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Forest Ecology and Management 143 (2001) 163–178

Forest Ecology
and
Management

www.elsevier.com/locate/foreco

Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment

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Abstract

Long-term changes (~20 years) in water yield, the storm hydrograph, stream inorganic chemistry, and sediment yield were analyzed for a 59 ha mixed hardwood covered catchment (Watershed 7) in the southern Appalachian mountains (USA) following clearcutting and cable logging. The first year after cutting, streamflow increased 26 cm or 28% above the flow expected if the forest had not been cut. In subsequent years, discharge increases declined at a rate of 5–7 cm per year until the fifth year when changes in flow returned to baseline values. Later in forest succession, between ages 15 and 18 years, both significant increases and decreases in annual water yield were observed; these discharge dynamics are discussed in relation to vegetation regrowth dynamics. Flow responses predicted from an empirical regional scale model were within 17% of experimental values during the first 4 years of regrowth. Intra-annual analysis showed that proportionally larger increases (48%) in flow occurred in the low flow months of August–October. Storm hydrograph analysis showed that, on an average, initial flow rate and peakflow rates increased 14–15% and stormflow volume increased 10%.

Analyses of stream solute concentrations and catchment nutrient fluxes showed small increases in nutrient losses following clearcutting and logging. Responses were largest the third year after treatment with annual values of 1.3, 2.4, 2.7, 3.2, 1.4, 0.39, and 2.1 kg ha⁻¹ for NO₃-N, K, Na, Ca, Mg, S, and Cl, respectively. Explanations for the retention of nutrients and high ecosystem resistance and resilience are discussed in relation to internal biogeochemical cycles based on long-term process level studies on the catchment. A second, sustained pulse of NO₃⁻ to the stream (exceeding post-harvest values) observed later in succession is also discussed in the context of ecosystem processes. Large increases in sediment yield were measured immediately after road construction due to two major storm events. Subsequently, during logging, sediment yield from roads was greatly reduced and insignificant when logging activities were completed. In contrast, cumulative increases in sediment yield were observed downstream over the next 15 years which illustrate the lag between pulsed sediment inputs to a stream and the routing of sediments through a stream system. The relevance of sedimentation to stream sustainability is discussed in the context of long-term responses in the benthic invertebrate community structure and productivity measured on WS7. Published by Elsevier Science B.V.

Keywords: Water yield; Storm hydrograph; Stream chemistry; Sediment yield; Mixed deciduous hardwoods; Forest cutting

1. Introduction

The need for knowledge to guide water resources planning on forested lands in the US is embedded in numerous federal and state legislative mandates and

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environmental statutes. Specifically, information on effects of silvicultural prescriptions on the quantity, quality, and timing of streamflow is at the forefront of planning needs. Watershed ecosystem analysis provides a scientific tool for quantifying forest resource responses to management and subsequent communication of findings to planners and practitioners (Hornbeck and Swank, 1992). Catchment scale analyses are also useful in addressing the emerging paradigm of ecosystem management in federal resource management agencies (Meyer and Swank, 1996) and issues of sustainability (Christensen et al., 1996).

In 1975, a long-term interdisciplinary study of forest watershed ecosystem response to clearcut cable logging on Watershed 7 (WS7) was initiated at the Coweeta Hydrologic Laboratory in the southern Appalachian mountains of North Carolina. One philosophical component of the research approach is that the quantity, timing, and quality of streamflow provides an integrated measure of the success or failure of land management practices (Swank and Crossley, 1988). Moreover, we have attempted to integrate individual research efforts on ecosystem structure and function into a holistic evaluation of catchment response. The practical experiment conducted on WS7 was established to test multiple hypotheses derived from previous ecosystem research at Coweeta. In this paper our objectives are (1) to describe and evaluate the long-term water yield, storm hydrograph, and water quality responses to management, and (2) to suggest cause-and-effect relationships by integrating

catchment level responses with previously conducted process level research within the catchment.

2. Site description

The study area is located in the 2185 ha experimental area of the Coweeta Hydrologic Laboratory which is in the Nantahala Mountain Range of western North Carolina within the Blue Ridge Physiographic Province, latitude 35°03'N, longitude 83°25'W. Climate at Coweeta is classed as Marine, Humid Temperate and characterized by cool summers, mild winters and abundant rainfall in all seasons (Swift et al., 1988). Average annual precipitation varies from 1700 mm at lower elevations (680 m) to 2500 mm on upper slopes (>1400 m). The hydrology is dominated by rain events; snow usually comprises less than 5% of the precipitation. The underlying bedrock is the Coweeta Group (Hatcher, 1979) which consists of quartz diorite gneiss, metasandstone and pelitic schist, and quartzose metasandstone (Hatcher, 1988). The regolith of the Coweeta basin is deeply weathered and averages about 7 m in depth.

The study site is Coweeta WS7, a 59 ha south-facing catchment drained by a second-order stream. Stream discharge measurements began on WS7 in 1935, shortly after establishment of Coweeta. A summary of the physical and hydrologic characteristics of the catchment are given in Table 1. Prior to logging in 1977, the only management disturbance on WS7 since

Table 1
Physical and hydrologic^a characteristics of WS7 and WS2, Coweeta Hydrologic Laboratory, Otto, NC

Characteristics	Watershed	
	WS7	WS2
Area (ha)	59.5	12.3
Slope (%)	57	60
Aspect	South-facing	South-southeast-facing
Elevation range (m)	724–1060	716–991
Main stream channel length (m)	1225	480
Soils	Typic Hapludult and Typic Dystrochrept	Typic Hapludult and Typic Halumbrept
Mean annual precipitation (cm)	189	181
Mean annual flow (cm)	106	99
Range in annual flow (cm)	76–149	59–130
Range in mean daily discharge ($1 \text{ s}^{-1} \text{ km}^{-1}$)	5–247	5–220
Mean annual quickflow volume (cm)	6.8	8.1
Mean annual evapotranspiration (cm)	83	82

^a Based on May–April water year from 1966 through 1976.

