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Recovery of Central Appalachian Forested Watersheds

Comparison of Fernow and Coweeta

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Introduction

The Fernow Experimental Forest (FEF) was established to conduct research in forest and watershed management in the central Appalachians. The 1868-ha FEF, located south of Parsons, West Virginia, is administered by the Northern Research Station of the USDA Forest Service and provides a valuable point of comparison with Coweeta Hydrologic Laboratory (CHL), located in the southern Appalachians. This chapter summarizes responses to clearcutting on four watersheds at FEF and compares the results to those from clearcutting on CHL Watershed 7 (WS 7).

The Elklick watershed (which later became the bulk of the FEF) was initially logged between 1903 and 1911 during the railroad-logging era (Trimble 1977). Wind is considered the dominant disturbance agent on the Fernow, but early snow, when leaves are still on some trees, has also been an important disturbance. Forest fires may have been an important disturbance agent prior to initial logging, but Bryant (1911), after examining the property in 1911, determined that there had been no fires on it for a long time. Most of the Elklick watershed was not farmed, and the forest was allowed to regenerate naturally following the cessation of logging activities. The current mature forest developed in the absence of deer, with very low levels of herbivory (DeGarmo and Gill 1958; Kochenderfer 1975). Chestnut blight was first noted in West Virginia as early as 1909 (Brooks 1911) and in places resulted in a 25% reduction in standing volume on the experimental forest in the 1930s (Weitzman,1949). More historical information was published by Kochenderfer (2006).

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Site Description

The ecological land type of the FEF is referred to as the Allegheny Mountains section of the Central Appalachian Broadleaf Forest, according to the Forest Service National Hierarchical Framework of Ecological Units (McNab and Avers 1994). The land-type association is designated as Allegheny Front Side Slopes, and vegetation is classified as mixed mesophytic. Characteristic species include northern red oak (*Quercus rubra*), yellow poplar (*Liriodendron tulipifera*), black cherry (*Prunus serotina*), sugar maple (*Acer saccharum*), sweet birch (*Betula lenta*), red maple (*A. rubrum*), and American beech (*Fagus grandifolia*). Leaf area index for mature forest on good to excellent sites is 4.5.

The topography is mountainous, with elevations ranging from 530 to 1115 m above sea level. Mean annual precipitation is about 1,480 mm, distributed evenly throughout the year. The growing season is May through October with an average total frost-free period of 145 days. Snow is common in winter, but a snowpack generally lasts no more than a few weeks; snow contributes approximately 14% of the precipitation to FEF (Adams et al. 1994). Mean annual temperature is 9.2°C but temperatures reach –20°C most winters. Large rainfall events are normally associated with hurricanes. About half of the largest storms on the Fernow have occurred during the dormant season (November 1–April 30; Adams et al. 1994), when evapotranspiration losses are low. The largest peak flow (0.72 m^3/s) recorded on FEF4 occurred in November 1985, after a 15.24-cm rainfall.

Slopes ranging from 20% to 50% cover most of the area. The soils are predominantly Inceptisols from the Calvin and Dekalb soil series. The Calvin series consists of moderately deep, well-drained soils formed in material weathered from interbedded shale, siltstone, and sandstone. Dekalb soils are also acidic, deriving from acidic sandstones. Average soil depth is about 1 m, and the soil contains a considerable amount of stones and large gravels.

Predictions: Fernow in Comparison and Contrast to Coweeta

There are many similarities between the two research locations, and some striking differences. The forest of the FEF is mesic, mixed hardwood, similar to the cove-hardwood and mixed-oak hardwood forests at CHL, but with some significant differences in species composition. For example, black locust (*Robinia pseudoacacia*) is an important part of early successional forests at CHL. Black locust is common at FEF but not in such abundance as at CHL, nor is the very high early mortality of black locust observed at CHL (55%; Elliott et al. 1997) so evident at FEF. Rhododendron (*Rhododendron maximum*) is more abundant at CHL, particularly in the riparian zone, than at FEF. Black cherry is much more abundant at FEF than at CHL. We therefore hypothesize that there may be differences in transpiration rates and nutrient cycling due to these species' physiological characteristics. Soils are also generally deeper at CHL, suggesting some differences in hydrologic characteristics, particularly soil moisture and storage. Because CHL receives more rainfall (~ 2000 mm/yr compared to 1500 mm/yr at FEF), soils at CHL are subjected to more leaching and are more well-developed than those at FEF.

Atmospheric deposition of nutrients historically has been and continues to be greater at FEF: N deposition is approximately 15 kg N ha^{-1} yr^{-1} at FEF compared with 4.5 kg N ha^{-1} yr^{-1} at CHL. Deposition of Ca and K to FEF is about twice that deposited at CHL, while sulfate deposition is approximately 40% greater at FEF than at CHL (www.nadp.sws.uiuc.edu/). These differences in deposition could contribute to significant differences in nutrient cycling and plant growth between the two locations. While we note these differences, we predict that the response to clearcutting will be similar between the two research forests. We expect to see the greatest differences in response to be relative to the cycling of nutrients because of the differences between the two regions in nutrient inputs, soil weathering, and growth of the forest vegetation.

Watershed Treatments at the Fernow

We examined the responses of 4 of the 10 gaged watersheds on the FEF: watersheds 1, 3, 6, 7 (FEF1, FEF3, FEF6, and FEF7, respectively). Each of these watersheds was clearcut, although at different times (table 12.1). FEF4 serves as the reference watershed for these 4 Fernow watersheds (figure 12.1). We compared our results with Coweeta's WS 7, a 59-ha watershed with a southern aspect that was commercially clearcut in 1977 (see Swank and Webster, chapter 1, this volume).

On the Fernow watersheds, stream discharge has been monitored using 120° sharp-crested V-notch weirs equipped with FW-1 water level recorders. FEF1, FEF3, and FEF4 have been gauged since May 1951; and FEF6 and FEF7, since November 1957.

Basic streamflow data presented here were determined from flow summaries. The hydrologic year begins on May 1 when the soil usually is fully recharged with moisture. For water yield determinations, growing and dormant seasons are designated to extend from May 1 to October 31 and from November 1 to April 30, respectively. Flow data have been analyzed as described by Reinhart et al. (1963) at $P \leq 0.05$. Stream water grab samples have been collected from FEF1 through FEF4 on a weekly or biweekly basis since 1960; and since 1971 on FEF6 and FEF7. Details of other measurements and analyses were given by Adams et al. (1994).

