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Comparisons with Results from the Hubbard Brook Experimental Forest in the Northern Appalachians

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Introduction

The Hubbard Brook Experimental Forest (HBEF) is located in central New Hampshire, in the heart of the White Mountains, toward the northern end of the Appalachian chain. HBEF was established in 1955, two decades after Coweeta Hydrologic Laboratory (CHL), but research objectives at both sites have long been similar, that is, to understand hydrologic and nutrient cycling processes for forest ecosystems and to determine responses to natural and human disturbances.

This chapter summarizes the responses to intensive cuttings on three watersheds at HBEF and compares the results with those from the clearcutting on Watershed 7 (WS 7) at CHL. HBEF and CHL have some major differences in site characteristics that would be expected to cause variability between sites in hydrologic and nutrient cycles and responses to disturbances. Northern hardwood types with patches of spruce and fir at higher elevations dominate the forests at HBEF. The combination of diffuse porous species, including American beech, sugar maple, and yellow birch, have stomatal resistances, water use characteristics, and regeneration strategies that are different from those of the oak and oak-pine types found at CHL. The climate is cooler and drier at HBEF (annual precipitation averages 130 cm), and, in contrast to CHL, snow has an important role in winter and spring hydrology. Approximately one-third of annual precipitation at HBEF occurs as snow that accumulates as a snowpack. Runoff from the melting snowpack occurs primarily in April and accounts for 25% (20 cm) of the average annual streamflow (80 cm). The

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growing season is shorter at HBEF (May 15 to September 30); and complete soil moisture recharge occurs near the end of every autumn.

Metasedimentary and igneous rocks that are relatively impermeable to water from overlying soils underlie the watersheds at HBEF. Retreating glaciers approximately 14,000 years ago left deposits of unconsolidated till that vary widely in composition and depth. Soils are derived solely from this till and are predominantly Typic Haplorthods with sandy loam textures and high infiltration capacities. Soil depth is variable but seldom averages over 1 m. Thus soil rooting depth and water holding capacity are considerably less than at CHL. The glacial till and underlying geology weather slowly, and soils are relatively infertile, giving rise to streams that are clear and dilute (Hornbeck et al. 1997a).

Three treatments on gauged watersheds at HBEF can be contrasted with the clearcut logging experiment on CHL WS 7: (1) a clearfelling on HBEF Watershed 2 in winter 1965, with no roads or product removals, and application of herbicides for three successive summers after the felling operation; (2) a shelterwood harvest on HBEF Watershed 4 spanning 1970 to 1974, during which one-third of the watershed was harvested every other year by progressive strip cutting; and (3) a whole-tree clearcutting on HBEF Watershed 5 from October 1983 through May 1984 (figure 13.1). The methods used and detailed descriptions of these studies were published by Hornbeck et al. (1997b) and Martin et al. (2000). Soil disturbances ranged from little after the clearfelling and herbicide treatment to substantial after the whole-tree clearcutting. Canopy removal ranged from immediate during the clearfelling to gradual on the shelterwood. Regeneration was natural on all watersheds but ranged from uncontrolled after the whole-tree clearcutting and shelterwood harvests to controlled for 3 years after the clearfelling. Results are available for 41 years after the clearfelling, 36 years after the shelterwood, and 23 years after the whole-tree clearcutting. While all three watershed treatments at HBEF involved intensive cutting, the whole-tree clearcutting (Watershed 5) most closely resembles the clearcutting performed on WS 7 at CHL.

Results of Experimental Treatments at HBEF

The three watershed treatments at HBEF (figure 13.1) are hereafter referred to as CF (clearfelling and herbicide applications on Watershed 2), SC (shelterwood or progressive strip cutting on Watershed 4), and WT (whole-tree clearcutting on Watershed 5).

Forest Regeneration

Northern hardwoods regenerate by four major approaches: new seed, buried seed, stump sprouts, and root suckers (Hornbeck and Leak 1992). In addition some species also depend upon advanced regeneration already present in the understory at the time of disturbance. This variety of regeneration strategies provides a means of complete and reasonably rapid, natural revegetation of almost any type or size of disturbance. To demonstrate, table 13.1 compares mature versus regenerating

