment approach described by Reinhart (1967). Linear regression was used to develop a calibration relationship between annual water yield from a control catchment (independent variable, X) and a catchment to be treated (dependent variable Y) (Table 2). At locations with multiple catchment experiments, the same control was used in developing all regressions. The calibrations are based on five or more water years of record (Table 2), and although most of the calibration periods ended at least two decades ago, the relationships are assumed still to apply. Forests on all control catchments are mature and reasonably steady state with regard to biomass and leaf area (Bormann and Likens, 1979) and annual evapotranspiration (Federer et al., 1990). Thus, water yield relationships for control catchments 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 catchments, are presented in both graphical and tabular form in this paper.

Table 2
Calibration statistics for paired catchment experiments

Location and catchment no	Calibration period (years)	Calibration regression for annual water yield	r^2	Standard error of estimate (mm)
Marcell Experimental Forest				
4	9	$Y = 32.82 + 1.52\,X$	0.96	9
Fernow Experimental Forest				
1	5	$Y = -14.64 + 0.94\,X$	0.99	18
2	6	$Y = -5.74 + 1.06\,X$	0.99	9
3	7	$Y = 7.53 + 0.98\,X$	0.99	13
6	7	$Y = -46.17 + 0.87\,X$	0.87	24
7	7	$Y = 24.67 + 1.18\,X$	0.93	24
Leading Ridge Watershed Research Unit				
2	8	$Y = -21.26 + 1.18\,X$	0.99	14
3	16	$Y = 25.98 + 0.96\,X$	0.97	24
Hubbard Brook Experimental Forest				
2	7	$Y = 1.78 + 1.10\,X$	0.99	23
4	9	$Y = 39.01 + 1.03\,X$	0.99	14
5	20	$Y = 1.67 + 0.97\,X$	0.99	29

Statistical significance is not indicated when using graphs. However, on average for all sites, deviations greater than ± 30 mm year^{-1} from the calibration regressions were statistically significant.

Impacts of treatments on annual water yield

The array of forest treatments across the four study locations caused a variety of responses in water yield (Fig. 2, Table 3). 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 they diminish rapidly, usually within 3–10 years; (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. The timing of snowmelt runoff was changed by forest treatments at both sites, but volume was not (Hornbeck, 1975; Verry et al., 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 catchments and more water was available for streamflow. Flow–duration curves for post-treatment 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 are not greatly affected (Hornbeck et al., 1970; Patric and Reinhart, 1971; Verry, 1972; Lynch et al., 1980). Further, the yield increases occur primarily in the growing season. Complete recharge of soil moisture on both forested and treated catchments 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 (Douglass and Swank, 1972; Bosch and Hewlett, 1982), increases in yield for the first water year after treatment were roughly proportional to percentage reductions in stand basal area. However, a comparison for all sites (Fig. 3) suggests that reductions in basal area must approach 25% to obtain measurable responses in annual water yield. Above this threshold, there is some variability in first-year responses among catchments with similar basal areas cut, but the differences usually can be explained

Table 3
Changes in annual water yield for selected catchments

Year after initial treatment	Marcell Experimental Forest Catchment 4				Fernow Experimental Forest Catchment 7			
	Estimated streamflow if untreated[a] (mm)	Change owing to treatment[b] (mm)	(%)	Precipitation (mm)	Estimated streamflow if untreated[a] (mm)	Change owing to treatment[b] (mm)	(%)	Precipitation (mm)
1	209	81[c]	39	871	715	165[c]	23	1316
2	195	114[c]	58	817	390	142[c]	36	1057
3	130	92[c]	70	779	669	157[c]	23	1231
4	188	38[c]	20	862	658	251[c]	38	1215
5	227	77[c]	34	780	637	258[c]	40	1217
6	76	34[c]	45	458	738	246[c]	33	1332
7	152	51[c]	34	935	675	224[c]	33	1268
8	246	52[c]	21	882	869	175[c]	20	1481
9	276	40[c]	15	786	1030	164[c]	16	1557
10	108	19	18	662	919	157[c]	17	1553
11	198	6	3	821	994	187[c]	20	1551
12	282	−22	−8	799	628	104[c]	17	1243
13	100	−9	−9	748	607	65	11	1170
14	202	33[c]	16	744	755	89[c]	12	1328
15	286	12	4	920	988	112[c]	11	1628
16	217	56[c]	26	796	828	99[c]	12	1451
17	178	−1	0	744	755	62[c]	8	1397
18	296	−25[c]	−8	995	987	61	6	1587
19	281	1	0	839	801	109[c]	14	1470
20	125	−12	−10	587	852	103[c]	12	1529
21	89	−4	−4	711	842	71[c]	8	1487
22					1073	52	5	1745
23					694	88[c]	13	1389

