CHANGES IN NUTRIENT OUTPUTS IN STREAMFLOW AFTER HARVESTING CENTRAL HARDWOODS[1/]

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Abstract.--During winter of 1981-82, two watersheds in a central hardwood forest in Connecticut were harvested, one by clearcutting with whole-tree removal, the other by commercial thinning. Streamflow, precipitation, and soil solution from harvested and control watersheds were sampled for major nutrient ions for 2 years before and 3 years after harvest. Daily streamflow was estimated using the BROOK hydrologic model. Commercial thinning had no detectable impacts on the hydrologic and nutrient ion budgets. However, whole-tree clearcutting increased nutrient outputs in streamflow by 28 kg ha^{-1} or 90% for Ca; 23 kg ha^{-1} or 171% for K; and 15 kg ha^{-1} or 75% for Mg over a 3-year period. Combined losses of NH_4-N and NO_3-N, which were near zero before treatment, were 19 kg ha^{-1}. These losses resulted from both increased concentrations of nutrient ions in streamwater, and from increased water yield. Nutrient ion outputs had nearly returned to pretreatment levels by the end of the third year after whole-tree clearcutting. The increased outputs in streamflow represented < 1% of the total site capitals. The losses are evaluated in terms of effects on regeneration and long-term site productivity.

Keywords: whole-tree clearcutting, commercial thinning, water yield, nutrient cycling, nitrogen, calcium, potassium, regrowth.

INTRODUCTION

Harvesting results in at least two important losses from forest nutrient capitals. The first and usually largest is the removal of nutrients in the harvested product. The second is an increase in nutrients leached to streams and groundwater. Harvest removals have been determined for a variety of sites in the Northeasern United States and Eastern Canada, and can be as much as 5% or more of total nutrient capital (Smith et al. 1986). Leaching losses are less well documented, partly because they are more difficult to measure. However, in the few studies conducted in eastern forest types, intensive harvests have resulted in increased leaching losses ranging from near zero in a loblolly pine forest in South Carolina (Van Lear et al. 1985) to maximums of 0.5 to 1% of total site capital after clearcutting northern hardwoods in New Hampshire (Hornbeck et al. 1986a).

While leaching losses usually are considerably smaller than harvest removals, they may be of equal or greater importance since they come directly from the pool of plant-available nutrients. Also, they occur during a critical period in which there is strong competition for nutrients by the regenerating forest. Thus, a knowledge of leaching losses and the mechanisms involved is needed to help determine harvesting practices that can minimize nutrient leaching and protect site productivity.

In our study we estimated nutrient leaching losses to streams from central hardwood forests in Connecticut using three study watersheds: one undisturbed, one harvested by clearcutting with whole-tree removal, and one harvested by commercial thinning. In addition to nutrient outputs in streams, other collected data included nutrient inputs in precipitation, nutrient

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removals in harvested products, nutrient accumulation in regrowth, and changes in soil solution chemistry as determined by lysimetry. We could thus evaluate leaching losses, their origin within the soil profile, and the effects on nutrient availability and total site capital.

THE STUDY AREA

The three study watersheds are located on the Cockaponset State Forest, Chester, Connecticut. Each is about 6 ha in area and drained by streams that flow continuously except during unusually dry periods in the growing season. Soils grade from the shallow, somewhat excessively drained Hollis-Chatfield-Rock association on the ridges, to the deep, well-drained Chatfield-Canton association on middle slopes, to the poorly drained Leicester series along stream channels. The central hardwood forest at the study site has an average basal area of 25 m^2 ha^{-1} and generally has been undisturbed for the past 80 to 100 years. Further details on the forest and other watershed characteristics are given in Martin et al. (this volume) and Tritton et al. (1982).

Harvesting of the study watersheds was carried out in the winter of 1981-82. On the watershed that was clearcut and whole-tree harvested, all trees > 5 cm dbh were felled and 91% of above-ground biomass was removed. On the watershed subjected to commercial thinning, 16% of the basal area was felled and merchantable boles and branches (10% of above-ground biomass) were removed. Precautions were taken during felling and skidding so that erosion and stream sedimentation were minimized. More details on the logging operation are given in Martin et al. (this volume) and Hornbeck et al. (1986b).

STUDY METHODS

Streamflow was sampled at the base of each watershed for chemical content at biweekly intervals. Precipitation was also sampled biweekly with a polyethylene collector located at a National Weather Service station 2.5 km north of the study watersheds. All samples were analyzed for concentrations of Ca, K, Mg, and Na (determined by atomic absorption spectrophotometry), and NH_4, NO_3, SO_4, PO_4, and Cl (determined by automated colorimetric analysis). Phosphate (PO_4) was always below the detection limit of 0.003 mg L^{-1}.