Forest Service acquisition of the land in 1924 was a woodland grazing experiment. Six cattle were grazed intermittently over the lower portion of the catchment from 1941 to 1949. Impacts were short-lived and limited to soil compaction and overgrazing in the cove forest community (Johnson, 1952; Williams, 1954). Twenty-five years after termination of the experiment, there were no measurable effects of grazing on stream chemistry or flow characteristics (Swank and Douglass, 1977). Prior to clearcutting in 1977, the vegetation was characterized by three plant communities (Boring et al., 1981; Elliott et al., 1997): (1) cove-hardwoods found at lower elevations adjacent to the streams and along ravines at intermediate elevations were dominated by *Liriodendron tulipifera* L., *Carya* spp., and *Quercus rubra* L.; (2) mixed-oak hardwoods on mesic southeast-facing and north-facing slopes at intermediate elevations dominated by *Q. velutina* Lam., *Q. prinus* L., *L. tulipifera*, and *Carya* spp.; (3) hardwood-pine on xeric southwest- and south-facing slopes at intermediate to upper elevations and ridgetops dominated by *Q. prinus*, *Q. coccinea* Muenchh, *Acer rubrum* L., and *Pinus rigida* Miller. Precut basal area for the combined communities averaged $25 \text{ m}^2 \text{ ha}^{-1}$ in 1974.

3. Treatment description

The commercial clearcut logging on WS7 was initiated to gain new and additional information on hydrologic, biogeochemical, and ecological processes and responses of mixed deciduous forests associated with disturbance. Watershed 7 was the only catchment available with pre-treatment calibration for a variety of ecological processes and functions. The size of the treated area exceeded National Forest Systems guidelines (<15 ha) at the time this study was initiated. Management prescriptions for the catchment were

applied in three phases: (1) road construction and stabilization; (2) tree felling and logging; (3) site preparation. Three roads with a total length of 2.95 km were constructed between April and June 30, 1976 for logging access. Best Management Practices and new features of road design standards developed at Coweeta were incorporated into road construction activities (Swift, 1984a). The roadbed was 4–5 m wide and drained by out-sloping (no inside ditchlines) and broad-based dips. Metal pipe culverts were installed at three crossings on the perennial stream. Immediately after construction, grass was seeded and commercial fertilizer 10–10–10 (N–P–K) and lime applied on cut-and-fill slopes by a hydroseeder. Roads were seeded by mid-May 1976, but record storms (38 cm) in the last 2 weeks of May eroded both unstable soil and hydroseeded materials from the roads.

Timber cutting and yarding with a mobile cable system began in January 1977 and was completed the following June. The cable system yarded logs up to 300 m from a road and could suspend logs completely above the ground. Tractor skidding was used on about 9 ha, where slopes were less than 20%. Due to insufficient volume of marketable timber, 16 ha on upper slopes and ridges were cut but all wood was left on the ground. Site preparation consisted of cutting all stems remaining after logging to encourage regeneration and this treatment was completed in October 1977. At the conclusion of the timber sale, roadbeds were reshaped and a light application of grass and fertilizer was applied to disturbed roadbeds and ungraveled sections of the roadbed. Subsequent road use has been access to the experimental area by light-weight vehicles.

Disturbance (mineral soil exposure) associated with each prescription activity was estimated from transects distributed across the catchment area. Half of the exposed soil area was on permanent roads (Table 2), which also were the only significant sources of surface

Table 2
Management activities and exposed mineral soil (disturbance) on WS7, Coweeta Hydrologic Laboratory, Otto, NC (after Swank et al., 1982)

Activity	Total area of activity (ha)	Total area disturbed (ha)	Percentage disturbance
Permanent road	2.9	2.9	100.0
Cable yarded (uphill)	27.8	1.5	5.6
Cable yarded (downhill)	4.9	0.4	8.5
Tractor skidded	8.9	1.0	10.8
Felled — not logged	15.9	0	0

soil compaction and overland flow during storm events.

4. Methods

4.1. General

The paired or control (reference) catchment method of analysis (Reinhart, 1967; Hewlett et al., 1969) was used to quantify the effects of treatment on quantity, timing, and quality of streamflow. With this method, stream characteristics of interest are measured for a period of years on two catchments located close together that are similar in soil, vegetation, and aspect. The relationship of stream attributes between the catchments for the calibration (pre-treatment) period is determined by regression analysis which incorporates experimental control for climatic and biological variation within and between years. Following calibration, the control remains untreated while the other catchment is treated. The difference between magnitude of observed and predicted response for the stream variable of interest is the treatment effect.

4.2. Water yield

Watershed 2 (WS2), a 12.6 ha catchment adjacent to WS7 served as the experimental control for assessing hydrologic and water quality responses to the treatment on WS7. A summary of physical and hydrologic characteristics of WS2 are given in Table 1. The calibration period for hydrologic analysis spanned 11 years from 1966 to 1976. Mean annual discharge from WS2 during this period averaged 99 cm and ranged from 59 to 130 cm (Table 1). The coefficient of determination (r^2) for total annual flow between the two catchments during the calibration period was 0.99. The error term ($p < 0.05$) for predicted individual annual flows for treatment years averaged ± 5 cm. Regression analysis using monthly flow data was used to quantify the within-year changes; r^2 during the calibration period ranged from 0.96 to 0.99.

4.3. Hydrograph

The paired basin approach was also used to assess changes in the storm hydrograph due to treatment.

Hydrograph parameters were derived from the separation techniques and computer compilation methods described by Hewlett and Hibbert (1966) and Hibbert and Cunningham (1966). The technique uses a flow separation line of $0.55 \text{ l s}^{-1} \text{ km}^{-1}$ and includes the following parameters: quickflow (stormflow), delayed flow (baseflow), time to peaking, duration of quickflow, initial flow rate, peakflow rate, total volume of quickflow, duration of quickflow and recession time. All hydrographs derived from precipitation events ≥ 2 cm were selected to assure that only storms producing single separations were analyzed. Using this process, 223 storms were available for the calibration or pre-harvest period, and 75 storms were used for the first 4 years after harvest. The significance testing procedure described by Gjarati (1970) and Swindel (1970) was used to test for equality between sets of linear coefficients (slopes and intercepts) using the F -statistic.

4.4. Stream chemistry

Stream chemistry measurements began on both WS7 and WS2 in 1971. Weekly grab samples have been collected since late 1971 and flow proportional samples in the period 1975–1981. Solute determinations include base cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+) and NO_3^- , NH_4^+ , SO_4^{2-} , PO_4^{3-} , and Cl^- using established analytical methods at Coweeta (Deal et al., 1996). Pre-treatment calibration regression equations of flow weighted solute concentrations ($\mu\text{eq l}^{-1}$) and export (kg ha^{-1}) were used to quantify ecosystem responses and effects of cutting on stream chemistry. Calibration r^2 's for most solutes exceeded 0.88.