Results of Experimental Treatments at FEF

Forest Regeneration

Recovery of vegetation on FEF3, FEF6, and FEF7 began with the 1970 growing season. Natural plant succession on FEF6 and FEF7 began at the grass and herbaceous stage (Kochenderfer and Wendel 1983) as a result of the herbicide treatment;

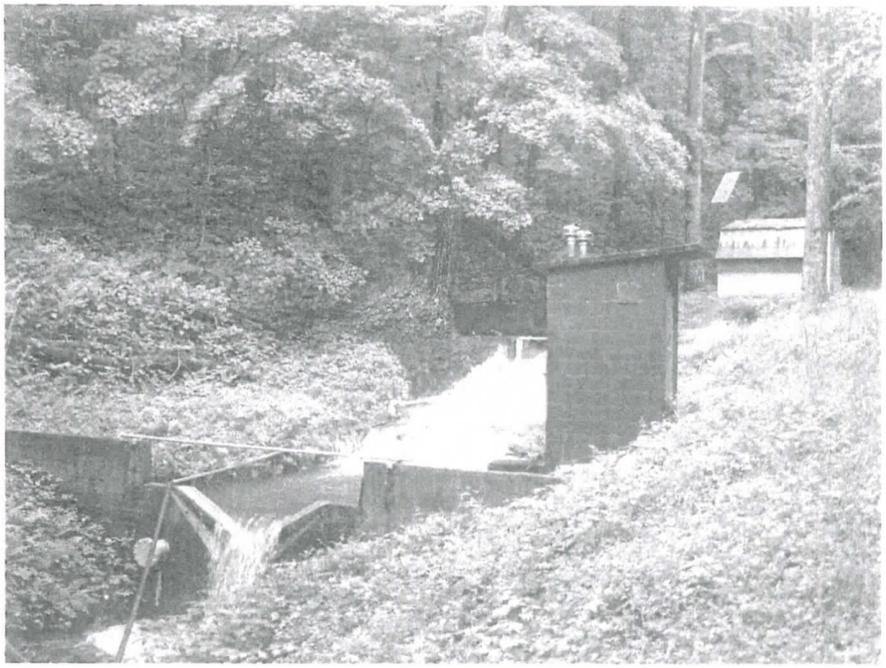

Figure 12.1 Stream gaging station at Fernow Experimental Forest 4 (FEF4), reference watershed, during high flow. (USDA Forest Service photo)

whereas on FEF3 vegetation development began at a more advanced successional stage, and consisted mainly of woody vegetation and *Rubus* spp. Much of the regrowth on FEF3 consisted of sprouts utilizing existing root systems, while regrowth on FEF6 and FEF7 originated mostly from seed, making regrowth and reoccupation of the site slower. Norway spruce (*Picea abies*) was planted on FEF6 in 1973, and further herbicide treatment of competing hardwoods was needed to ensure occupation of the site by the spruce trees.

Total aboveground biomass on FEF7 increased to approximately 33 T/ha within the first 10 years after the end of the herbicide treatment, with 77% of that biomass being produced in the last three years (Kochenderfer and Wendel 1983). By 1991, aboveground biomass was 80 T/ha for FEF7 and 97 T/ha for FEF3, compared to 312 T/ ha for a mature (~90 years old) stand (Adams et al. 1995). Thus, within 30 years, FEF3 had accumulated approximately 53% of the biomass of a 90-year-old stand, and FEF7, 40% of the biomass of the mature stand. Average annual leaf fall mass, measured since 1989, did not vary significantly between FEF3 and FEF7 (Adams 2008), although it was significantly less than that from FEF4 (74% that of FEF4).

In 1999, FEF3 supported a young hardwood stand dominated by black cherry, red maple, American beech, and black birch, while FEF7 supported a young stand dominated by black birch, sugar maple, red maple, black cherry, and yellow poplar. In 1999, black cherry accounted for more than half of the basal area in trees 2.5 cm

Table 12.1 Description of Fernow watersheds and the treatments applied.

Watershed	Treatment	Treatment Date	Basal Area cut %	Aspect	Area (ha)
1	Clearcut to 15 cm d.b.h., except culls	May 57–June 58	74	NE	30.11
	Fertilized with 500 kg/ha urea	May 71			
3	Intensive selection cut, including culls in trees > 12.7 cm d.b.h.,	Oct. 58–Feb. 59	13	S	34.39
	Repeat treatment	Sept. 63–Oct. 63	8		
	0.16 ha patch cuttings totaling 2.3 ha, cut down to 12.6 cm, 2–12 cm stems sprayed with herbicide	July 68–Aug. 68	6		
	Clearcut to 2.5 cm d.b.h., except for a partially cut 3.0-ha shade strip along the stream channel	July 69–May 70	91		
	Shade strip clearcut	Nov. 72	9		
	Ammonium sulfate fertilizer applied,	Dec. 89–present			
4	Reference	None		ESE	38.73
6	Lower 11 ha clearcut	Mar 64–Oct. 64	51	S	22.34
	Maintained barren w/ herbicides	May 65–Oct. 69			
	Upper 11 ha clearcut	Oct. 67–Feb. 68	49		
	Entire watershed maintained barren with herbicides	May 68–Oct. 69			
	Planted with Norway spruce	Mar. 73			
	Aerially spray with herbicides	Aug. 75, Aug. 80			
7	Upper 12 ha clearcut	Nov. 63–Mar. 64	49	E	24.23
	Maintained barren with herbicides	May 64–Oct. 69			
	Lower 12 ha clearcut	Oct. 66–Mar. 67	51		
	Entire watershed maintained barren with herbicides	May 67–Oct. 69			

and larger on FEF3. The dominant trees on good sites on FEF1 in 1995 were sugar maple, yellow poplar and basswood. The percentage of yellow poplar and sugar maple basal area on FEF1 increased 7% and 8%, respectively, in 1995 from the original inventory in 1958, while the percentage of hickory basal area decreased from 10% to 0% and northern red oak from 13% to 7% on good sites. This decrease in large-seeded species was also observed on FEF3 and on other areas across the Fernow (Schuler and Gillespie 2000). An increase in shade-intolerant tree species and a decrease in large-seeded and shade-tolerant species was also reported for Coweeta (Elliott et al. 1997). We cannot attribute these species changes solely to the clearcutting treatments, however. The species composition of a stand is a complex issue, reflecting factors such as past land-use history, disturbance history, deer browsing, seed predation, insects, and disease. For example, small canopy gaps in the overstory combined with recent high deer density and no control of shade tolerant species in the understory on the Fernow has heavily favored red maple, sugar maple, and an understory of American beech and striped maple at the expense of most other species (Kochenderfer 2006).