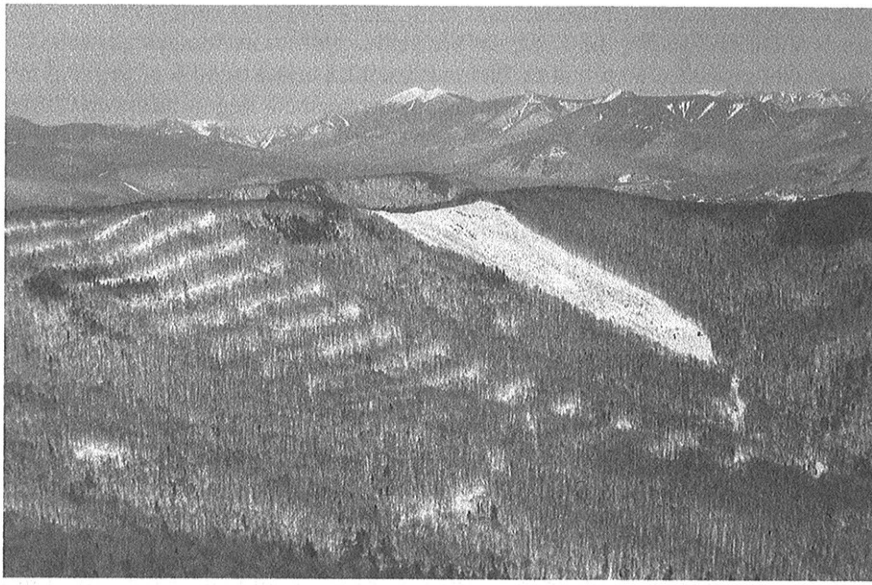

Figure 13.1 The Hubbard Brook experimental watersheds. The clearfelled watershed (CF) is right of center in this photo. The progressive strip-cut watershed (SC) is to the left of center and is shown with one-third of the strips harvested. The whole-tree harvest watershed (WT) is located to the left of the SC watershed and had not yet been harvested when this photo was taken. (USDA Forest Service photo)

Table 13.1 Basal area (m^2/ha) by species for control and regenerating watersheds.

Species	Control mature[a]	CF, year 25[b]	SC, year 27[c]	WT, year 15[d]
Sugar maple (*Acer saccharum*)	9.1	1.0	2.1	0.4
Red maple (*Acer rubrum*)	0.2	0.5	0.3	0.1
Striped maple (*Acer pensylvanicum*)	0.1	0.4	1.1	0.6
American beech (*Fagus grandifolia*)	10.0	0.3	1.4	2.1
Yellow birch (*Betula alleghaniensis*)	5.3	2.4	7.6	3.1
Paper birch (*Betula papyrifera*)	1.7	4.0	2.7	2.3
White ash (*Fraxinus americana*)	0.3	0.5	1.1	0.1
Red spruce (*Picea rubens*)	0.7	< 0.05	0.1	0.1
Balsam fir (*Abies balsamea*)	0.7	0.7	0.2	0.7
Pin cherry (*Prunus pensylvanica*)	0.0	6.3	7.1	4.9
Trembling aspen (*Populus tremuloides*)	0.0	0.7	0.1	0.2
Others	0.2	0.3	0.5	0.2
Total	28.3	17.1	24.3	14.8

[a] 100% measurement in 1997 of all trees ≥ 10 cm DBH (data provided by T. G. Siccama, Yale University, New Haven, Connecticut)

[b] Measurements in 1991 of trees ≥ 2.5 cm DBH on 69 plots.

[c] Measurements in 1997 of trees ≥ 2.5 cm DBH on 57 plots

[d] Measurements in 1999 of trees ≥ 2.5 cm DBH on 101 plots (data provided by T.G. Siccama)

forests at HBEF. Despite the 3 years of herbicide applications, basal area of the CF watershed by year 25 after cutting had reached 17.1 m^2/ha or 60% of the 28.3 m^2/ha occurring on the mature forest of the control watershed. Regeneration grew even more rapidly on the SC, reaching an average basal area of 24.3 m^2/ha at 27 years after initiation of cutting.

The forest treatments have caused a change in the species composition when compared with the control watershed. Eighty-six percent of the basal area on the control watershed consists of the primary northern hardwood species sugar maple (32%), American beech (35%), and yellow birch (19%) (table 13.1). In contrast, these same three species combine for only 22% of the basal area at 25 years after treatment on the CF watershed. Pin cherry (37%) and paper birch (23%), common pioneer species in northern hardwood forests, assumed early dominancy in the new forest. The same pattern occurred after SC and WT (table 13.1). These changes in species composition have important implications for water yield as discussed below.

Water Yield and Peakflow Rates

All three experimental treatments at HBEF were severe in that each nearly eliminated basal area and transpiration. However, responses in annual water yields varied markedly among treatments (table 13.2). CF produced the most dramatic response, causing annual water yields to increase by an average of 288 mm (32%) for the 3-year period immediately after cutting and while herbicides were being applied. With the ending of herbicide applications and with the occurrence of natural regeneration, the water yield increases rapidly diminished. Statistically significant but progressively smaller increases occurred in years 4 and 5 (table 13.2). Increases in streamflow were indicated in years 6 through 12, but only those in years 9 and 12 were statistically significant. Beginning in year 13 and continuing through year 34, all changes in annual streamflow were indicated to be decreases. Based only on decreases that were statistically significant (12 of 18 years), streamflow during much of the period of stand regeneration averaged 62 mm/yr less (–7%) than if CF had not been performed.

Water yield increases for the SC, which was cut in thirds over a 4-year period, were rather modest. For years 2 through 4 during, and years 5 through 7 following the SC, there were significant increases in annual water yield ranging from 4% to 9% (table 13.2). As with the CF, regeneration caused water yield to decrease by 3% to 9% compared to the control watershed. And just as with the CF, these decreases persisted for several decades (table 13.2). These decreases are the result of lower stomatal resistance and greater water use by the pioneer species that dominate the early regeneration (Hornbeck et al. 1997b).