4.5. Soil loss

Effects of management on soil loss to streams were determined by periodically measuring sediment accumulations in the weir ponding basin and on the approach apron to the ponding basin. Ponding basin sediment represented both bedload and some suspended sediment, but excludes suspended sediment that passed across the weir blade. Thus, total sediment loss is underestimated. Sediment volumes were quantified by measuring sediment elevations along transects with a transit and level rod before and after cleaning the ponding basin. Bulk density samples

collected at each elevation measurement were used to estimate weight. The pre-treatment calibration regression of periodic sediment loss over a 2-year period between WS7 and WS2 had an r^2 of 0.91. Samplers were also installed on sub-drainages within WS7 to separate soil losses from roads versus logging. Discharge and soil export of four sub-drainages within WS7 were measured with a 0.30 m H flume and a 0.61 m coshocton wheel using procedures described by Douglass and Van Lear (1983) and Douglass and Goodwin (1980). One installation was located in a perennial stream below the middle logging road on WS7 and three installations (one perennial and two intermittent streams) were placed above the influence of logging roads to evaluate effects of cutting and logging only.

5. Results and discussion

5.1. Annual water yield

In the first full water year (1978) following logging, streamflow on WS7 increased about 26 cm, or 28% above the flow expected without forest cutting (Fig. 1). Thereafter, annual discharge increases declined at a rate of 5–7 cm per year until the fifth year after cutting when annual flow was only 4 cm above pre-treatment levels. In subsequent years, changes in flow were not significant ($p>0.05$) and discharge oscillated around

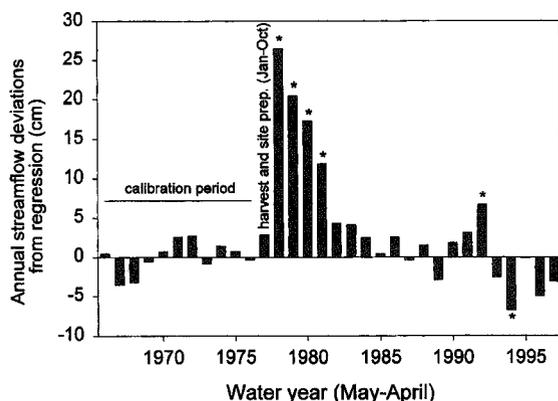


Fig. 1. Annual changes in streamflow on WS7 following clearcutting and commercial logging, Coweeta Hydrologic Laboratory, Otto, NC, 1967–1995 (*denotes significant change, $p<0.05$).

baseline conditions until 1992 when a significant increase (6.6 cm) in streamflow was observed for the 15-year-old successional forest, followed by a significant decrease (6.7 cm) in 1994 (Fig. 1). In 1996–1997, flows were below pre-treatment levels although they are not statistically significant ($p>0.05$).

The magnitude and initial recovery of annual streamflow after clearcutting on WS7 are generally consistent with other experimental results at Coweeta and in other locations of the Appalachian region of the US (Douglass and Swank, 1975; Hornbeck et al., 1993). The largest water yield increases occurred the first year after cutting when evapotranspiration (Et) was most reduced due to minimal leaf area index (LAI). As sprouts and seedlings regrew, LAI and Et increased, and streamflow increases declined logarithmically over time. Earlier syntheses of catchment experiments in the Appalachian Highlands Physiographic region (Douglass and Swank, 1972, 1975) provide empirical relationships between first-year water yield increases as a function of percent basal area cut and an insolation index (energy variable) for a catchment. Another empirical model was developed (Douglass and Swank, 1975) for predicting the yield for any year after harvest until streamflow returns to baseline levels. These empirical models lack data from south-facing clearcut catchments with natural forest succession. However, results of these models agreed well with the annual water yield responses on south-facing WS7 (Fig. 2). In the first year after cutting, the

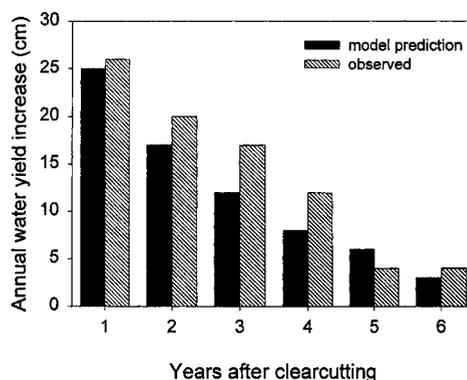


Fig. 2. Comparison of observed annual increases in water yield on WS7 with predicted values derived from an empirical model for mixed hardwood forests, Coweeta Hydrologic Laboratory, Otto, NC, 1978–1983 water years.

predicted versus observed increases were within 1 cm. In subsequent years, predicted values tended to be below observed flow increases but the total change predicted for the entire 6-year period (71 cm) was within 17% of the observed change (85 cm). Considering the limitations of the models (Douglass, 1983) and that both predicted and observed values contain error terms, WS7 results support the general use of these models in forest management planning for southern Appalachian hardwood ecosystems.

However, empirical models do not capture the longer-term dynamics of forest succession, water use, and streamflow. For example, we attribute the significant increase in 1992, when the forest was 15 years old, to a reduction in stem density and LAI associated with natural competition (stem exclusion stage) of fast growing coppice vegetation. Net primary production (NPP) and LAI recovered rapidly during the first 3 years of regrowth on WS7, especially by herbaceous species on mesic sites (Boring et al., 1988). Subsequently, stand structure and species composition have changed substantially (Elliott et al., 1997). Stem density of woody species decreased from 70 000 stems ha^{-1} at age 8 to 20 000 stems ha^{-1} at age 17; high stem density is due to inclusion of *Kalmia latifolia* L. and *Rhododendron maximum* L., two common understorey evergreen species. Based on visual observations, the majority of the mortality occurred between ages 12 and 14 years. We hypothesize a concomitant decrease in LAI and Et which resulted in small but statistically significant increases in discharge in 1992. Similar relationships between changes in stand structure, water use, and streamflow have been found in another long-term clearcutting experiment at Coweeta (Swank and Helvey, 1970).