Because the study watersheds do not have streamgaging stations, daily streamflow was simulated using BROOK, a hydrologic model developed and tested on both forested and harvested watersheds in the eastern United States (Federer and Lash 1978). The required driving variables, daily mean air temperature and daily precipitation, were collected at the National Weather Service station mentioned above. Except for changes in soil depth, the parameters for simulating preharvest streamflow were those used by Federer and Lash (1978) for the Hubbard Brook Experimental Forest in New Hampshire. Three parameters, leaf-area index, stem-area index, and depth of rooting zone, were altered to simulate flow during the post harvest period. The BROOK model is sensitive to variations in leaf-area index, especially during the first few years after cutting. Values of four or greater are used when estimating evapotranspiration for a closed canopy. Values of zero to four are used to represent changing leaf area of a regrowing forest. Measured leaf area index for the regrowth period will usually be unavailable, as was the case for our study. Thus, we arbitrarily chose values of 0.5 for year 1 after harvest, 1.5 for year 2, and 2.2 for year 3.

Daily outputs of nutrients were calculated as the product of average ionic concentration (mg L^{-1}) at the beginning and end of the biweekly sample period times simulated volume (L) of water for the period. Impacts of harvest were determined on an annual basis by obtaining the ratio of outputs of individual nutrients between the watershed to be harvested and the undisturbed control watershed during a 2-year, preharvest calibration period. After harvest, the control watershed values were multiplied by this ratio to estimate what the annual output for the harvested watershed would have been in the absence of cutting. The difference between this estimate and the actual value was attributed to harvest. While our study design does not provide the accuracy of rigorous, long-term ecosystem studies, calculations of annual values by the above methods are well within the accuracy needed to detect and evaluate important changes in nutrient outputs in streamflow (Hornbeck et al. 1987).

RESULTS AND DISCUSSION

Changes in nutrient outputs and water yield for years 1 through 3 after harvest are summarized in Table 1. Commercial thinning, involving felling of 16% of the basal area, had little impact on either water yield or nutrient outputs in streamflow. Maximum changes occurred in the first year after harvest, and amounted to an increase in the loss of K of 2 kg ha^{-1}, and a decrease in the loss of SO_4-S of 4 kg ha^{-1}.

Changes after whole-tree clearcutting were much more dramatic. For the first year after harvst, water yield increased by an estimated 390 mm, or 32% (Table 1). Outputs of all measured cations also increased, with maximums of 13 kg ha^{-1} (260%) for K and 10 kg ha^{-1} (77%) for Ca. Combined losses of NH_4-N and NO_3-N, which were near zero before treatment, were 11 kg ha^{-1} for year 1 after harvest. Chloride showed a

Table 1. Impact of commercial thinning and whole-tree clearcutting on water yield and nutrient outputs in streamflow (water yield data determined from BROOK hydrologic simulation model).

Year after harvest	Water yield			Ca			K		
	If uncut	Actual	Change	If uncut	Actual	Change	If uncut	Actual	Change
	kg ha^{-1}								
				COMMERCIAL THINNING					
1	1210	1220	+10	20	20	0	3	5	+2
2	1020	1020	0	19	19	0	4	4	0
3	580	590	+10	9	9	0	2	3	+1
				WHOLE-TREE CLEARCUTTING					
1	1210	1600	+390	13	23	+10	5	18	+13
2	1020	1240	+220	12	25	+13	6	12	+6
3	580	770	+190	6	11	+5	3	7	+4
	Mg			Na			NH_4-N		
				COMMERCIAL THINNING					
1	10	10	0	30	30	0	0	0	0
2	10	10	0	23	23	0	0	0	0
3	5	5	0	13	13	0	0	0	0
				WHOLE-TREE CLEARCUTTING					
1	8	13	+5	29	40	+11	0	3	+3
2	8	16	+8	23	32	+9	0	1	+1
3	4	6	+2	13	16	+3	0	0	0
	NO_3-N			SO_4-S			Cl		
				COMMERCIAL THINNING					
1	0	0	0	38	34	-4	40	37	-3
2	0	0	0	34	33	-1	33	32	-1
3	0	0	0	19	19	0	17	15	-2
				WHOLE-TREE CLEARCUTTING					
1	0	8	+8	32	31	-1	37	55	+18
2	0	6	+6	29	42	+13	31	29	-2
3	0	1	+1	16	23	+7	16	14	-2

substantial increase of 18 kg ha^{-1} (49%) in year 1, while output of SO_4-S was reduced slightly.