Water yield increased 23% the first year following the WT. There were also significant increases of 5% to 8% during years 7, 8, and 13 following cutting. Since year 14 after WT there has been a mixture of small increases and decreases in streamflow (table 13.2). Several possible explanations for the different response on the WT compared to the CF and SC include a lack of regeneration on the skid roads, heavy moose browse near the top of the watershed, and a greater proportion of American beech in the regenerating forest. All these factors could reduce transpiration rates without decreasing water yield (Campbell et al. 2007; Hornbeck et al. 1997b).

The water yield increases occurred primarily as augmentation to low flows during the growing season. Complete recharge of soil moisture usually occurs in mid- to late autumn at HBEF, and transpiration-induced increases in streamflow seldom extend into the dormant season. Depending upon antecedent soil moisture, peakflow rates during the growing season can be increased by up to 60% in the first 1 to 2 years after harvest. Any increases in peakflow rates quickly disappear with the establishment of a new forest (Hornbeck et al. 1997b). Total snowmelt runoff was largely unaffected by treatments, but timing was changed. In the absence of shade provided by branches and stems, snowmelt and snowmelt runoff were advanced by up to 17 days compared with the control watershed.

The amount and duration of water yield changes at HBEF are determined in large part by differences in how the forests were cut and how rapidly new forests regenerated. The harvesting of the SC was spread over 4 years, allowing regeneration to develop on adjacent strips during harvesting and for water yield increases from cut strips to be utilized by the uncut strips. As a result annual water yield increases from the SC were small and short-lived (table 13.2). The WT was harvested in one large block, hence the larger initial increase in annual water yield. However, the regrowing forest reduced the water yield increases from the WT by more than half in the second year after harvest (table 13.2).

Soil Disturbance and Sediment Yield

Logging on the SC and WT adhered to best management practices (BMPs) prescribed by the state of New Hampshire, but considerable soil disturbance still occurred. For example, surveys after the SC and WT at HBEF showed that 70% and 67% of the respective watershed areas had soil disturbances of varying degrees. Disturbance on the WT (table 13.3) ranged from nearly 4% of the entire watershed having the forest floor intact but depressed by one pass of logging equipment, to 18% covered with wheel or track ruts into mineral soil. Logging disturbed the forest-floor organic horizons to the point where nearly 28% of the WT exhibited bare mineral soil (including scalped mineral mounds, mineral ruts, and bare rocks; Martin and Hornbeck 1994).

The soil disturbances during logging led to some increases in sediment yield. Annual sediment yields for several decades from control watersheds at HBEF (Watersheds (WSs) 3 and 6) varied widely from 1 to 95 kg/ha (table 13.4). By comparison, annual sediment yields since initiation of the SC in 1970 ranged from 3 to 146 kg/ha. The maximum value occurred during the 1973 water year when the second series of strips were cut. Annual sediment yields since initiation of the WT in 1983 ranged from 3 to 208 kg/ha. Sediment yields from the WT watershed prior to harvest had been as great as 134 kg/ha. Statistically significant increases occurred during the first 3 years after WT, and in year 12 (table 13.4).

When sediment reaches a stream it may cause the water to become turbid. This effect is measured in Jackson turbidimeter units, or JTU, and can be used as an index of the effects of harvesting on water quality (Martin and Hornbeck 1994).

Table 13.2 Changes in annual water yield for treated watersheds.

	CF			SC			WT		
Year after initial treatment	Estimated flow if untreated	Change due to treatment		Estimated flow if untreated	Change due to treatment		Estimated flow if untreated	Change due to treatment	
	(mm)	(mm)	(%)	(mm)	(mm)	(%)	(mm)	(mm)	(%)
1	851	347*	41	777	22	3	649	151*	23
2	954	278*	29	1032	46*	4	883	48	5
3	919	240*	26	1415	116*	8	806	−15	−2
4	902	201*	22	818	68*	8	743	−12	−2
5	840	146*	17	1263	55*	4	682	4	1
6	787	44*	6	867	81*	9	1019	46	5
7	1059	13	1	973	69*	7	1086	52*	5
8	1467	53	4	885	−15	−2	835	66*	8
9	832	67*	8	755	−31*	−4	860	47	5
10	1305	2	0	795	−26*	−3	879	19	2
11	884	48	5	1144	−18	−2	605	22	4
12	996	64*	6	869	−44*	−5	1348	25	2
13	902	−15	−2	1069	−33*	−3	1150	64*	6
14	764	−13	−2	709	−46*	−7	746	−4	−1
15	807	−33	−4	927	−45*	−5	1006	−36*	−4
16	1179	−42*	−4	857	−67*	−8	1112	9	1
17	885	−70*	−8	779	−36*	−5	675	−3	0
18	1098	−62*	−6	702	−59*	−8	740	28	4
19	715	−64*	−9	1080	−43*	−4	622	−5	−1
20	948	−44*	−5	1159	−63*	−5	1198	−6	−1
21	872	−80*	−9	904	−42*	−5	951	−45*	−5
22	790	−83*	−10	943	−59*	−6	1225	6	0
23	708	−55*	−8	918	−30*	−3	1015	−19	−2
24	1110	−35	−3	624	−37*	−6			
25	1194	−48*	−4	1362	−22	−2			
26	923	−36	−4	1181	−18	−2			
27	964	−79*	−8	768	−66*	−9			
28	938	−71*	−8	1020	−46	−4			
29	625	−54*	−9	1132	−34*	−3			
30	1410	−26	−2	673	4	1			
31	1218	−34	−3	771	−18	−2			
32	778	−39*	−5	652	−18	−3			
33	1047	−31	−3	1203	−1	0			
34	1165	−71*	−6	998	−38*	−4			
35	677	18	3	1263	−11	−1			
36	781	9	1	1010	−21	−2			
37	654	70*	11						
38	1241	1	0						
39	1023	19	2						
40	1306	17	1						
41	1036	5	0						