Reasons for the significant reductions in flow in 1994, and continued patterns of reduced flow to the present, are less clear. Previous long-term water yield studies following clearcutting at Coweeta have not shown later reductions in flow (Swank et al., 1988). Canopy openings created during the stem exclusion stage of succession were quite transient and stand basal area increased to 23 $\text{m}^2 \text{ha}^{-1}$ at age 17 which is comparable to the 25 $\text{m}^2 \text{ha}^{-1}$ basal area of the original forest (Elliott et al., 1997). Plausible hypotheses for higher Et for the regrowing versus mature forest include greater LAI for the regrowth and/or higher

transpiration loss associated with species changes. A preliminary estimate of LAI for the regrowth on WS7 in 1993 is 6.0 (unpublished data), which is in the range (5.0–6.0) of mature mixed hardwood forests at low elevations in Coweeta. However, large species differences exist between the coppice (17-year-old) and mature forests. The most notable shifts are proportionally more basal area of *L. tulipifera*, *Robinia pseudoacacia* L., and *A. rubrum* L. in the young forest along with large reductions in basal area of *Carya* and *Quercus* spp. In the two most extensive community types (cove-hardwoods, and mixed-oak hardwoods), *L. tulipifera* plus *R. pseudoacacia* increased from an average of 8% of total basal area in the mature forest to 24% in the 17-year-old forest with a concurrent decline from 24 to 4% for combined *Carya* and *Quercus* spp. Thus, higher transpiration rates due to these species changes from the mature forest could reduce flows. Species-specific transpiration data are generally lacking at Coweeta but other catchment scale experiments provide linkages between annual water yield reductions of successional forests associated with increased transpiration. For example, Hornbeck et al. (1997) found small but measurable reduced annual flows for successional northern hardwood forests 4–10 years after harvest with long-term sustained reductions in subsequent years. Based on differences in stomatal resistance data of northern hardwood species, they present evidence for greater growing-season transpiration of early successional species compared with species composition of the pre-harvest forest.

5.2. Monthly water yield

The within-year distribution of flow increases on WS7 (data not shown) are similar to other cutting experiments at Coweeta (Swank et al., 1988) during the first three post-treatment years. Flow increases occurred in nearly every month, with the smallest changes in the spring months of April and May, when soil moisture beneath the undisturbed forest is fully recharged. With progression of the growing season, streamflow increases became larger (generally >2 cm) due to reduced Et. Increases continued into the fall and early winter with monthly values greater than 2.5 cm. They began diminishing as soil moisture storage differences between the cut and uncut forest

decreased. The proportionally largest increases in flow during the low flow months of August–October were most important; streamflow increased about 48%, at a time when flow from undisturbed forests is normally lowest.

5.3. Storm hydrograph

Using pre-treatment storm data, each hydrograph parameter on WS7 was regressed against the same parameter on WS2, the control catchment. A total of 75 storms (≥ 2 cm) in the first 4 years after treatment (period of maximum water yield increase) were available for post-treatment hydrograph analysis. Following harvest, statistically significant changes in regression intercepts and slopes were found for the initial flow rate (flow prior to a storm); quickflow before and after the peak; total quickflow; peakflow rate; duration of quickflow; and recession time (Table 3). Time to peak was the only parameter that did not change significantly.

The largest increases occurred for peakflow (15%) and initial flow rate (14%); the latter is an indication of elevated rates of baseflow from the basin. Quickflow (stormflow) volume increased an average of 10% and most of the change occurred on the recession limb of the hydrograph which was associated with a 10% increase in recession time (Table 3). These responses are of rather minor importance to downstream

flooding. For example, during the first 4 years after clearcutting the average precipitation storm ≥ 2 cm increased the quickflow volume by only 0.03 cm or $2.43 \text{ m}^3 \text{ ha}^{-1}$ and the peakflow rate by $0.017 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$. The composite change for the average storm hydrograph for WS7 is depicted in Fig. 3.

Compared to other cutting experiments at Coweeta (Table 4), WS7 hydrograph responses are most similar to WS37 a high elevation, high rainfall basin with thin soils that was clearcut without road construction or timber harvest (Hewlett and Helvey, 1970). The response factor (ratio of mean quickflow volume to mean rainfall) for the uncut forest on WS37 (Table 4) was much higher (0.19) than for WS7 (0.04). Although the percent increase in quickflows following clearcutting of both catchments were about the same (10%), mean storm peakflow rates were about double on WS7 (15% versus 7%). However, the harvesting effect on WS7 quickflow volume and peakflow rate was only about one-half that for another Coweeta catchment (WS28) where 65% of the basal area was commercially logged with tractor skidding and a high road density (Douglass and Swank, 1976). The average response factor (0.09) for the uncut forest on WS28 was intermediate to WS7 and WS37. Quickflow volume increased an average of 17% over the 9-year post-treatment period on WS28; mean peakflow rates increased 30% the first 2 years after treatment (Table 4) and then declined.

Table 3

Storm hydrograph parameters and changes over the first 4 years following clearcutting and logging on WS7, Coweeta Hydrologic Laboratory, Otto, NC

Parameter	Mean for treatment watershed		Significance of regression coefficients		Percent change in parameter after treatment for mean storm ^a
	WS7	WS2	Intercept	Slope	
Initial flow rate ($\text{m}^3 \text{ s}^{-1} \text{ km}^{-2}$)	0.037	0.27	**	**	14
Peakflow rate ($\text{m}^3 \text{ s}^{-1} \text{ km}^{-2}$)	0.136	0.127	**	*	15
Time to peak (h)	8.0	8.0	NS ^b	NS	0
Total quickflow volume (cm)	0.32	0.40	**	**	10
Quickflow before peak (cm)	0.08	0.09	**	**	6
Quickflow after peak (cm)	0.24	0.31	*	NS	11
Quickflow duration (h)	27.6	28.3	**	*	5
Recession time (h)	20.0	21.0	**	NS	10

^a Derived from difference between value predicted from calibration regression and measured value.

^b Nonsignificant.

* $p < 0.05$.

** $p < 0.01$.

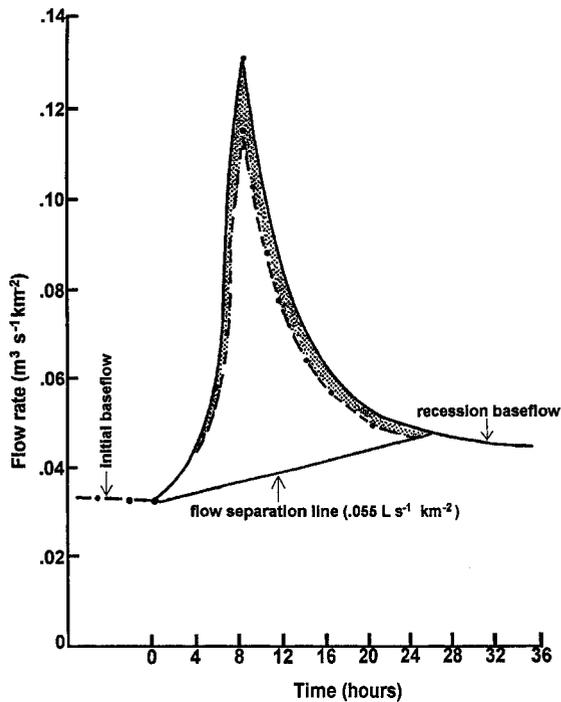


Fig. 3. Average storm hydrographs for WS7 during the pre-cutting period of 1966–1976 (—) and the first 4 years after clearcutting (---) for storms ≥ 2 cm. The shaded portion represents the increases in quickflow volume, peakflow rate, storm duration, and recession time (after Swank et al., 1982).