In the second year after harvest, nutrient losses began to moderate for all elements except Ca, which showed an increase of 13 kg ha^{-1} (108%); Mg, which showed an increase of 8 kg ha^{-1} (100%); and SO_4-S, which showed an increase of 13 kg ha^{-1} (44%). For year 3, all elements except Cl continued to show increased losses. However, the increases were markedly lower than in the previous 2 years, indicating a rapid return to preharvest levels.

Causes of Changes in Nutrient Outputs

Increases in nutrient outputs result from a combination of increased streamflow available to transport nutrient ions, and from changes in nutrient ion concentrations in streams. In our study, the increases in nutrient outputs usually were greater than could be explained solely by increased volume of streamflow. Thus, changes in ion concentrations in streams also played an important role in nutrient leaching losses.

Postharvest changes in streamwater concentrations are mediated by processes (usually biological) that increase mobile anions in soil solution. The anions associate with base cations on an equivalent basis, move to streams, and leave the ecosystem. Anions commonly controlling cation leaching in forest ecosystems include SO_4 (Cronan 1980); NO_3 (Vitousek and Melillo 1979); HCO_3 (Cole et al. 1975); and Cl (Johnson 1981).

In our whole-tree clearcutting experiment, all of these anions appeared to be involved in changes in nutrient outputs occurring after

Table 2. Impact of whole-tree clearcutting on mean annual concentrations of anions in streamflow.

Year after harvest	NO_3 If uncut	NO_3 Actual	NO_3 Change	SO_4 If uncut	SO_4 Actual	SO_4 Change
	mg L^{-1}					
1	0	2.1	+2.1	7.7	5.8	-1.9
2	0	2.2	+2.2	8.3	10.2	+1.9
3	0	0.4	+0.4	8.0	9.0	+1.0
	Cl			HCO_3		
1	3.1	1.5	+0.4	1.2	5.5	+4.3
2	3.1	2.4	-0.7	0.9	3.7	+2.8
3	2.8	1.8	-1.0	0.8	2.5	+1.7

harvest. During the first year after harvest, NO_3, Cl, and HCO_3 in streamflow showed an increase, and SO_4 showed a slight decrease (Table 2). In years 2 and 3, NO_3, HCO_3, and SO_4 increased, while Cl decreased. The increases in NO_3 are due to increased nitrification rates that accompany forest harvest throughout New England and elsewhere (Vitousek et al. 1982; Hornbeck et al. 1986a). Increases in HCO_3 may result from increased organism respiration in the favorable, postharvest environment (McColl and Cole 1968). Laboratory incubations suggested that respiration in organic horizons increased by one-third after whole-tree clearcutting (Hornbeck et al. 1983).

Explanations for the first year increase but second- and third-year decreases in Cl are less clear, especially since Cl usually is not involved in biologic processes. The study area is near the ocean and receives substantial inputs of seasalt. Harvesting may have triggered a first-year flush of surplus Cl that had accumulated from inputs in precipitation or as aerosols. The pattern for SO_4 also is complex. The decrease in concentration that occurred in year 1 also occurred after harvesting northern hardwoods (Hornbeck et al. 1986a), and is partly a dilution effect. The increases in subsequent years probably are due to oxidation of sulfide or reduced sulfur compounds to SO_4 (Tamm 1979).

Most of the ion mobilization appears to originate in the upper and middle soil horizons. Our study included installation of suction cup-type lysimeters at 15-cm intervals to a maximum soil depth of 75 cm at three locations on each watershed. Chemical analyses of soil solution

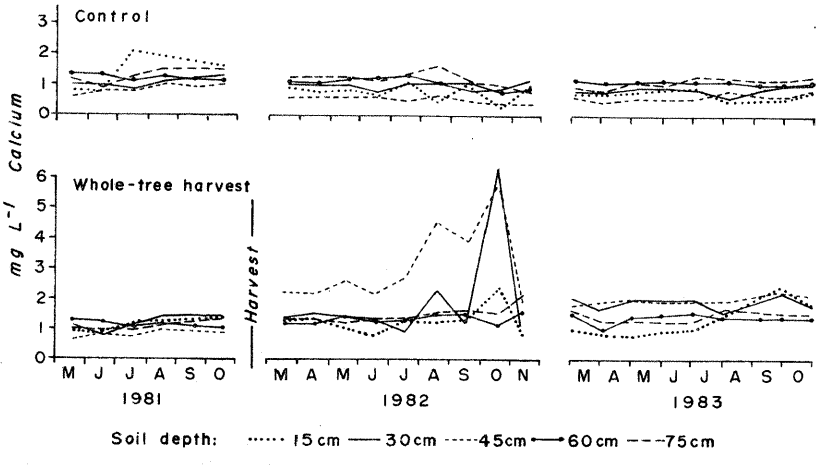

Figure 1. Concentrations of Ca in soil solution.