Water Yield and Peakflow

Figures 12.2 through 12.5 depict deviation of water yields from the predicted flows for FEF1, FEF3, FEF6, and FEF7, using prediction equations developed during the appropriate calibration period. Effects of the harvesting treatments on streamflow have previously been summarized for these and other watersheds by Kochenderfer et al. (1990) and Hornbeck et al. (1993). Annual water yield increased immediately after cutting in these watersheds. The initial flow increases were generally greater

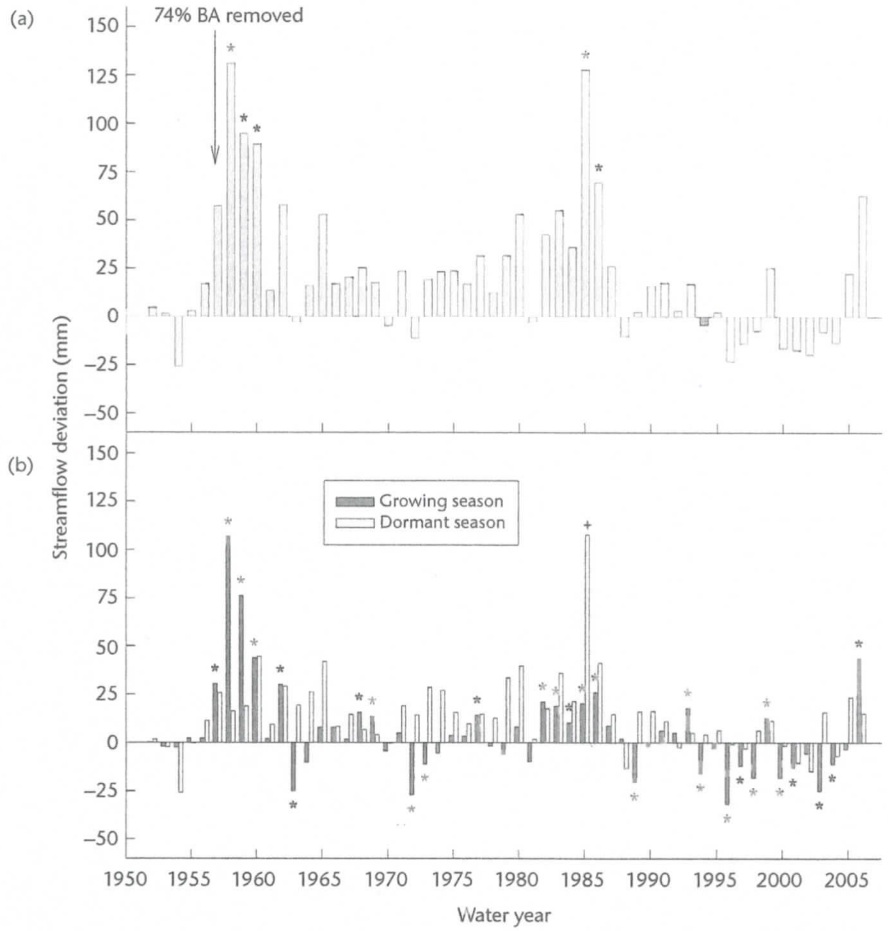

Figure 12.2 Fernow Experimental Forest 1 (FEF1) actual streamflow compared with predicted. (A) Annual water yield variation from predictions. Asterisk indicates statistically significant deviation from prediction ($P = 0.05$). (B) Growing season and dormant season streamflow variation from predicted values. Asterisk (*) indicates statistically significant deviations for growing season; plus indicates statistically significant deviation for dormant season flows ($P = 0.05$).

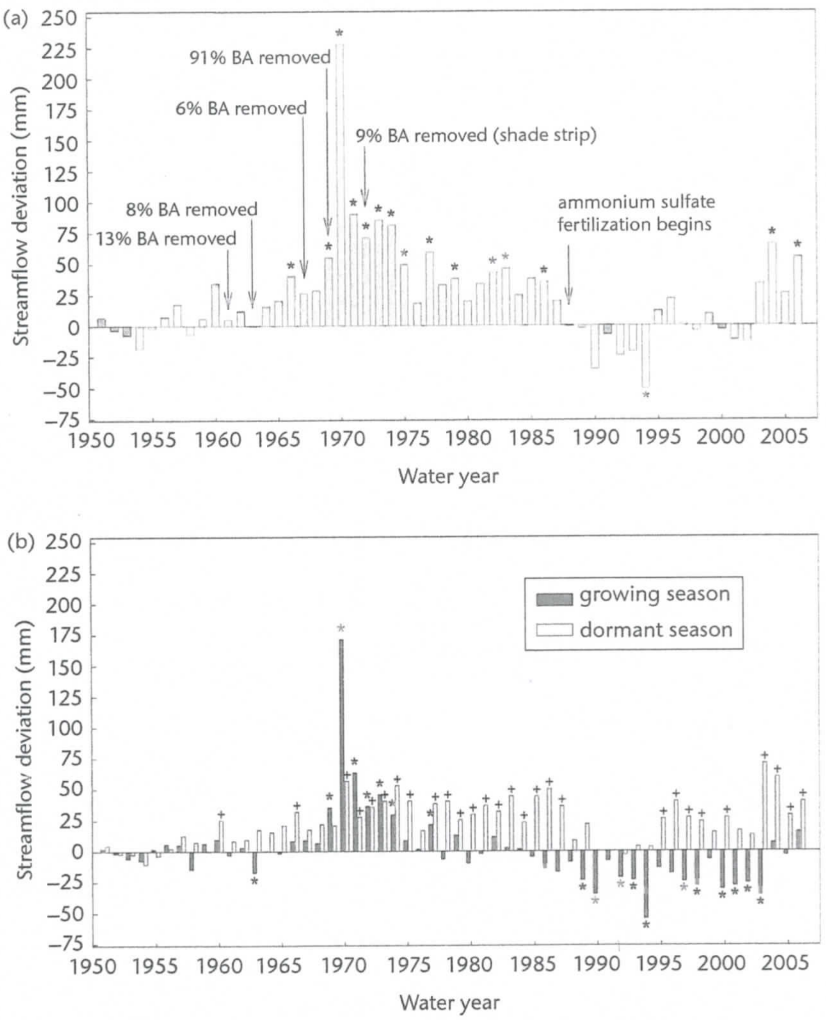

Figure 12.3 Fernow Experimental Forest 3 (FEF3) actual streamflow compared with predicted. (A) Annual water yield variation from predictions. Asterisk indicates statistically significant deviation from prediction ($P = 0.05$). (B) Growing season and dormant season streamflow variation from predicted values. Asterisks indicate statistically significant deviations for growing season; plus signs indicate statistically significant deviation for dormant season flows ($P = 0.05$).