*Change exceeded 95% confidence interval about the calibration regression.

Table 13.3 Soil disturbance on the whole-tree watershed (WT).

Type of disturbance	%	Standard error
Undisturbed	30	3
Depressed (undisturbed but compressed by equipment)	4	1
Scarified (organic and mineral soils mixed)	13	1
Scalped (organic pad scraped from mineral soil)	1	1
Organic mounds (mounds of organic soil)	13	2
Mineral mounds (mounds of mineral soil)	6	1
Organic ruts (wheel ruts lined with organic soil)	10	1
Mineral ruts (wheel ruts into mineral soil)	18	3
Vegetation (stumps and logging slash)	2	1
Bare rocks (rocks > 10 cm diameter)	3	1
Total		100

Three hundred and twenty-five samples for turbidity were collected from a control watershed and the same number of samples were collected from the SC during both storm and nonstorm periods. No samples exceeded 5 JTU from the control watershed. Nine samples (3%) exceeded 10 JTU (the drinking water standard) from the SC, with 40 JTU being the maximum value measured.

Soil Chemical Status

Effects of forest cutting on soil chemistry have been determined only for the WT. Total soil pools of exchangeable Ca, Mg, and K were unchanged in the first 8 years after cutting (Johnson et al. 1997). Decreases in exchangeable cation concentrations in upper soil horizons (Oa and E horizons) were offset by large increases in the spodic horizons (Bh and Bsl). Soil organic matter is the principal source of cation exchange capacity in soils at HBEF. The cation exchange capacity to organic matter ratio increased by about 25% in spodic horizons for the first 8 years after cutting, suggesting that the cutting altered the charge properties and character of organic matter (Johnson et al. 1997).

The mean N pool for the forest floor was 17% lower 8 years after WT (Johnson 1995). Carbon was preferentially lost from soil organic matter, relative to N, resulting in significant decreases in the C/N and C/organic matter ratios in the soil (Johnson 1995).

Stream Water Nutrients

All three experimental treatments at HBEF caused stream water concentrations of Ca^{+2}, K^{+}, H^{+}, and NO_3^{-} to increase, concentrations of SO_4^{-2} to decrease, and concentrations of other ions to change very little. Responses to the WT were intermediate between those from the CF and SC and can be used to demonstrate effects of cutting at HBEF (figure 13.2).

For the WT, mean monthly Ca^{+2} concentrations increased by as much as 3.5 mg/L by the second year after cutting, then gradually declined through year 5

Table 13.4 Sediment yields from four watersheds at the HBEF and from two untreated control watersheds (WS 3 and WS 6)

Water year	WS 3	WS 6	SC	WT	WS 6
	Control watersheds (kg ha^{-1} yr^{-1})		Treatment watersheds (kg ha^{-1} yr^{-1})		Precip. (mm)
1970[b]	—	42	3[a]	—	1360
1971	—	5	13[a]	—	1329
1972[c]	—	6	27[a]	—	1280
1973	—	95	146[a]	—	1565
1974[d]	—	25	16[a]	—	1888
1975	35	18	67	24	1308
1976	10	15	6	12	1769
1977	29	79	132	134	1402
1978	37	18	65	68	1532
1979	47	25	30	97	1362
1980	64	32	38	89	1194
1981	25	34	36	41	1355
1982	28	10	27	35	1585
1983[e]	11	3	5	14	1410
1984[e]	47	35	52	64	1638
1985	5	4	10	112*	1200
1986	45	17	77	129*	1425
1987	71	52	89	208*	1311
1988	4	1	10	6	1290
1989	19	7	35	15	1234
1990	24	13	37	44	1553
1991	17	14	64	33	1669
1992	8	3	13	7	1422
1993	15	12	87	16	1372
1994	8	13	48	11	1405
1995	5	3	3	3	1156
1996	23	71	125	176*	1805
1997	9	7	8	30	1608
1998	3	2	12	10	1290
Mean	25	23			1439
s.e.	4	5			35
C.V.(%)	78	100			13

* Significant increase ($p < 0.05$).
[a] Estimated by linear regression with WS 6 as the independent variable.
[b] First set of strips harvested on Watershed 4.
[c] Second set of strips harvested on Watershed 4.
[d] Third set of strips harvested on Watershed 4.
[e] Whole-tree clearcutting on Watershed 5.