Table 3 (continued)

Year after initial treatment	Marcell Experimental Forest Catchment 4				Fernow Experimental Forest Catchment 7			
	Estimated streamflow if untreated[a]	Change owing to treatment[b]		Precipitation	Estimated streamflow if untreated[a]	Change owing to treatment[b]		Precipitation
	(mm)	(mm)	(%)	(mm)	(mm)	(mm)	(%)	(mm)
24					516	48	9	1191
25					766	55[c]	7	1435
26					958	37	4	1561
27					936	−2	0	1583

Year after initial treatment	Leading Ridge Watershed Research Unit Catchment 2				Hubbard Brook Experimental Forest Catchment 2			
	Estimated streamflow if untreated[a]	Change owing to treatment[b]		Precipitation	Estimated streamflow if untreated[a]	Change owing to treatment[b]		Precipitation
	(mm)	(mm)	(%)	(mm)	(mm)	(mm)	(%)	(mm)
1	433	51[c]	12	967	851	347[c]	41	1279
2	302	32[c]	11	897	954	278[c]	29	1394
3	401	63[c]	16	1008	919	240[c]	26	1271
4	562	76[c]	14	1167	902	200[c]	22	1294
5	507	50[c]	10	1061	840	146[c]	17	1225
6	940	94[c]	10	1435	787	44	6	1221
7	462	79[c]	17	1018	1059	12	1	1504
8	529	132[c]	25	1104	1469	52	4	1832
9	658	61[c]	9	1210	832	67[c]	8	1240
10	606	193[c]	32	1214	1305	3	0	1659
11	682	239[c]	35	1285	884	48	5	1323
12	648	138[c]	21	1220	996	64[c]	6	1431

13	687	63[c]	9	1255	902	−13	−1	1287
14	260	73[c]	28	877	764	−13	−2	1139
15	570	−25	−4	1089	807	−34	−4	1261
16	528	−37	−7	1060	1179	−41[c]	−3	1530
17	570	49[c]	9	1091	885	−70[c]	−8	1328
18	559	22	4	1121	1099	−62[c]	−6	1522
19	500	56[c]	11	1106	715	−64[c]	−9	1087
20	558	64[c]	11	1178	958	−44[c]	−5	1310
21	422	−28	−7	964	872	−80[c]	−9	1210
22	410	26	6	964	790	−82[c]	−10	1190
23	584	36[c]	6	1163	708	−56[c]	−8	1149
24	777	27	3	1139	1109	−34	−3	1468
25					1194	−48[c]	−4	1590

[a] Determined from calibration regression.
[b] Determined by subtracting estimated streamflow from actual streamflow.
[c] Change exceeded 95% confidence interval about the calibration regression.