extracted with the lysimeters showed that changes in concentrations of all ions were most pronounced at depths of 30 and 45 cm. Figure 1 shows data for Ca, which typifies the patterns for most ions. The absence of elevated concentrations above 30 cm suggests increased uptake by shallow-rooted, early regrowth. By contrast, root uptake below 30 cm is minimal in the first few years after harvest, allowing ion concentrations to increase and move directly to streams and groundwater.

The Importance of Nutrient Losses

One approach to evaluating the importance of increased nutrient outputs is to contrast them with other pools comprising the ecosystem nutrient capital. Table 3 gives data on nutrient capital for N, Ca, and K, the nutrient elements impacted most by harvest.

The increased nutrient outputs in streamflow were a much smaller portion of the total nutrient capital than were harvest removals. For whole-tree clearcutting, the 3-year sum of the increased outputs in streamflow (Table 3) represented 0.5% of total N capital, 0.7% of total Ca, and 0.4% of total K. By contrast, harvest removals represented 5.5% of total N capital, 12.5% of total Ca, and 3.0% of total K.

Opportunities for replacing the lost capital over the next growth rotation are best for N. Data on inputs in precipitation versus outputs in streamflow from the control watershed (Table 3) indicate that once the effects of harvest subside, nearly all N in preciptation will stay within the forest and add to the total nutrient capital. However, K and Ca would continue to show net annual losses. In the case of Ca, continued net losses, such as the average 11.7 kg ha^{-1} yr^{-1} (Table 3) that occurred from the control watershed over our 5-year study period, could have a serious impact on total Ca capital. The occurrence of permanent net annual losses of Ca and K emphasizes the need to minimize additional losses that occur at the time of harvest.

An immediate concern is whether there will be adequate nutrients to sustain optimum regrowth. Our studies of nutrient uptake on the

Table 3. Summary of nutrient removals, nutrient outputs in streamflow, and nutrient pools.

Element	N		Ca		K	
Commercial thinning (CT), or Whole-Tree Clearcutting (WTC)	CT	WTC	CT	WTC	CT	WTC
	kg ha^{-1}					
Removal by harvest	26	273	96	530	17	162
Increases in stream nutrient outputs, summed over 3 years	< 1	19	< 1	28	3	23
Total due to harvest	26	292	96	558	20	185
	Estimated Preharvest Nutrient Pools, kg ha^{-1}					
Above-ground vegetation	303		589		180	
Roots	121		236		72	
Soil organic horizons						
Available	NA		58		39	
Total	995		96		72	
Soil mineral horizons						
Available	NA		118		93	
Total	3570		3318		5045	
Total site capital	4989		4239		5369	
	Control Watershed kg ha^{-1} yr^{-1}					
Dissolved ion input, precipitation	7.9		2.1		3.8	
Dissolved ion output, streamflow	0.1		13.8		4.4	
Net	+7.8		-11.7		-0.6	

whole-tree harvest site indicate that by year 3 after harvest, nutrient content of regrowth was 64 kg N ha^{-1}, 34 kg Ca ha^{-1}, and 38 kg K ha^{-1} (Martin et al., this volume). Since amounts stored in above-ground biomass may represent as little as 10-20% of total uptake (the remainder is returned to the forest floor in litterfall or throughfall) (Waring and Schlesinger 1985), substantial demands are being made on the available nutrient capital immediately after harvest. For example, we estimate that total K uptake over the first 3 years may have been as much as 170 kg ha^{-1}. This exceeds our estimates of available K in the soil profile (Table 3), and gives added significance to the 23 kg ha^{-1} of K that was lost from the available pool to streamflow as a result of harvest.