(figure 13.2). From years 5 through 14, Ca^{+2} concentrations from the WT have remained elevated by an average of 0.5 mg/L when compared to the control watershed.

Concentrations of K^{+} increased in the first year after WT to a maximum of 1.5 mg/L greater than the control watershed (figure 13.2). K^{+} from the WT then gradually declined over years 2 and 3 but elevated levels of K^{+} have persisted for the period of measurement (figure 13.2).

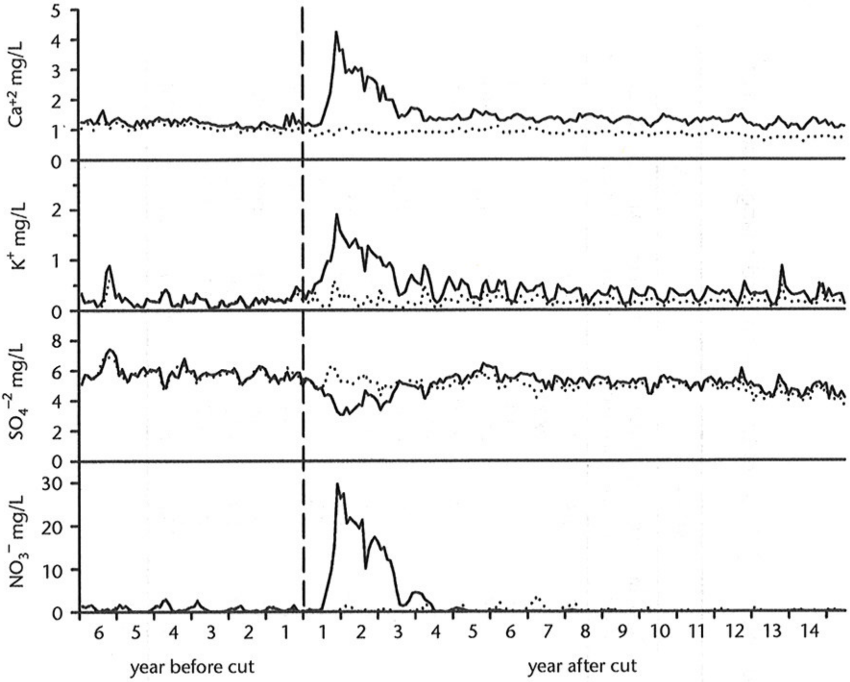

Figure 13.2 Volume-weighted mean monthly concentrations of nutrient ions for the WT (*solid line*) and control watersheds (*dotted line*). The vertical dashed line indicates the beginning of the harvest. Data are from Martin et al. (2000).

Forest harvest has the greatest impact on concentrations of NO_3^-. Concentrations for control watersheds have nearly always been < 5 mg/L, and in recent years have usually been < 1 mg/L (figure 13.2). In the first year after WT mean monthly concentrations of NO_3^- increased from background levels of < 1 mg/L to a maximum of 30 mg/L (figure 13.2). The increases gradually disappeared and concentrations of NO_3^- fell below those for the control watershed by the sixth year after harvest. The decreased level of NO_3^- from the WT has continued through year 14 after harvest.

Concentrations of SO_4^{-2} during precutting ranged between 5 and 7 mg/L and seldom varied between watersheds by more than 0.5 mg/L. WT caused mean monthly SO_4^{-2} to decrease by up to 2 mg/L during the first 3 years after harvest, then return to about the same or slightly higher concentrations than from the control watershed (figure 13.2).

Nutrient Budgets

The changes in water yield and ion concentrations for the harvested watersheds caused streamflow nutrient outputs and net gains or losses from input/output budgets to differ from values for uncut watersheds. Using WT an example, a total of statistically significant increases and decreases in annual streamflow ouputs (table 13.5)

Table 13.5 Input-output budgets in kg/ha/yr for WT. To obtain total output for WT, add output if uncut and change due to cut. Data are from Martin et al. (2000)