during the growing season, suggesting that the increases in flow were largely due to reduced transpiration after cutting. Statistically significant increases in annual water yield from FEF3 over a longer time period reflected the additional removal of the streamside buffer. Use of herbicides on FEF6 and FEF7 to control regrowth also significantly prolonged increases in annual flow relative to FEF1. Both growing season and dormant season flows from FEF6 and FEF7 increased during the first 20–25 years after treatment (Kochenderfer et al. 1990), although these increases

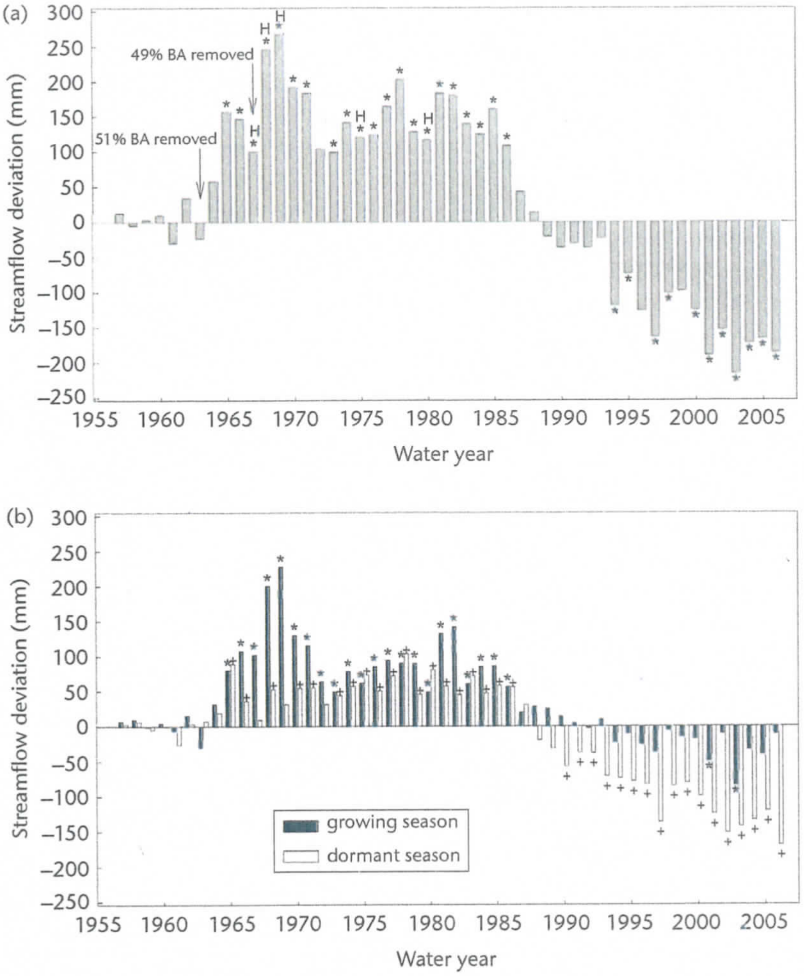

Figure 12.4 Fernow Experimental Forest 6 (FEF6) actual streamflow compared with predicted. *H* indicates herbicide treatments. (**A**) Annual water yield variation from predictions. Asterisk indicates statistically significant deviation from prediction ($P = 0.05$). (**B**) Growing season and dormant season streamflow variation from predicted values. Asterisks indicate statistically significant deviations for growing season; plus signs indicate statistically significant deviation for dormant season flows ($P = 0.05$).

were not always statistically significant. Note that this trend has changed and decreases in flow, relative to that predicted, have been observed on FEF1, FEF3, FEF6, and FEF7 since the 1990s (figures 12.2–5), although most differences were not statistically significant, except for FEF6.

Annual water yields for FEF1 returned to pretreatment levels within 4 years. Repeated disturbances to FEF3 (harvesting) and FEF6 and FEF7 (herbicides) appeared to extend statistically significant increases in annual yield to about 20–30 years post clearcutting. Note that statistically significant increases in annual yield were again

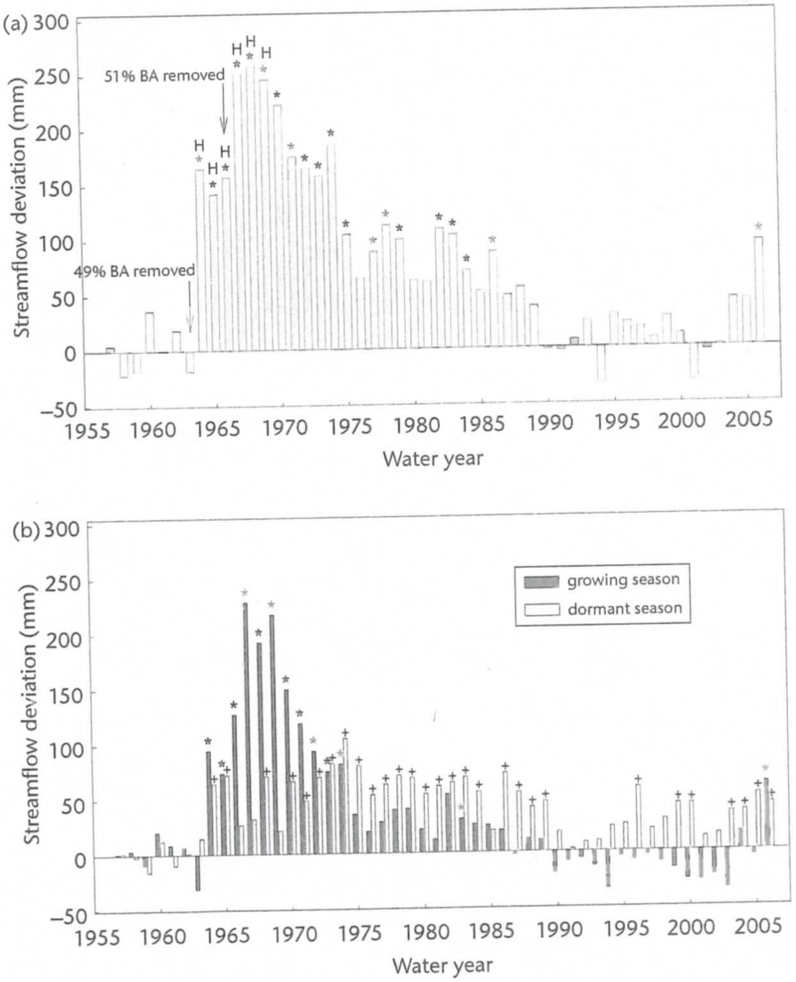

Figure 12.5 Fernow Experimental Forest 7 (FEF7) actual streamflow compared with predicted. *H* indicates herbicide treatments. (A) Annual water yield variation from predictions. Asterisk indicates statistically significant deviation from prediction ($P = 0.05$). (B) Growing season and dormant season streamflow variation from predicted values. Asterisks indicate statistically significant deviations for growing season; plus signs indicate statistically significant deviation for dormant season flows ($P = 0.05$).