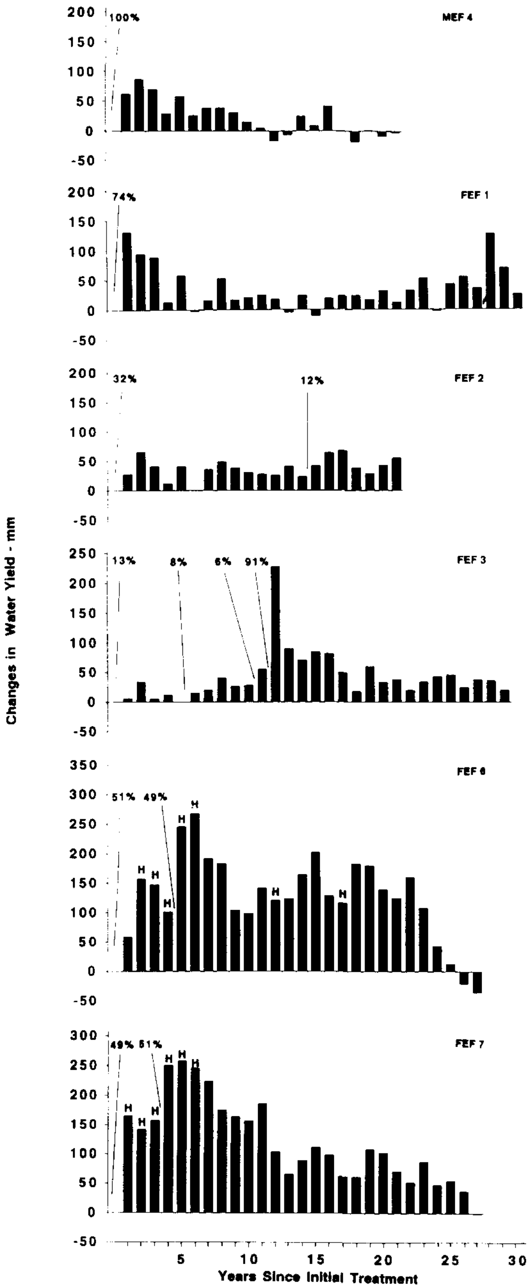

Fig. 2. Changes in annual water yield for 11 experimental catchment studies. MEF, Marcell Experimental Forest;. FEF, Fernow Experimental Forest; LR, Leading Ridge Watershed Research Unit; HB, Hubbard Brook Experimental Forest. Percentage values denote existing basal area cut during experimental treatments and H signifies herbicide application to cut portions of catchments.

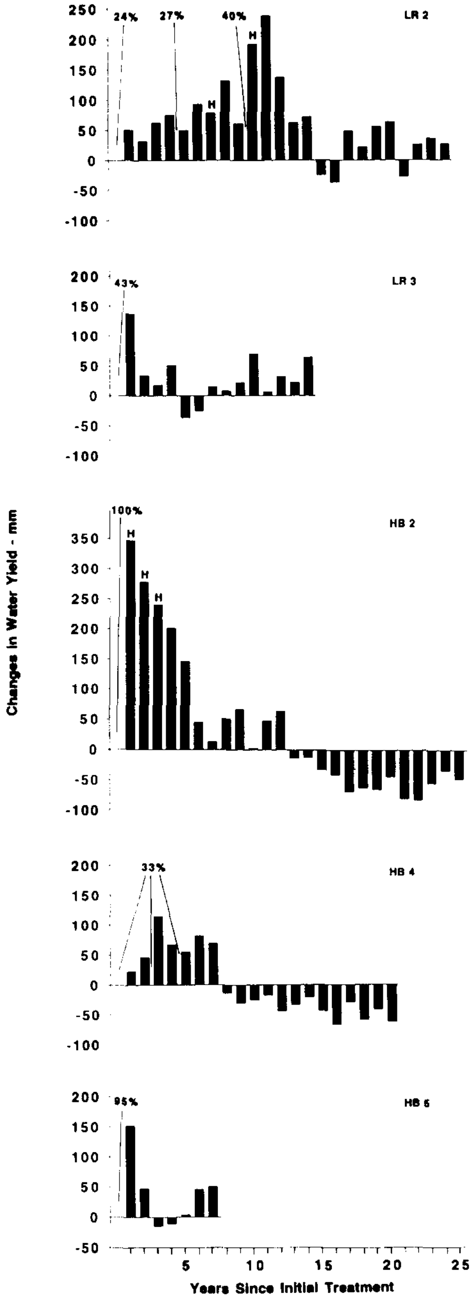

Fig. 2. Continued

by factors such as configuration and timing of the cutting, and whether regrowth was controlled with herbicides.