	Ca			K			NO_3-N			SO_4-S		
Water year after harvest	Input in precip.	Output if uncut	Change due to cut	Input in precip.	Output if Uncut	Change due to cut	Input in precip.	Output if Uncut	Change due to cut	Input in precip.	Output if Uncut	Change due to cut
1	1.0	7.0	14.0*	0.6	1.5	8.2*	4.5	0.9	28.3*	9.2	11.1	−1.1
2	0.9	8.9	12.3*	0.4	1.7	7.6*	4.2	0.9	28.8*	7.9	14.6	−2.3
3	0.6	8.5	2.9*	0.3	2.0	3.2*	3.6	1.6	3.5*	8.3	12.7	−0.3
4	1.1	7.9	1.9*	0.7	1.4	2.0*	4.6	0.8	−0.3	8.3	12.2	0.9*
5	1.1	7.6	1.8*	0.5	1.8	1.7*	4.8	1.5	−1.3*	8.3	11.4	1.5*
6	1.4	11.1	3.0*	0.8	2.2	2.4*	5.4	3.8	−3.7*	10.1	16.5	3.1*
7	1.2	10.8	4.2*	0.8	1.5	2.5*	5.6	1.9	−1.6*	11.6	17.6	1.8*
8	1.1	8.2	3.8*	0.6	1.4	1.7*	4.8	0.6	−0.4	8.9	13.7	1.9*
9	0.9	7.8	3.2*	0.6	1.4	1.7*	5.0	0.4	−0.3	9.0	13.4	1.2*
10	1.2	8.1	3.1*	0.6	1.4	1.6*	5.8	0.2	−0.2	10.0	4.2	1.0*
11	0.9	6.1	2.1*	0.6	1.0	1.1*	4.8	0.4	−0.4	7.8	9.5	1.2*
12	1.3	10.6	4.9*	0.7	2.3	2.5*	5.8	0.7	−0.6	9.0	19.6	2.6*
13	1.1	8.6	4.5*	0.6	1.8	2.2*	5.3	0.4	−0.2	8.9	15.8	2.2*
14	1.0	6.3	2.0*	0.8	1.4	0.9*	4.4	0.3	−0.2	6.7	10.2	0.9
Sum	14.8	117.5	63.7[a]	8.6	22.8	39.3[a]	68.6	14.4	54.0[a]	124.0	192.5	17.4

*Significant at 0.05 level of probability.
[a]Sum of significant differences only.
Source: Data are from Martin et al. (2000).

shows that in the 14 years since initiation of WT, there has been an increased loss of 64 kg Ca/ha, 39 kg K/ha, 54 kg NO_3-N/ha, and 17 kg S/ha^{-1} (table 13.5).

To put these losses in perspective, streamwater outputs of Ca in the absence of WT would have been 117.5 kg Ca/ha (table 13.5). The additional 63.7 kg Ca/ha lost due to WT thus represents an increase of 54% in Ca outputs in streamwater. Corresponding increases due to stripcutting for other nutrients are 172% for K, 375% for N, and 9% for S.

Despite the large increase in N loss after WT, the watershed still experienced a small net gain in N for the postharvest period due to inputs in bulk precipitation that continued to exceed outputs in streamflow (table 13.5). This was not the case for Ca and K. The input/output budgets for both of these nutrients show substantial net losses before harvesting, and therefore even greater net losses after harvest (table 13.5).

Stream Invertebrates

After the WT, increases in streamflow, light, temperature, and nutrients translated into increased algal abundance with little change in species composition or diversity (Ulrich et al. 1993). The increase in the algal abundance in turn affected the macroinvertebrate community. The standing crop of invertebrates increased the first growing season after cutting due to an increase in herbivorous forms (Burton and Ulrich 1994). At the same time, the populations of two predatory invertebrates also increased. These increases were at the expense of the leaf shredding detritivores.

Comparisons of Results from HBEF with CHL

Forest Regeneration

At CHL, the three communities making up the forest prior to clearcutting had an average basal area of 25.3 m^2/ha (Elliott et al. 1997). The mature, northern hardwood forest on the control watershed at HBEF had an average basal area of 28.3 m^2/ha^{-1} (table 13.1). Hardwood forests at both CHL and HBEF revegetated quickly after the experimental cuttings. However, growth rates during the regeneration period were considerably higher at CHL. By year 16 after the clearcutting at CHL, regeneration for the three major communities found on the watershed had average basal areas between 75% and 105% of that for the preharvest forest (Elliott et al. 1997). In contrast, by year 15 after the WT at HBEF, basal area was 52% of the mature forest (table 13.1). By year 27 on the SC, the basal area of the regenerating forest had reached 86% of that of the mature forest (table 13.1).

At both CHL and HBEF the species composition of the regenerating forest showed some marked differences from the preharvest forest. During the first two or more decades of regrowth, opportunistic species, such as tulip poplar and black locust at CHL and pin cherry and paper birch at HBEF, dominated regeneration (table 13.1) (Elliott et al. 1997). At HBEF, yellow birch, sugar maple, and American beech are gradually increasing on all the treated watersheds and are expected to assume their traditional dominant role between 30 and 40 years after the experimental treatments (Hornbeck and Leak 1992). At CHL some of the oak and hickory species that were dominant in the preharvest forest may not become significant components of the new stand for many decades due to their slow rates of seed dispersal and low survival (Elliott et al. 1997).