detected for FEF1 in 1985 when dormant season flows were dramatically increased. A record storm in November 1985 (Kochenderfer et al. 2007) filled the weir pond on FEF1 with debris rendering streamflow measurement accuracies questionable during the storm. Hornbeck (1973) pointed to the problems of extrapolating extreme flow events. In addition, the steep unplanned road system used in 1957–58, closely associated with a high-gradient stream network, makes the FEF1 gaging station especially vulnerable to large debris flows during such unusual storms.

Significant increases in dormant season flow increases generally persisted longer for FEF3, FEF6, and FEF7 than for FEF1 and also generally longer than growing season increases for FEF3 and FEF7. The rapid decline in growing season water yield increases on FEF3 was attributed to luxuriant vegetative regrowth (Aubertin and Patric 1974). The lower than predicted growing season yields on FEF3 in the late 1980s through 2003, though not all statistically significant, could be due to the large increase in black cherry stems (from 5% to 50% of basal area) and to the fertilizer applications beginning in 1989, which coincided with the start of significant growing season declines. Black cherry consistently transpires at the highest rate per unit of leaf surface area found in hardwoods (Kochenderfer and Lee 1973). Also, a short-term growth response of black cherry to fertilization of FEF3 was observed (DeWalle et al. 2006). Therefore, some of the difference in growing season water yields between FEF3 and FEF7 during this time period could also be due to the greater importance of black cherry on FEF3 and to increased growth and transpiration due to the fertilization treatment. Hornbeck et al. (1993) advanced a similar hypothesis to explain effects of change in dominant species at Hubbard Brook—a significant increase in pin cherry (*Prunus pensylvanica*) and birch (*Betula allgeheniensis*) at the expense of beech and maple. Pin cherry has significantly lower leaf resistances, suggesting transpiration may be greater from a regrowing stand dominated by pin cherry and birch, with less water available for streamflow. Converting a hardwood-covered watershed at Coweeta (WS 6) to grass increased streamflow when the grass was not fertilized, but fertilization stimulated gross productivity and decreased streamflow to levels expected for the original hardwood forest (Swank et al. 1988).

Crown closure on FEF7 was delayed somewhat compared to FEF3, which may be attributed to the effect of the herbicide on regeneration sources. Because of the repeated herbicide treatments, stump sprouts were nearly eliminated on FEF7, and most regeneration originated from seeds (Kochenderfer and Wendel 1983). On FEF3, stump sprouts were the dominant regeneration source. Utilizing the existing rooting network on FEF3, the sprouts have had better access to soil moisture, resulting in greater transpiration at an earlier time than for FEF7.

Growing season water yield increases were longer lived for FEF6 than FEF7 because other vegetative regrowth (competing hardwoods) was controlled with aerial herbicide applications in 1975 and 1980 to release planted Norway spruce (Wendel and Kochenderfer 1984). Also, the planted spruce grew more slowly than the native hardwoods, and full site occupancy by the spruce required a longer time period. A survey in 1986 indicated that spruce crowns only covered about 24% of the ground area.

Reductions in annual water yield on FEF6 beginning in the 1980s can be attributed to the greater interception and transpiration, especially during the dormant season, by the planted conifer (Norway spruce) stand compared to the original hardwood stand (Helvey 1967; Delfs 1967). Annual streamflow reductions during the past 6 years on FEF6 have averaged 23%. Most of the significant decreases in FEF6 streamflow have occurred during the dormant season, when interception and transpiration by hardwood stands is low.

Streamflow is expected to continue to decline as the spruce stand matures. Delfs (1967) found that mean annual interception ranged from 21% in a 30-year-old Norway spruce stand in Germany to 36% in an 80-year-old stand. An estimate of mean annual hardwood interception (12.9%) was determined by applying Fernow precipitation data to dormant and growing season hardwood interception equations developed by Helvey and Patric (1965). Transpiration losses would also be expected to be much greater during the dormant season in the spruce stand. However, model simulations at Coweeta indicated that differences in annual interception and transpiration losses between white pine (*Pinus strobis*) and hardwood stands were about equal, despite greater dormant season transpiration by the white pine stand (Swank et al. 1988).

Dormant season peak flows on the harvested watersheds appeared little changed relative to the control watershed. This is attributed to the relatively small soil moisture deficits (higher soil moisture), because of low evapotranspiration during the dormant season. However, growing season peak flows were consistently higher on the clearcut watersheds where soil moisture deficits are reduced for a short period after cutting until vegetation regrows. This effect is more pronounced for the smaller storms, which provides support for the idea that differences in soil moisture are largely responsible for differences in growing season peak storm flows (Hornbeck et al. 1993).

The number of events considered to be storms increased with clearcutting (Bates 2000) due to increased soil moisture causing more response on clearcut watersheds. Because the relative increase is greater for small peaks, the number of events large enough to be considered storms is higher. Bates (2000) also reported that snowmelt peakflows appeared to occur and peak earlier on the FEF1 immediately after cutting relative to FEF4, probably due to greater net radiation on the snow cover, an effect also noted by Hornbeck (1970). Examination of hydrographs showed that, with the possible exception of snowmelt and excess runoff from logging roads when water was not controlled, there were no dramatic timing changes in the hydrographs after harvest, and subsurface flow was the main runoff production mechanism both before and after harvests.