Storm hydrograph responses to harvest appear to depend on both the inherent responsiveness of the basin to precipitation events and the magnitude of logging and road disturbance. The very low response factor for WS7 partially accounts for the small changes in the storm hydrograph after cutting. Additionally, the low density and careful design of roads and minimal disturbance of the surface soil by cable logging also limited changes in stormflow on WS7.

5.4. Stream chemistry

Stream chemistry has been measured on both WS7 and WS2 since late 1971. The effects of treatment are examined in two ways, i.e., changes in solute concentrations ($\mu\text{eq l}^{-1}$) and net changes in solute export (kg ha^{-1}). Stream chemistry responses were small and only the more important nutrients are selected for discussion.

5.4.1. Solute concentrations

During the 5-year calibration period, mean monthly Ca^{2+} concentrations on WS7 were typically 10–20 $\mu\text{eq l}^{-1}$ higher on WS7 than WS2 (Fig. 4a). Within-year concentration patterns are similar for both streams — minimum concentrations occurred in the winter and maximum concentrations in mid-summer.

Table 4

Summary of responses for select storm hydrograph parameters following clearcutting and/or commercial logging in Coweeta catchments, Coweeta Hydrologic Laboratory, Otto, NC

Watershed number	Size (ha)	Response factor ^a	Treatment	Inclusive years after treatment	Mean storm increases for selected hydrograph parameters (%)			
					Total quickflow volume	Peak flow rate	Initial flow rate	Recession time
7	58.7	0.04	Clearcutting, cable logging product removal and minimal road density	4	10	15	14	10
37 ^b	43.7	0.19	Clearcut, no products removed, no roads	4	11	7	NS ^e	NS ^e
28 ^c	144.1	0.09	77 ha clearcut, 39 ha thinned, 28 ha no cutting; products removed; high road density	9, 2 ^d	17	30	NA ^f	NA ^f

^a (Mean stormflow volume)/mean precipitation.

^b Hewlett and Helvey (1970).

^c Douglass and Swank (1976).

^d Inclusive years after treatment used for total quickflow and peak flow rates, respectively.

^e Nonsignificant ($p > 0.05$).

^f Not available.

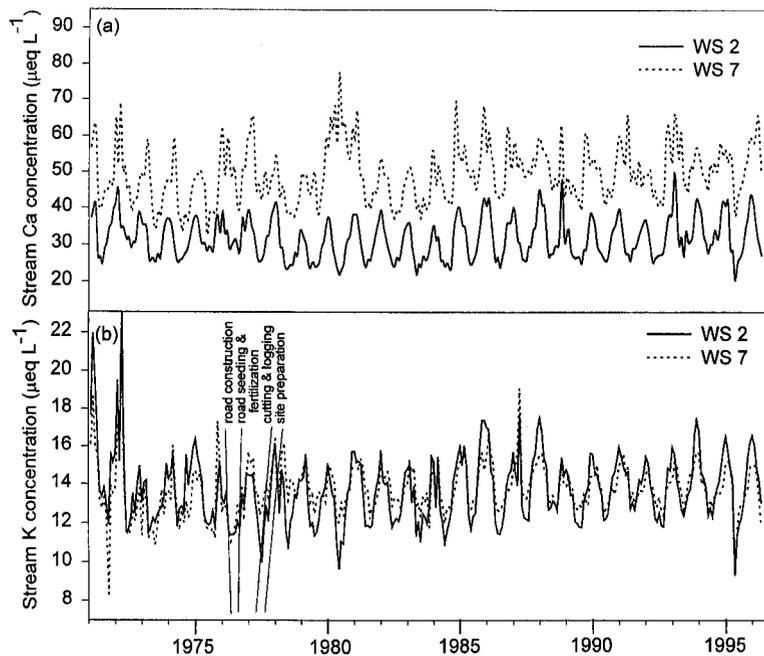


Fig. 4. Mean monthly concentrations (flow weighted) of Ca^{2+} (a) and K^{+} (b) in streamwater of WS7 and WS2 during calibration (1971–1976), treatment activities (1976–1977), and post-harvest period (1978–1996), Coweeta Hydrologic Laboratory, Otto, NC.

Ca^{2+} concentrations increased significantly ($p < 0.05$) during June and July of 1976 due to road seeding and liming. Following cutting and logging in 1977, Ca^{2+} concentrations increased significantly ($p < 0.05$), and the largest increases ($17\text{--}20 \mu\text{eq l}^{-1}$) occurred in the third full growing season after cutting (Fig. 4a). As the forest has regrown, Ca^{2+} concentrations have remained elevated with an average annual increase of only $5 \mu\text{eq l}^{-1}$ during stand development between ages 5 and 20 years. Most of the change occurs in the winter period.

Baseline monthly K^{+} concentrations on WS7 were about 10–15% lower than on WS2 (Fig. 4b). The road fertilization on WS7 increased stream K^{+} concentrations to levels exceeding the control by 10–40%. They remained elevated for most months through 1983. Based on regression analysis, most of the monthly increases on WS7 were statistically significant ($p < 0.05$). Subsequently, with stand succession K^{+} concentrations did not change measurably.