In the years immediately following harvest, the size of available nutrient pools should increase temporarily due to increased rates of weathering, mineralization, and nitrification. The extent of these increases are not presently known. Thus, intensive harvests of central hardwoods, such as clearcutting with whole-tree removal, presents something of a risk. Our data suggest that there is potential for nutrient shortages in the years immediately after harvest. Further, large imbalances in the input-output budgets for elements such as Ca (Table 3) suggest that nutrient shortages also could develop in future years. The losses of nutrients that occur as a result of increased leaching and harvest removals exacerbate these problems.

Forest managers should use care in applying intensive harvests and removals in central hardwoods until more is known about impacts on nutrient cycles. Precautions such as use of group selection or shelterwood cutting, leaving harvest residues on site, and maintaining rotation lengths adequate for nutrient cycle recovery will minimize the occurrence and impacts of increased nutrient outputs in streamflow.

LITERATURE CITED

Cole, D. W., W. J. B. Crane, and C. C. Grier.
1975. The effect of forest management practices on water chemistry in a second-growth Douglas-fir ecosystem. In: Forest soils and land management. B. Bernier and C. H. Winget, eds. Les Presses de L'Univ. Laval, PQ. p. 195-207.

Cronan, C. S.
1980. Solution chemistry of a New Hampshire subalpine ecosystem: A biogeochemical analysis. Oikos 34:272-281.

Federer, C. A., and D. Lash.
1978. Simulated streamflow response to possible differences in transpiration among species of hardwood trees. Water Resour. Res. 14:1089-1097.

Hornbeck, J. W., C. A. Federer, and R. S. Pierce.
1987. Effects of whole-tree clearcutting on streamflow can be adequately estimated by simulated. Proceedings of symposium on forest hydrology and watershed management. International Association of Hydrological Sciences, Vancouver, Canada. August, 1987. Submitted.

Hornbeck, J. W., C. W. Martin, R. S. Pierce, F. H. Bormann, G. E. Likens, and J. S. Eaton.
1986a. Clearcutting northern hardwoods: Effects on hydrologic and nutrient ion budgets. For. Sci. 32:667-686.

Hornbeck, J. W., C. W. Martin, and C. T. Smith.
1986b. Protecting forest streams during whole-tree harvesting. North. J. Appl. For. 3:97-100.

Hornbeck, J. W., F. Peterson, and N. T. Edwards.
1983. Effects of whole-tree harvesting on soil carbon transfer. Bull. Ecol. Soc. of Am. 64:189.

Johnson, D. W.
1981. The natural acidity of some unpolluted waters in southeastern Alaska and potential impacts of acid rain. Water, Air, and Soil Pollut. 16:243-252.

Martin, C. W., L. M. Tritton, and J. W. Hornbeck.
1987. The dynamics of revegetation after whole-tree harvest of a central hardwood forest in Connecticut. Proceedings, 6th central hardwood forest conference. Univ. of Kentucky, Lexington.

McColl, J. G. and D. W. Cole.
1968. A mechanism of cation transport in a forest soil. Northwest Sci. 42:134-140.

Smith, C. T., M. L. McCormack, J. W. Hornbeck, and C. W. Martin.
1986. Nutrient and biomass removals from a red spruce-balsam fir whole-tree harvest. Can. J. For. Res. 16:381-388.

Tamm, C. O.
1979. Nutrient cycling and productivity of forest ecosystems. In: Proceedings, impact of intensive harvesting on forest nutrient cycling. A. Leaf, ed. SUNY Coll. of Environ. Sci. and For., Syracuse. p. 2-21.

Tritton, L. M., C. W. Martin, J. W. Hornbeck, R. S. Pierce, and C. A. Federer.
1982. Organic matter and nitrogen content of a central hardwood forest in Connecticut. In: Proceedings, 4th central hardwood forest conference. Univ. of Kentucky, Lexington. p. 271-284.

Van Lear, D. H., J. E. Douglass, S. K. Cox, and M. K. Augspurger.
1985. Sediment and nutrient export in runoff from burned and harvested pine watersheds in the South Carolina Piedmont. J. Environ. Qual. 14:169-174.

Vitousek, P. M., J. R. Gosz, J. M. Melillo, and W. A. Reiner.
1982. A comparative analysis of potential nitrification and nitrate mobility in forest eocystems. Ecol. Monogr. 52:155-177.

Vitousek, P. M. and J. M. Melillo.
1979. Nitrate losses from disturbed forests: patterns and mechanisms. For. Sci. 25:605-619.

Waring, R. H. and W. H. Schlesinger.
1985. Forest ecosystem concepts and management. Academic Press, Orlando, FL. 340 p.