Sediment Yields

Sediment yields prior to treatment and on the reference watershed ranged from 6 to 25 kg ha^{-1} yr^{-1} (Patric 1980; Kochenderfer et al. 1987). Clearcutting using an unplanned road system and no BMPs increased annual sediment yields to more than 3000 kg/ha on FEF1 during the logging operation (Kochenderfer and Hornbeck 1999) in 1957 and 1958, and to 97 kg/ha in 1970 for FEF3 where careful road management practices were followed. For both watersheds, within 5 years, annual sediment yield decreased rapidly to 44 and 28 kg/ha, respectively (Kochenderfer and Helvey 1984). Sediment yields are not available for FEF6 and FEF7, but deforestation of these watersheds did increase maximum turbidities observed during storm flows. However, nonstorm flows, constituting more than 90% of water yield, did not exceed 5 ppm of turbidity (Patric and Rinehart 1971). Most sediment was produced during storm flows (Kochenderfer et al. 1987). For all these studies, turbidity or suspended sediment returned to pretreatment or reference levels within a few years (Kochenderfer and Helvey 1984). Overland flow was seldom observed, only occurring on or directly below steeper roads (Patric 1973). Most of the sediment produced was delivered from roads, more rarely log landings, and the stream channels (Kochenderfer and Aubertin 1975).

Stream Temperature.

Clearcutting FEF1 raised stream temperature 4.5°C during the growing season and decreased temperature 2°C during the dormant season (Reinhart et al. 1963), and temperatures returned to pretreatment levels within 3 years. Eschner and Larmoyeux (1963) reported that clearcutting increased the maximum stream temperatures in summer and decreased the minimums in winter. There was a slight increase in growing season maximum temperatures for diameter-limit harvesting but no obvious effect of selection harvesting on stream temperatures. Clearcutting FEF3 in 1969 had no effect on temperature when a 50-foot-wide buffer strip was left along the channel. Removal of that buffer strip increased stream temperature about 4°C during the summer the shade strip was cut (Patric 1980). Channel shading was sufficient after 5 years of regrowth to return temperatures to preclearcutting levels (Patric 1980).

Stream Water Chemistry

Because of the relatively high levels of nitrogen deposition to the Fernow watersheds (Adams et al. 1993), the high rates of nitrification in the soil (Gilliam et al. 1996), and increasing levels of nitrogen emissions nationally, stream water nitrate concentrations are of particular interest. Stream water nitrate concentrations for the 4 watersheds are shown in figure 12.5. For all of these watersheds, only post-disturbance nutrient concentration data exist, with the exception of limited pretreatment data on FEF1. Therefore statistical analyses of pre- and posttreatment differences are not feasible. However, several trends are particularly striking from even a quick glance at figure 12.6. In particular, the relatively high initial nitrate concentrations for FEF1, FEF6, and FEF7 are notable. The nitrate values for FEF1 reflect a fertilization with 500 kg/ha of urea in 1971. Prefertilization monthly maximum stream concentrations of nitrate-N were less than 2 mg/L, which increased to 16 mg/L immediately after fertilization (Kochenderfer and Aubertin 1975). Patric and Smith (1978) measured streamwater nitrogen and reported an annual loss of 25 kg/ha immediately after fertilization. The relatively high nitrate-N values recorded for FEF6 and FEF7 occurred 2 years after cessation of herbiciding. Clearcutting alone (FEF3) did not result in such large changes in stream nitrate-N or in any other chemical constituents (Aubertin 1971). FEF3 nitrate-N losses were less than 3 kg ha^{-1} yr^{-1} during the first 4 years after clearcutting, primarily because of rapid vegetative regrowth, retention of a lightly cut streamside zone, and good road management (Patric 1980). These study results demonstrate the importance

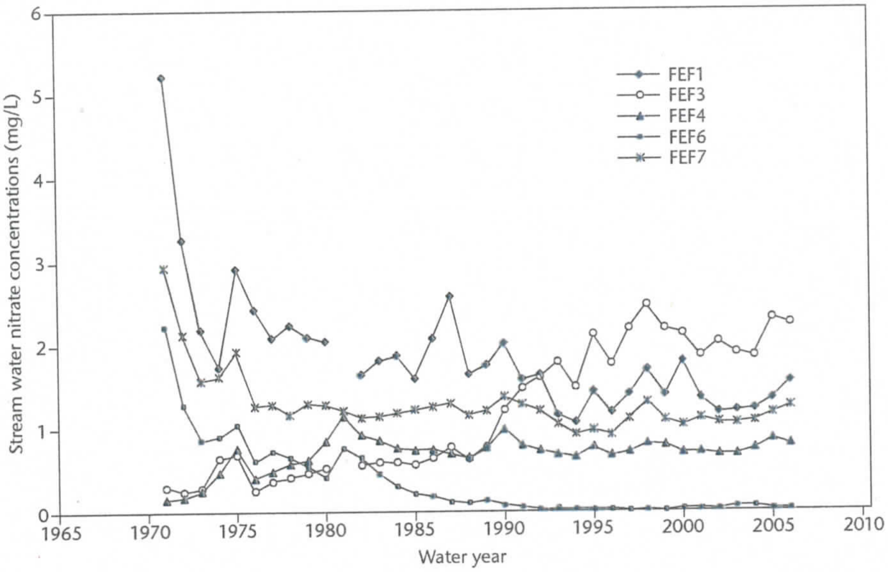

Figure 12.6 Stream water nitrate concentrations from five watersheds on the Fernow Experimental Forest, West Virginia. See table 12.1 for treatment descriptions.

of vegetation in maintaining water quality through nutrient uptake and control of microclimate.

Stream nitrate concentrations decreased quickly for FEF6 and FEF7 over the next 5 years to nearly the same level as FEF3 and FEF4. After 1983, nitrate concentrations from FEF6 decreased to near zero, while those of the other watersheds remained relatively constant, although FEF1 nitrate concentrations were consistently greater and more variable from year to year than those of the other watersheds. The extremely low nitrate concentrations recently observed on FEF6 may be due to increased interception along with preferential uptake of ammonium by the spruce trees and sequestration of nitrogen by an aggrading forest floor. Research is underway to elucidate the mechanisms. Nitrate concentrations increased in FEF3 as a result of fertilization with ammonium sulfate beginning in 1989 (Adams et al. 2006). In recent years, nitrate concentrations in FEF3 are approaching those observed on FEF6 and FEF7 immediately after deforestation.

The pattern for streamflow calcium concentrations is similar to that of nitrate concentrations for most streams (figure 12.7). The leaching of base cations is linked with the strong acid anions, particularly nitrate (Adams et al. 2006). Stream water magnesium concentrations are much lower than calcium concentrations, but the relative ranking of the watersheds by concentrations are the same as for calcium. Stream water sulfate concentrations showed no consistent pattern related to the cutting or herbicide treatments. Stream water pH has remained unchanged except on FEF3, where, as a result of fertilization, pH has decreased from 6.0 to 5.5.