Baseline concentrations of NO_3^- in streams draining undisturbed catchments at Coweeta are frequently near analytical detection limits of $0.2 \mu\text{eq l}^{-1}$ (Fig. 5)

and thus, stream NO_3^- provides a sensitive indicator of ecosystem disturbance (Swank and Vose, 1997). No measurable NO_3^- increases were observed at the weir during road fertilization in 1976, which was in contrast to Ca^{2+} and K^{+} responses. Lack of NO_3^- response probably was due to within-stream biological processes that depleted NO_3^- before it reached the weir (Swank and Caskey, 1982). Nitrate concentrations began to increase on WS7 in early fall 1977, about 9 months after the initiation of logging and at the conclusion of site preparation cutting (Fig. 5). Concentration increases remained low ($4 \mu\text{eq l}^{-1}$) through the following summer and then peaked ($12 \mu\text{eq l}^{-1}$) during the winter of 1978. A second peak also occurred the next summer. With forest regrowth, NO_3^- concentrations declined; peak summer values during the next 9 years were $5\text{--}6 \mu\text{eq l}^{-1}$. However, beginning in the summer of 1989, NO_3^- concentrations began to increase again, with peak values near $10 \mu\text{eq l}^{-1}$. In fact, in the summers of 1992 and 1995 stream water NO_3^- concentrations ($15 \mu\text{eq l}^{-1}$) equaled or exceeded values observed in the first several years after clearcutting.

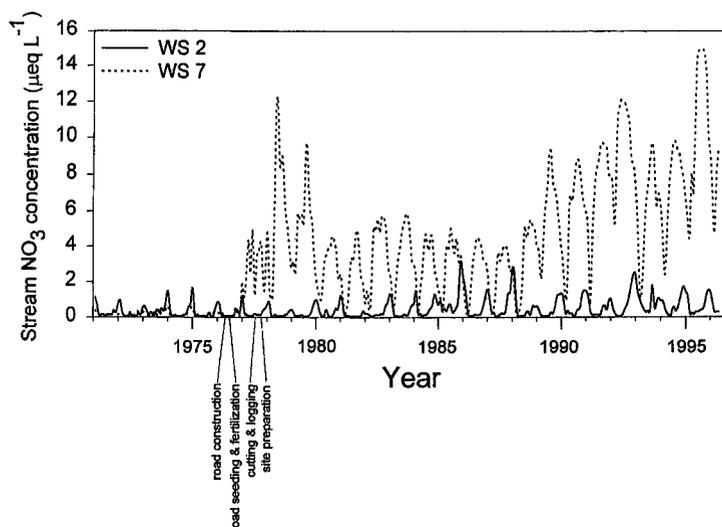


Fig. 5. Mean monthly concentrations (flow weighted) of NO_3^- in streamwater of WS7 and WS2 during calibration (1971–1976), treatment activities (1976–1977), and post-harvest period (1978–1996), Coweeta Hydrologic Laboratory, Otto, NC.

5.4.2. Solute export

Stream solutes showed small but measurable increases in concentrations, indicating disruption of nutrient recycling processes associated with cutting. However, losses from the catchment must be quantified to evaluate the relevance to forest sustainability. Solute concentration data were combined with streamflow volume data to calculate nutrient export; annual change in export of each ion were estimated from pre-treatment calibration regressions of monthly exports between WS7 and WS2. Relationships of monthly exports between the two catchments were good with r^2

values ≥ 0.92 for most ions. Exports of $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, and $\text{PO}_4\text{-P}$ were low and almost identical for the two catchments during the pre-treatment period. Treatment effects for these ions were derived by differences in total export between post-treatment and pre-treatment periods. Annual increases in streamflow and nutrient export during the first 6 post-treatment years are shown in Table 5.

Elevated nutrient exports were greatest in the third water year (May–April) after cutting and logging (Table 5). Cutting had little effect on $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ exports except for the small increase in P export

Table 5
Annual changes in streamflow and solutes following clearcutting and logging (post-treatment–pre-treatment) on WS7, Coweeta Hydrologic Laboratory, Otto, NC

Time since treatment (May–April water year)	Flow (cm)	Increase or decrease in streamflow and solute export (kg ha^{-1}) ^a								
		$\text{NO}_3\text{-N}$	$\text{NH}_4\text{-N}$	$\text{PO}_4\text{-P}$	K	Na	Ca	Mg	$\text{SO}_4\text{-S}$	Cl
First 4 months	0.5	0.01	<0.01	0.01	0.43	0.42	0.24	0.26	0.39	0.68
First full year	26.5	0.26	0.03	0.04	1.98	1.37	2.60	0.96	0.27	1.13
Year 2	20.5	1.12	<0.01	0.01	1.95	2.22	2.51	1.15	-0.08	1.62
Year 3	17.3	1.27	0.05	0.02	2.40	2.68	3.16	1.42	0.39	2.08
Year 4	11.9	0.25	0.15	0.02	0.80	1.07	1.63	0.46	0.31	0.59
Year 5	4.3	0.28	0.01	<0.01	0.52	0.13	1.19	0.18	0.04	0.10
Year 6	4.1	0.62	0.06	<0.01	0.73	0.69	0.89	0.42	-0.06	0.33

^a Annual increase or decrease derived from sum of deviations using monthly calibration regressions.

the first year of treatment which was related to P released from fertilizer applied to roads. The magnitude of nutrient export is influenced by both increased discharge resulting from reduced Et following cutting and increases in solute concentrations. Annual flow increased an average of 23.5 cm the first 2 years after cutting but the maximum concentrations of most solutes were not reached until the third year when discharge on WS7 was still more than 17 cm above pre-treatment levels. Hence, increases in exports, except $\text{NO}_3\text{-N}$, were slightly higher the third year after treatment. $\text{NO}_3\text{-N}$ exports during the later stages of forest succession exceeded early post-disturbance losses. For example, elevated $\text{NO}_3\text{-N}$ losses of 1.5, 2.3, 1.3, and 1.7 kg per year were observed in four of the years between stand age 14 and 20 years.

Nutrient losses observed in this commercial logging study are relatively small and should not adversely impact the sustainability of growth in the successional forest. Atmospheric deposition of inorganic N, Ca, and K on WS7 averaged 4.5, 3.7, 1.8 kg ha^{-1} per year, respectively, which exceed the elevated losses in most years. Findings support previous theoretical analyses suggesting that hardwood ecosystems in the southern Appalachians are highly resistance and highly resilient to changes in biogeochemical cycles associated with forest harvesting activities (Swank and Waide, 1980; Waide, 1988). Large pools of organic matter and elements which turn over slowly are characteristics of high ecosystem resistance (Webster et al., 1975); previously reported Coweeta data (Waide, 1988) and the small increases in catchment nutrient losses in this study are indicative of high resistance. Moreover, the rapid return of nutrient losses to near baseline levels, exclusive of $\text{NO}_3\text{-N}$, are suggestive of high ecosystem resilience (Waide, 1988). Other research at Coweeta on older (31 years) clearcut successional hardwood forests at Coweeta also indicate minor change in nutrient exports in later successional development (Swank, 1988).