As an example of the role of configuration, the cutting of 24% of the basal area on Catchment 2 at Leading Ridge produced a nearly two-fold larger increase than cutting one-third of the basal area on Catchment 4 at Hubbard Brook and Catchment 2 at Fernow (Fig. 3). The cutting at Leading Ridge was in a single block on the lowest portion of the catchment, the cutting at Hubbard Brook was in a series of strips spaced equidistant from bottom to top of the catchment, and the cutting on the Fernow involved harvesting individual trees scattered about the catchment. The cutting of strips and individual trees increases the 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. The larger increases for the first water years after cutting the second and third sets of strips at Hubbard Brook Catchment 4 (Fig. 2) support this explanation.

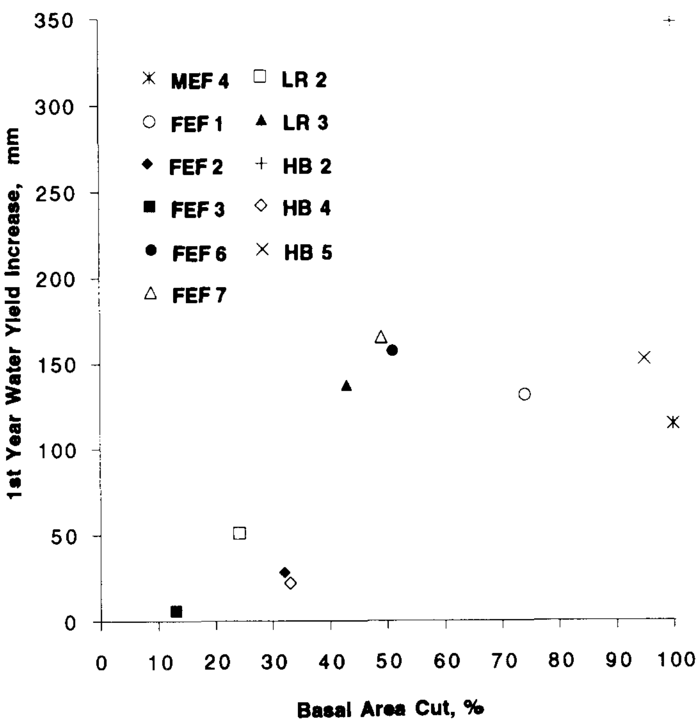

Fig. 3. First-year increases in water yield in response to forest cutting.

The importance of timing of cutting and control of regrowth are demonstrated by comparing Hubbard Brook Catchments 2 and 5. On Catchment 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 optimal for increasing water yield and resulted in a first-year increase of 347 mm, the maximum for all experimental treatments (Figs. 2 and 3). By contrast, 95% of the basal area on Catchment 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 Catchment 5 was only 152 mm, or 44% of that from Catchment 2. The difference in first-year increases from the two catchments is due largely to greater transpiration and interception by regrowth on Catchment 5.

Impacts of controlled vs. natural regrowth

Herbicides were used to control regrowth on Catchments 6 and 7 at Fernow, Catchment 2 at Leading Ridge, and Catchment 2 at Hubbard Brook (Table 1). In all cases, the impact was to prolong and substantially to increase annual water yields compared with treated catchments on which natural regrowth was uncontrolled. The use of herbicides for three successive growing seasons after felling all trees on Catchment 2 at Hubbard Brook resulted in average annual yield increases of 288 mm for the 3 year period (Table 3). Herbicide applications to completely cleared catchments at Fernow and Leading Ridge resulted in maximal annual increases of about 250 mm (Fig. 2, Table 3). Upon cessation of herbicide applications, sizeable 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 Catchments 4 and 5, where increases in water yield either disappeared or were greatly reduced within 3 or 4 years after cessation of intensive harvests.

The increases declined equally rapidly on Catchment 3 at Leading Ridge and 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 catchment 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 catchment was not defoliated, resulting in greater transpiration from the harvested catchment and decreases in water yields compared with the control.

The decline with regrowth was less rapid on Fernow and Marcell catchments (Fig. 2, Table 3). Yield increases persisted for two decades on Catchment 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 less than 50 mm year^{-1}, persisted for up to a decade or more after clearcuttings on Catchment 4 at Marcell (Fig. 2). For Years 12–21 after 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 was found for Catchment 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.'