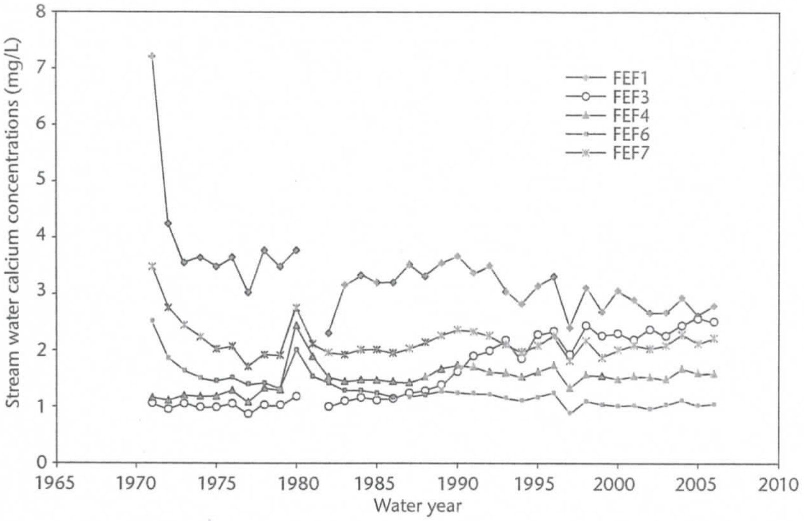

Figure 12.7 Annual stream water calcium concentrations from five watersheds on the Fernow Experimental Forest, West Virginia. See table 12.1 for treatment descriptions.

Comparisons with CHL Watershed 7

A comparison of results from Fernow and Coweeta clearcut watersheds reveals many similarities and a few differences. Hardwood forests regenerated quickly at both locations but slightly more quickly at CHL. By age 17 years at CHL, the stand had recovered most of its original basal area (Elliott et al. 1997), whereas this had occurred by 21 years at the FEF. Volume on FEF3 at 34 years was 65% of the precutting volume. Regeneration trajectories differed somewhat between the sites but were qualitatively similar. In the near term, clearcutting was found to favor shade-intolerant species, concomitant with a decrease in oaks, hickories, and shade-tolerant species at both locations. Many of the same tree species are common to both locations, but there are differences in relative proportions, mainly in the abundance of black locust, mountain laurel (*Kalmia latifolia* L.) and rhododendron (more common on Coweeta) and black cherry (more common at Fernow).

This comparison supports the conclusions of early research at Coweeta and Fernow, as well as other small watershed studies in the eastern United States, that increases in annual water yield could be expected from clearcutting, although the actual amount varied. Patric and Reinhart (1971) reported first-year water yield increases of 30 cm, compared with 41 cm in North Carolina and 33 cm at Hubbard Brook. Although the amounts may vary, the same pattern generally holds true over the long term: a rapid increase in annual water yields after clearcutting hardwood forested watersheds, followed by a quick return to pretreatment levels as revegetation occurs. However, there is a notable difference in water yield results between some of the Fernow watersheds and CHL WS 7. Significant increases in annual water yield seem to be of longer duration at three of the watersheds at Fernow (FEF3, 15 yr; FEF6, 20 yr; FEF7, 20 yr) than reported for CHL WS 7 or for FEF1(~ 4 yr). Each of the Fernow watersheds with longer recovery times received repeated vegetation removal treatments (whether by cutting or herbicides) as opposed to the single clearcuts on CHL WS 7 and FEF1. Hornbeck et al. (1993) identified intermediate cuttings and repeated herbicide use as contributors to prolonged streamflow increases.

For CHL WS 7, the largest flow increases occurred during the growing season; this was initially true for all the Fernow watersheds, providing evidence of the importance of transpiration in these forests' water balance. A few years after harvesting, however, on FEF3, FEF6, and FEF7, dormant season flows were significantly increased and sustained for a longer period of time relative to FEF1 and CHL WS 7. The reasons for this difference are not fully known but may be partially attributed to effects of the repeated treatments on evapotranspiration and consequent effects on soil moisture storage. It also could be due to differences in climate during the calibration period and during the intervening years. For example, cooler temperatures during the calibration period might suggest a larger proportion of dormant season precipitation came in the form of rain rather than snow during the treatment period. Consequently, evaporative losses and soil water content would be much smaller than predicted. We will continue to investigate these discrepancies.

Lessons learned from research on sediment yield and erosion are consistent across the two sites. Generally, overland flow does not occur in forested watersheds except on exposed roads where water was not properly controlled. Harvesting alone does not usually result in increased erosion or sediment inputs to streams. Carefully planned and prepared road systems, and use of Best Management Practices can minimize erosion and sediment inputs to streams.

The differences in stream chemistry between Fernow and Coweeta are probably due to the greater atmospheric inputs over a longer time period, particularly of nitrogen, at Fernow. At Fernow, streamwater concentrations of nitrate and calcium are much higher than CHL, but we did not see such a large relative increase after only clearcutting (FEF3)—on CHL WS 7 nitrate increased threefold or more as a result of clearcutting. However, this may be partly due to the very low background levels on CHL WS 7 (near detection limits), which connotes a more sensitive system. Converting hardwood watersheds to white pine at CHL also resulted in elevated nitrate concentrations up to 25 years later (Swank et al. 1988), whereas converting an FEF hardwood watershed to spruce resulted in significantly lower nitrate concentrations after an equal period of time.

It has been suggested that FEF4 is the best example of a "naturally" nitrogen-saturated watershed (Peterjohn et al. 1997), and this watershed has been used as an example of Stage 2 of nitrogen saturation (Stoddard 1994), whereas CHL WS 7 is considered to be in the latter phases of Stage 1 of nitrogen saturation (Swank and Vose 1997). At the Fernow, the largest increases in streamwater nitrate occurred when herbicide was used to prevent revegetation. This is similar to results from Hubbard Brook (see Bormann et al. 1968, chapter 17, this volume). Such results are not surprising, as inhibiting revegetation significantly decreases nutrient uptake and simultaneously increases water content and potentially water movement through the soil. Also by preventing revegetation, soil temperatures are elevated, increasing rates of decomposition and nutrient cycling. However, unless revegetation is prevented or delayed, as with herbicides, these cutting-induced peaks in nutrient concentrations generally are relatively short-lived. Results from both locations (FEF and CHL) suggest that elevated ecosystem nitrate availability, whether through atmospheric deposition or biological nitrogen fixation, can increase leaching of nitrate from forested watersheds. However, we can also conclude that in general, clearcutting did not affect nutrient concentrations to the extent of adversely affecting water quality for downstream users.