Additional process level research on WS7 provides explanations for high nutrient retention in these disturbed ecosystems. Biogeochemical cycles recovered rapidly due to high rates of NPP and sequestration and storage of nutrients in successional vegetation (Boring et al., 1988). In the third year after cutting on WS7, above-ground NPP on mesic sites was 60% of the NPP of the pre-cut forest, and nutrient pools in NPP for N,

P, K, Mg, and Ca were 57–141% of the NPP of the original hardwood forest (Boring et al., 1988). Other research showed that C and N concentrations and pools increased 20–70% the first three years after logging (Waide et al., 1988; Knoepp and Swank, 1997) along with proportionally larger increases (20–250%) in mineral N pools (Waide et al., 1988). Increased available mineral N was attributed to small increases (25%) in soil N mineralization and substantial increases (200%) in nitrification (Waide et al., 1988). Most of the increased mineral N was recycled through rapidly growing vegetation and only a small fraction was exported from the catchment.

An interesting and important indicator of major shifts in internal ecosystem N cycling is the second and apparently more sustained pulse of NO_3^- to the stream in the later stages of succession (Fig. 5). Reasons for the temporal dynamics in stream NO_3^- involve a complex combination of ecological processes. Corollary hypotheses include: (1) reduction in nutrient uptake due to vegetation mortality and changes in species composition, (2) nutrient release from woody decomposition, (3) elevated soil N transformations, and (4) reduction in the soil C/N ratio. The accelerated release of NO_3^- coincides with the stem exclusion stage of the regrowing forest, when an increase in discharge was observed in 1992 (Fig. 1). Thus, reduced NO_3^- uptake due to high mortality may account for some of the initial NO_3^- loss to the stream in 1989–1991. However, canopy closure occurred rapidly following mortality, as evidenced by a stand basal area in 1996 equivalent to the mature forest ($25 \text{ m}^2 \text{ ha}^{-1}$). In contrast, during the same time period stream NO_3^- concentrations continued to increase.

Probably the most important source of available N is associated with the mortality of *R. pseudoacacia* as observed in another catchment study at Coweeta (Swank, 1988). In 4-year-old *R. pseudoacacia* stands on WS7, symbiotic fixation was estimated to be 30 kg N ha^{-1} per year and catchment-wide fixation was estimated at 10 kg N ha^{-1} per year (Boring and Swank, 1984a). *Robinia pseudoacacia* has also been shown to accumulate large quantities of N in stems, branches, roots, and foliage (Boring and Swank, 1984b). Mortality of black locust during the stem exclusion stage was 55% or 330 stems ha^{-1} (Elliott et al., 1997) and decomposition of the N-rich organic

matter above- and below-ground could be a major source of stream NO_3^- later in succession.

Another potential long-term source of nitrogen is from decomposing logging residue. Large quantities of coarse and fine woody debris (122 Mg ha^{-1}) were delivered to the forest floor from logging and site preparation activities (Mattson et al., 1987); previous research at Coweeta found large accumulations of N in decomposing logs over a 5-year period (Schowalter et al., 1998). Log decomposition studies on WS7 showed relatively high decay constants and by the sixth year after clearcutting mass loss for predominant species was 50% (Mattson et al., 1987). By the 14th year of succession, most log material less than 35 cm diameter was indistinguishable from the forest floor, thus providing a source of available N to the soil and/or stream.

The C/N ratio averaged 22 during the first 3 years after cutting and remeasurement over the next 15 years showed no significant change in C/N with an average of 24 in 1992–1994 (Knoepp and Swank, 1997). The status of soil N mineralization and nitrification is under investigation to compare current transformation rates with those early in succession.

5.5. Sediment yield

During the 2 years of pre-treatment calibration, sediment yield from WS7 and WS2 averaged 230 and 135 kg ha^{-1} per year, respectively; these yields exclude that portion of suspended sediment not collected in the ponding basin that passed across the weir blade. These baseline sediment yields are similar to the mean values for small forested catchment in the eastern US summarized by Patric et al. (1984). By mid-May 1976, roads in WS7 were seeded and fertilized but road fills and the running surface were not settled and without grass or gravel cover. In the third week of May 1976, a 16 cm storm occurred and was followed by an even larger storm on 28 May of 22 cm with intensities of 7 cm h^{-1} . This latter event produced the highest discharges measured on most catchments at Coweeta during the 65 years of the Laboratory gauging history. Sediment yield in these events was greatly accelerated on both WS7 and WS2 with an estimated increase in soil loss on WS7 of 7 t (Fig. 6b). Roads were the source of most of the elevated sediment yield as illustrated by soil loss

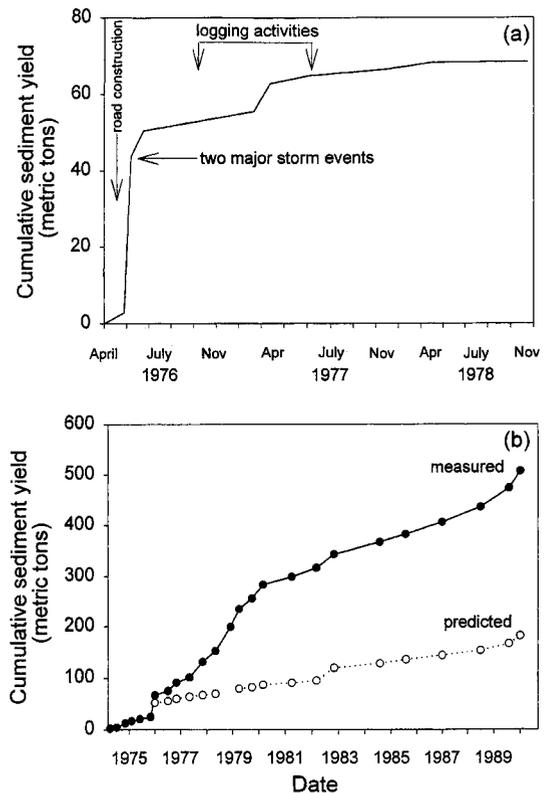


Fig. 6. Cumulative sediment yield measured on WS7: (a) in one of the first-order streams below a logging road during the first 32 months after treatment; (b) in the ponding basin of the second-order stream at the gauging site during 15 years after treatment, Coweeta Hydrologic Laboratory, Otto, NC.

measured at a gauging station in a stream immediately below a road crossing (Fig. 6a) in the middle of the catchment. In the latter 2 weeks of May, sediment yield was nearly 50 t from 0.086 ha of road contributing area (roadbed, cut, and fill). In the ensuing period of road stabilization and minimum use (June–December 1976), soil loss from the road was low but accelerated again briefly during the peak of logging activities (Fig. 6a). In the next year, soil loss declined to baseline levels. In the same period, sediment samplers influenced only by cutting and yarding activities (i.e., located above roads) collected only small amounts of material which was primarily organic matter (data not shown). Other research at Coweeta (Swift, 1984b) provides detailed descriptions of the magnitude, source, and fate of soil loss from

roads constructed in this study and techniques for controlling soil loss.