Water Yield and Peakflow Rates

The first-year increase in annual water yield after the clearcutting at CHL was 260 mm (Swank et al. 2001), compared to HBEF values of 347 mm after the CF, 116 mm after the second stage of SC, and 151 mm after WT (table 13.2). Increases declined rapidly at both CHL and HBEF, and annual water yields returned within a few mm of precutting levels within 5 to 6 years after conclusion of treatments. However, in the years since the initial recovery, there have been decreases in water yield at both CHL and HBEF. The persistent decreases in annual water yield at HBEF (since year 8 on the SC and year 12 on the CF) are due to the regeneration having substantial numbers of pioneer species that have lower stomatal resistances and greater transpiration than mature northern hardwood forests (Hornbeck et al. 1997b). As the short-lived pioneer species drop from the stand, transpiration is expected to decrease and streamflow should eventually return to precutting levels. An extended period of decreases in water yield has not occurred after WT. Possible explanations are greater area of watershed in skid trails that were slow to regenerate, reductions in regeneration due to browse by moose, and prolific sprouting of beech and sugar maple, which have greater stomatal resistances than pioneer species (Hornbeck et al. 1997b). At CHL the decreases in water yield after clearcutting did not begin to occur consistently until 1994 or 16 to 17 years after harvest. It is likely that these decreases at CHL are also linked to changes in stomatal resistance or leaf area as the regenerating forest goes through successional changes (Swank et al. 2001).

On a monthly basis, the proportionally largest increases occurred during the low flow months of July through October at both CHL and HBEF. However, increases at CHL occurred in nearly every month while at HBEF the increases were restricted to growing season months. At HBEF there is complete recharge of soil moisture on both treated and control watersheds by the start of the dormant season, thus eliminating opportunities for any yield increases until the beginning of the next growing season.

Peakflow rates at CHL increased by an average of 15% during the first 4 years after clearcutting (Swank et al. 2001). The corresponding value for the WT at HBEF was 29% (Hornbeck et al. 1997b), although increases in peakflow rates were as high as 60% in the first 2 years after WT. The increases in peakflow rates diminished quickly at both CHL and HBEF as regeneration became established and created greater soil water deficits.

Sediment Yield

Sediment yields at CHL are generally higher than at HBEF, most likely because HBEF receives less precipitation, has less steep slopes, and has more stony and coarse-textured soils with higher infiltration capacities. In the 2 years before the clearcutting at CHL, annual sediment yields were 230 and 135 kg/ha (Swank et al. 2001). In contrast, annual sediment yields from control watersheds at HBEF averaged about 25 kg ha/yr over the period 1970 to 1998, with a maximum of 95 kg ha/yr (table 13.4). Clearcutting at CHL caused elevated annual sediment yields during roadbuilding, logging, and for a lengthy period after. During the 5- to 15-year period after clearcutting, sediment yields averaged about 340 kg/ha/yr or nearly 50% above pretreatment levels (Swank et al. 2001). Harvesting at HBEF also resulted in increased sediment with maximum values of 146 kg ha/yr during cutting of the second set of strips on the SC, and 208 kg ha/yr during the third year after performing the WT (table 13.4). The increases in annual sediment yield have moderated more quickly after harvest at HBEF than at CHL (table 13.4; Swank et al. 2001).

Sediment yields at both CHL and HBEF are highly variable from year to year and are not correlated with annual precipitation amounts. Instead, sediment yields are driven by the occurrence of large, individual storms, by site differences, and by the specifics of the particular logging operation producing the sediment (Martin and Hornbeck 1994; Swank et al. 2001).

Soil Chemical Status

Effects of cutting on exchangeable soil cations in upper soil horizons were in opposite directions: an increase at CHL (Knoepp and Swank 1996), and a decrease at HBEF (Johnson et al. 1997). At CHL exchangeable Mg and K remained above pretreatment levels at 17 to 20 years after harvest. The decreases in exchangeable cations in upper horizons at HBEF were short-lived (3 to 8 years) and were countered by increases in deeper horizons, with the end result being no net change in exchangeable cations. Total soil N and C concentrations increased in the upper horizons (0 to 10 cm) at CHL by 50% or more in the first 3 years after harvest and remained near or above preharvest levels for 18 years (Knoepp and Swank 1997). In contrast, there were no changes in N and C concentrations in the forest floor at the eighth year after harvest at HBEF. However, soil N and C pools in the forest floor at HBEF were decreased by 17% and 27% respectively at the eighth year after harvest due to reductions in mass of the forest floor (Johnson 1995).

Differences in responses of soil chemical status between CHL and HBEF may be the result of logging disturbances and harvest intensity. Compared to the WT at HBEF, the cable yarding technique and removal of sawlogs only at CHL cretated less soil disturbance and left more biomass to decompose and supply nutrients. At HBEF, the steep midsection of the WT, where logging disturbances were greatest, experienced the greatest losses of soil N and C. Nutrient pools in the relatively flat upper elevations were unchanged.

Streamwater Nutrients and Nutrient Budgets

Table 13.6 contrasts nutrient ions in streamflow and bulk precipitation for control watersheds at CHL and HBEF. Precipitation and streamflow are dilute at both locations, but HBEF is more acidic due to higher concentrations of SO_4^{-2} and NO_3^- and minimal buffering by HCO_3^-.