Conclusions

Comparisons between Fernow and Coweeta clear-cut watersheds reveal a number of consistencies:

- Regeneration/revegetation of harvested watersheds occurred rapidly.
- Clearcutting generally caused short-term increases in annual streamflow but generally had no effect on large peakflows.
- Repeated cuttings or devegetation using herbicides prolonged flow increases.
- Changes in species composition or species conversions can alter streamflow, but the duration of the effects may vary with successional trajectories.
- Nutrient losses increased after clearcutting, but the effects are variable depending on the intensity of the disturbance and the length of time revegetation requires.
- Sediment losses from clearcutting can be minimized through careful planning and use of Best Management Practices.

The differences observed between the two sites were relatively small and mostly dealt with rates of revegetation and nutrient cycling. These are probably due to differences in climate, atmospheric deposition, and soil depth.

The comparison of such research studies provides important opportunities to identify commonalities and differences and improve our understanding of forest ecosystem processes over a long timescale. The two research sites, Fernow and Coweeta, complement each other and provide valuable opportunities for broadening the conclusions of small watershed research through these comparisons. Such comparisons also speak to the importance of continuing such long-term watershed studies. As new questions and problems arise, we can use such long-term research in new contexts to further our understanding of ecosystems to help us address these new challenges. Finally, because trees are such long-lived organisms and forest ecosystems are dynamic in time and space, it is important to continue research throughout the life cycles our forests experience.

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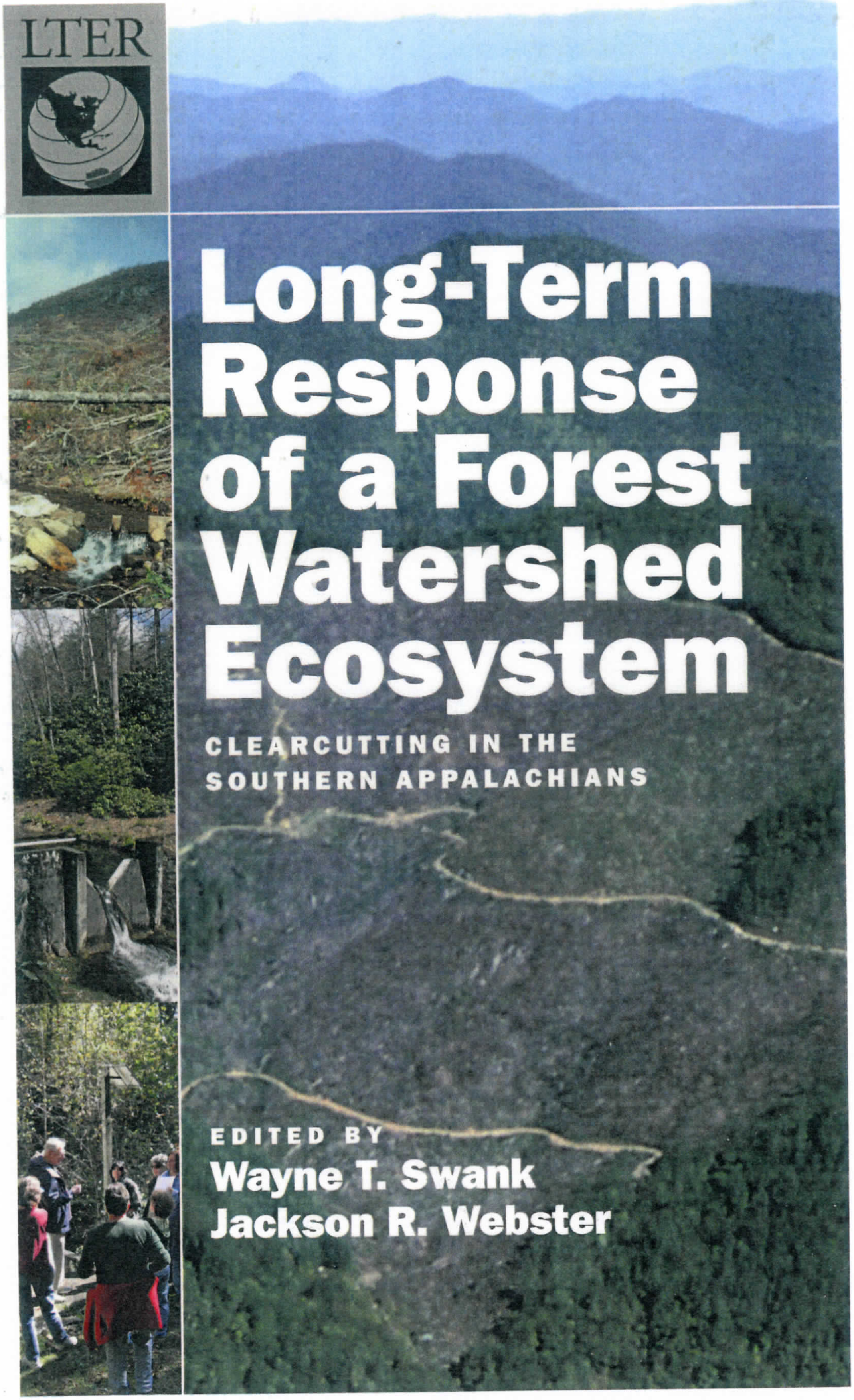

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Long-Term Response of a Forest Watershed Ecosystem

CLEARCUTTING IN THE SOUTHERN APPALACHIANS

EDITED BY

Wayne T. Swank

Jackson R. Webster

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Our North American forests are no longer the wild areas of past centuries; they are an economic and ecological resource undergoing changes from both natural and management disturbances. A watershed-scale and long-term perspective of forest ecosystem responses is requisite to understanding and predicting cause and effect relationships. This book synthesizes interdisciplinary studies conducted over thirty years, to evaluate responses of a clear-cut, cable-logged watershed at the Coweeta Hydrologic Laboratory in the Nantahala Mountain Range of western North Carolina. This research was the result of collaboration among Forest Service and university researchers on the most studied watershed in the Lab's 78-year history. During the experiment, a variety of natural disturbances occurred: two record floods, two record droughts, a major hurricane, a blizzard of the century, major forest diseases, and insect infestations. These disturbances provided a unique opportunity to study how they altered the recovery of the forest ecosystem. This book also shows that some long-term forest trends cannot be forecast from short-term findings, which could lead to incorrect conclusions of cause and effect relationships and natural resource management decisions.

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