Sediment yield at the weir (Fig. 6b) showed different temporal patterns than sediment loss from the roads. Following the initial pulse of sediment export from the catchment, sediment yield remained substantially elevated during and after logging. In the 3-year period between 1977 and 1980, there was a cumulative increase of 200 t in sediment yield. During the next 10 years, sediment yield declined with a cumulative increase in export of 200 t (Fig. 6b). Thus the rate of sediment yield over the 5–15-year period after disturbance was about 340 kg ha^{-1} per year, or nearly 50% above pre-treatment levels.

These long-term sediment yield data illustrate the lag or delay between pulsed sediment inputs to a stream and the routing of sediments through the watershed. Soil loss from roads to the stream was very low following stabilization with grass and gravel cover (Fig. 6a). Cross-section measurements of the main stream channel during the past 20 years on WS7 show only infrequent and minor instances of stream bank erosion (Webster et al., unpublished data). In the absence of significant additional sources of sediment to streams on WS7, annual sediment yield at the base of the catchment was still 50% above pre-disturbance levels at least 15 years later. Thus, there has been a continual release of sediment from upstream storage that was primarily deposited from three road crossings of perennial streams and four crossings of intermittent streams on WS7 in the May 1976 storm events. However, we wish to emphasize the uniqueness of conditions that produced these sediment responses, i.e., record storms occurred at the precise time when roads were most vulnerable to erosion (freshly constructed and without vegetation cover). Hence, we suggest that the magnitude and duration of sediment yield measured in this study are toward the upper limits that might be expected in southern Appalachian mixed hardwood forests after clearcutting and cable logging.

5.6. Stream invertebrates

The relevance of disturbances on WS7 to stream structure and function has been a topic of long-term research by a team of stream ecologists (Meyer et al., 1988; Wallace, 1988; Webster et al., 1988), and

responses in benthic invertebrate community structure following 16 years of forest succession after logging WS7 have been measured (Stone and Wallace, 1998). Immediately after clearcutting, invertebrate taxonomic diversity increased in the stream of WS7 and was accompanied by a shift in functional benthic groups (increased scrapers and reduced shredders). Gurtz and Wallace (1984) found that many taxa decreased in abundance in the lower stream gradient (sand and pebble habitat), whereas taxa increases were observed in the steep gradient (bedrock-moss habitat). Following 16 years of succession, benthic invertebrate abundance was three times higher and invertebrate biomass and production were two times higher (habitat weighted) in the stream draining WS7 compared to the adjacent control stream (Stone and Wallace, 1998). Five biotic indices were used to assess the effects of and recovery from the disturbance on WS7; results showed contrasting patterns of return to baseline (Stone and Wallace, 1998). Taken collectively, shifts in the structure and function of benthic communities on WS7 are an integrated product of alterations in the physical habitat, food base, nutrient dynamics, light levels, and temperature of the stream. Evidence from long-term benthic studies on WS7 indicates that the increased sediment load in the stream altered the abundance, biomass, and productivity of taxa among habitats and the stream invertebrate community is gradually returning toward that found in an adjacent reference stream.

6. Conclusions

Two decades of research on hydrologic and water quality responses to clearcutting and cable logging of a mixed hardwood forest in the southern Appalachians indicates little long-term effect of this management practice on water, soil, and vegetation sustainability and health. Harvesting increased annual water yield, during the first 4 years after cutting and flow then returned to baseline values. However, later in succession (15–18 years), both increases and decreases in annual water yield occurred due to changes in vegetation structure and composition. Findings support the generalized use of a previously derived empirical model for predicting short-term (<10 years) annual streamflow responses for forest management planning

in similar hardwood forests of the region. The extra water delivered to the stream early in succession was distributed throughout most of the year; most important, discharge was doubled in the low flow months when water needs for human and aquatic sustainability are greatest. Stormflow response to management was low due to inherent hydrologic response factors of the catchment, the low density and careful design of roads, and minimal soil disturbance by cable logging.

Further evidence for minimal impact of the management prescription on ecosystem health was the small initial nutrient losses following disturbance. Nutrient retention was related to rapid recovery of biogeochemical cycles associated with high rates of NPP and storage of nutrients in successional vegetation. Later in succession, stream NO_3^- concentrations increased above levels observed in the initial post-harvest period, a response indicative of significant changes in internal N cycling processes. A major effect of management was pulsed sediment inputs from newly constructed roads on the catchment associated with two major storms. Subsequently, with logging activity and road stabilization, sediment yield within the catchment was low. However, over the next 15 years, sediment yield at the base of the catchment remained elevated due to the lag between pulsed sediment inputs and within-stream transport processes. Evidence from long-term benthic studies indicates that 16 years after disturbance stream benthic abundance, biomass, and productivity are still higher than that found in the adjacent reference stream but returning toward baseline conditions.

It is important to point out that Best Management Practices were used in harvesting and in logging road location and design. However, the clearcut size (59 ha) was guided by experimental requirements and exceeded normal guidelines (<15 ha) by National Forest Systems when the study was initiated. We emphasize that sediment responses associated with the management practices are toward the upper limits for the magnitude and duration of sediment yields due to the uniqueness of storm/road conditions. It is also important to recognize that impacts on resources could be substantially greater for practices with higher road density and/or logging techniques that produce more surface soil disturbance.

Acknowledgements

This research was partially supported by USDA Forest Service, Southern Research Station and partially supported through grants from the National Science Foundation, Division of Environmental Biology to the University of Georgia for the LTER Program. We also acknowledge the support of many individuals at Coweeta over the years in the collection and analysis of samples, maintenance of the hydrologic network, and manuscript typing; most recently: Jim Deal, Barbara Reynolds, Cindi Brown, Carol Holland, Julia Moore, Bruce McCoy, Mark Crawford, and Teresa Moss.

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