Although above-average precipitation stimulates increases in water yield from cutting, excessive amounts can create problems with statistical procedures used in paired catchment studies. When precipitation is well above the range normally encountered, calibration statistics must be extrapolated to accommodate resulting extremes in streamflow, providing a potential source of error in determining treatment effects (Hornbeck, 1973). A case in point may be Years 28 and 29 after harvest on Fernow Catchment 1. The increases in water yield were about the same magnitude as those for Years 1 and 2 after cutting (Fig. 2). As the regrowing forest on Catchment 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 suddenly to occur late in the post-cutting period. In fact, both Years 28 and 29 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 Catchments 6 and 7 and Hubbard Brook Catchments 2 and 4. The Fernow catchments are recovering from clearcutting and several years of herbicide application. Catchment 6 also was planted to Norway spruce 9 years after the initiation of clearcutting, and herbicides subsequently were applied twice to reduce competition to spruce (Table 1). Water yields had remained at elevated levels on both Catchments 6 and 7, with slightly higher values on Catchment 6 (Fig. 2). In recent years, however, the spruce canopy on Catchment 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 confer conversion. Swank et al. (1988) pointed out that transpiration and interception losses are greater from young conifers than mature hardwoods, particularly during the dormant season.

On Fernow Catchment 7, a final herbicide application to kill back all regrowth took place 6 years after the initial cutting. The substantial increases in water yield that resulted (more than 250 mm year $^{-1}$) 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 Catchment 3 suggest a possible explanation for this extended period of increases of 50–100 mm. After a series of selection and patch cuttings, Catchment 3 was clearcut but herbicide was not applied. Increases in water yield declined much more rapidly than on Catchment 7 (Fig. 2). Species composition of regrowth is similar on both catchments, but regrowth on Catchment 3 consisted almost exclusively of sprouts. By contrast, herbicide applications on Catchment 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 15–20 years of stand establishment, than for regrowth originating from seeds. The final 2 years of water yield data from Catchment 7 suggest a shift more in line with Catchment 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 Catchments 2 and 4, and persisted through the remaining 13 years of record on both catchments (Fig. 2). The explanation may lie with a post-treatment 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 (4.0–4.5 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.

Implications

Surface water supplies

Results from the four study sites indicate the potential to increase water yield from forested catchments in the northeastern USA. Based on experiments at Hubbard Brook, Fernow and Leading Ridge, in which catchments were clearcut and then herbicide was applied, the maximum possible increase is in the range of 250–300 mm year^{-1}. However, in the 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 100 mm at Marcell to 150 mm at Hubbard Brook and Leading Ridge and 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 the USA, such as from deeper soils of the southeast (Swank et al., 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 northern 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 year^{-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 et al., 1987). The mobilization and leaching of nutrients usually coincide with maximum increase in water yield. Thus, the larger the increases in water yield, the greater the potential to transport an additional mass of nutrients from cutover catchments.

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 et al., 1968; Hornbeck et al., 1987). In the 7 years after the clearfelling and herbicide experiment on Catchment 2 at Hubbard Brook, increased leaching losses of nitrogen to streams represented a loss of nearly one-fourth of the total nitrogen capital of the catchment. 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 Catchment 4 represented less than 1% of total capital (Hornbeck et al., 1987). Part of the explanation for this reduced loss lies with the much smaller increases in water yield, and thus the reduced opportunity for nitrogen to be transported from the catchment. Before recommendations are made to increase water yields from forests where nutrient leaching may be a problem, the potential impacts of further nutrient losses on site productivity and water quality must be considered.

Hydrological modeling

A primary objective of catchment studies is to provide data for developing and testing hydrological models. The variety of responses to treatments in the northeastern USA 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, most 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 return 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 three decades at Marcell, Leading Ridge, and Hubbard Brook, and four decades at Fernow. The reward for this long-term commitment is a more complete understanding of the impacts of forests and forest treatments on the hydrological cycle. Catchment studies have taken on an added dimension over the past two decades as they have been expanded into ecosystem studies (Hornbeck and Swank, 1992). The merging of forest hydrology with ecosystem studies insures that catchment studies will continue as a primary source of knowledge about the role of forests in the hydrological cycle.

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