Table 13.6 Volume-weighted mean annual concentrations* of dissolved inorganic concentrations for undisturbed watersheds at HBEF and CHL.

	Bulk precipitation		Streamflow	
Substance	HBEF	CHL	HBEF	CHL
Ca^{+2}	0.093	0.194	1.153	0.583
Mg^{+2}	0.025	0.041	0.305	0.326
K^{+}	0.049	0.094	0.192	0.499
Na^{+}	0.088	0.170	0.835	1.220
NH_4^{+}	0.095	0.183	0.016	0.002
H^{+}	0.058	0.027	0.011	0.000
SO_4^{-2}	2.169	1.590	5.859	0.450
NO_3^{-}	1.674	0.143	1.073	0.003
Cl^{-}	0.271	0.262	0.474	0.662
PO_4^{-3}	0.021	0.013	0.003	0.006
HCO_3^{-}	—	0.074	1.620	4.970
Si	T**	0.030	4.592	8.800
pH	4.23	4.57	4.96	>6.00

* Data are means for 1973–1983.
** T = trace
Sources: Data from Likens and Bormann (1995); and Swank and Waide (1988).

Streamwater concentrations and nutrient budgets at HBEF are more responsive to cutting disturbances than at CHL. To illustrate, the WT at HBEF caused streamwater concentrations of nutrient ions to increase by maximums of 3.5 mg/L for Ca^{+2}, 1.5 mg/L for K^{+}, and 30 mg/L for NO_3^{-} Corresponding maximum increases after clearcutting at CHL were 0.4 mg/L for Ca^{+2}, 0.5 mg/L for K^{+}, and 0.7 mg/L for NO_3^{-}. The increases in streamwater concentrations from the treated watersheds translated into increased nutrient losses for the first six years after harvest of 35.9 kg Ca/ha at HBEF versus 12.0 kg Ca/ha at CHL; 25.1 kg K/ha for HBEF versus 8.4 kg K/ha at CHL; and 55.3 kg NO_3-N/ha at HBEF versus 3.8 kg NO_3-N/ha at CHL (Swank et al. 2001, Martin et al. 2000). Swank et al. (2001) attributed the resiliance of nutrient cycles to disturbance at CHL to large pools of organic matter and elements that turn over slowly and to the high rates of net primary productivity and sequestration and storage of nutrients in successional vegetation.

An interesting difference between CHL and HBEF occurred in the nitrogen cycle during regeneration. At the fourth year after both the SC and WT, losses of NO_3-N became less than from mature forests and continued as such for a decade or more (table 13.5). This pattern has been attributed to uptake and sequestration by the regrowing forest (Martin et al. 2000). At CHL, there was a second and more sustained pulse of NO_3-N that began around the 15th year after clearcutting. This pulse, which has not occurred at HBEF, has been attributed to a series of events including reduction in uptake due to mortality of early successional species (including black locust, an important N-fixing species), nutrient release from woody decomposition, elevated soil nitrogen transformations, and reduction in soil C/N ratio (Swank et al. 2001).

In general, the increased nutrient losses via leaching to streamflow are relatively small after harvests at both CHL and HBEF and should not impact productivity in the next rotation. The increased losses represent minute portions of total site nutrient capitals and are small relative to nutrients removed in biomass. The only possible concern might be with losses of base cations from soils at HBEF, where capitals are significantly lower than at CHL.

Stream Invertebrates

At HBEF, WT reduced the species diversity of stream invertebrates, but increased the abundance (Burton and Ulrich 1994). At CHL, clearcutting was accompanied by a greater sediment load than at HBEF and impacted all aspects of the invertebrate habitat and community. However, by 16 years after clearcutting, benthic invertebrate abundance was 3 times higher and invertebrate biomass and production were two times higher than in an adjacent control stream (see Wallace and Ely, chapter 11, this volume).

Conclusions

Despite significant differences in site characteristics between CHL and HBEF, responses to intensive harvests showed several similarities:

- Harvested sites regenerated rapidly, with opportunistic and pioneer species dominating regrowth for the first 20+ years after harvest.
- Water yield increases occurred during the early years after harvest but declined rapidly with regrowth. Changes in species composition eventually resulted in decreases in water yield when compared to mature forests. Water yield increases were proportionally largest during late summer and early autumn. Peakflow rates were increased by 30% to 60% immediately after harvest.
- Sediment yields increased at both locations but were minimized by careful roading and logging practices.
- Harvesting caused contrasting responses in soil chemical status but in general the harvests at both sites did not cause adverse impacts on soil cations, N, or C.
- Streamwater concentrations of Ca^{+2}, K^{+}, and NO_3^{-} and their corresponding output budgets were increased after harvest, but water quality was not adversely impacted and losses from nutrient capitols were relatively small and should not impact site productivity.

Results from both CHL and HBEF show that intensive harvests can be conducted with minimal impact on hydrologic and nutrient cycles and sediment yields. Careful planning of harvesting operations and application of BMP are imperative to achieving these results. It is important to realize that species composition of the regrowing forest will, at least initially, be dramatically changed from that of the previously harvested forest.

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