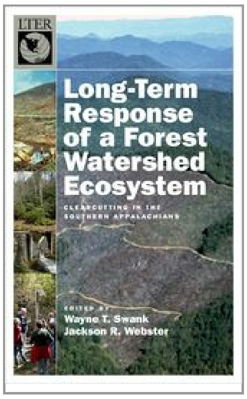

Long-Term Response of a Forest Watershed Ecosystem: Clearcutting in the Southern Appalachians

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Bridging the Gap between Ecosystem Theory and Forest Watershed Management

A Synthesis of 30+ Years of Research on WS 7

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[–] Abstract and Keywords

This chapter provides a synthesis of the more than 30 years of research on Watershed 7 (WS 7) at Coweeta Hydrologic Laboratory. It argues that findings from WS 7 provide important information on the management of southern Appalachians mixed-hardwood forests. The WS 7 study provides an opportunity to conduct detailed research on the effectiveness of previously established best management practices for forest road construction activities, and to evaluate some new road standards meant to reduce erosion and sediment movement. Water yield responses measured following harvest on WS 7 also support the regional use of a previously derived empirical model for predicting short-term annual flow responses for forest management planning in similar hardwood forests. The chapter concludes with a summary of perceptions of long-term changes in economic values and ecological services in a management context.

Keywords: Coweeta Hydrologic Laboratory, watersheds, forest management, mixed hardwood forests

Introduction

The history of forests and logging in North America provides a backdrop for our study of Watershed (WS) 7. Prior to European settlement, potentially commercial forests covered approximately 45% of North America (Clawson 1979), but not all of it was the pristine, ancient forest that some have imagined. Prior to 1492, Native Americans had extensive settlements throughout eastern North America (Mann 2005), but to European settlers, the area was a wilderness. It was described by early settlers as “repugnant, forbidding, and repulsive…The forests were wild areas, alien to man and in need of felling, firing, grazing, and cultivating so that they could become civilized abodes” (Williams 1989). Across North America, forests were cleared for agriculture and forest products, primarily lumber and fuel (MacCleery 1992). First in the Northeast, then in the Midwest, the Great Lakes region, the Southeast, and the Pacific Northwest, forests were cleared, with little regard for future forest values. Forests were viewed as an inexhaustible natural resource, and large logging companies would “cut and run” to the next tract of forest. By the mid-nineteenth century, commercial forest land in the United States had been reduced to about half its original area. In the southern Appalachian region, almost 90% of the forests were cut; and many of these **(p.230)** areas were burned by the turn of the century (Yarnell 1998). In the later nineteenth century, George Perkins Marsh, Frederic Starr, and others began to raise concerns about extensive forest loss. Scientists such as Bernhard Fernow and Gilford Pinchot began the era of forest management in the United States. As a result of improved forest management, declining demand for forest products (especially fuel), fire suppression, and agricultural land abandonment, the area of forest land began to increase (Clawson 1979). “Regrowth can be seen everywhere, and one is struck by the robustness of the forest” (Williams 1989). The resilience of American forests is especially evident in the southern Appalachians. For example, there was a 38% increase in wood volume in the forests of the southern Appalachian region of North Carolina between 1984 and 2006, with no change in forest area (Fox et al. 2010).

When the original research proposal was developed in 1974 to examine ecosystem response to logging, the ideas were based on fairly simple concepts of stability (Monk et al. 1977) and on two aspects of ecosystem response to disturbance, resistance and resilience (Webster et al. 1975). First, ecosystems exhibit varying degrees of resistance to disturbance—stable systems show little change in response to a disturbance; whereas less-stable systems show large change. Second, resilience, the ability of an ecosystem to recover following disturbance, also differs: resilient systems recover rapidly; nonresilient systems are much slower to recover. These concepts were consistent with ecosystem theory 35 years ago (e.g., Holling 1973). Ecosystem stability concepts and lexicon have broadened extensively since then (e.g., Waide 1988; Grimm and Wissel 1997; Hooper et al. 2005); however, these two fundamental concepts remain central to any discussion of ecosystem stability (e.g., Levin and Lubchenco 2008). Our research on the response of the Coweeta WS 7 to logging provides an opportunity to intensively examine ecosystem response to disturbance from the evolving perspective of ecosystem stability.

Our original notions of ecosystem stability were derived from engineering concepts in which disturbance is an impulse function that can be represented by an instantaneous change in initial conditions (Waide and Webster 1976). Many ecological disturbances, such as fire and flash floods, approximate instantaneous change; other disturbances, however, occur over longer periods of time, even when related to the recovery time of ecosystems. These two types of disturbances have been termed *pulse* and *press* disturbances, respectively (Bender et al. 1984). Early in the studies of WS 7, it was recognized that logging the terrestrial system approximated a pulse disturbance; whereas, the stream on WS 7, Big Hurricane Branch, was responding to a press disturbance (Webster and Patten 1979; Gurtz et al. 1980; Webster et al. 1992). This press disturbance results from the continued modification of organic (leaf and wood) inputs and nutrient supply to Big Hurricane Branch from the terrestrial system (see Swank et al., chapter 3, and Webster et al., chapter 10, this volume).

Assumption of Asymptotic Stability

The original research proposal also made the assumption that ecosystems are asymptotically stable; that is, that following a small disturbance, ecosystems will return to their original state. However, ecosystems are not globally stable—more extreme disturbances may move an ecosystem outside its domain of stability (sensu **(p.231)** Holling 1973; Gunderson 2000) to an alternate state. This has occurred in forest ecosystems in eastern United States; for example, with the loss of a foundation species, such as American chestnut (Ellison et al. 2005; Elliott and Swank 2008), and extreme disturbances, such as the deposition of toxic chemicals from copper smelting at Copper Hill, Tennessee, and the massive erosion during cotton farming, which resulted in loss of much of the organic soil from the southern United States. (Richter and Markewitz 2001). These extreme disturbances may result in permanently altered systems. Significant management intervention may restore some system attributes, for example, the planting of nearly 20 million trees and shrubs at Copper Hill may eventually result in an ecosystem that is similar in structure to what was there before. European settlement (Johnson 2002). However, it may take centuries for full recovery of ecosystem structure and function. In the original proposal, we hypothesized that the disturbance impacts of commercial sawlog harvest would not move a watershed ecosystem to an alternate stable state.

What Was the Original Condition of WS 7?

Interpreting ecosystem responses to contemporary disturbances must be viewed in the context of historical disturbance regimes because in many cases, disturbance responses are shaped by the legacy of earlier disturbances. WS 7 was certainly subjected to many disturbances: a major hurricane in 1835, burning by Native Americans prior to 1837, logging and grazing in the nineteenth century, and chestnut blight in the early twentieth century (see Boring et al., chapter 2, this volume)

By 1975, WS 7 was clearly not a pristine, old-growth forest due to a wide range of human and natural disturbances. It is likely that these historical disturbances have influenced the postharvest response trajectory on WS 7. The time required for forest recovery to a preharvest condition in terms of tree-species composition, age–class distribution, and soil chemistry would be substantially longer than the time required for forest maturation defined as when the forest reaches an age at which harvesting is economically viable. For example, in the case of nutrient cycling, Swank (1984) showed that annual nutrient inputs in bulk precipitation at Coweeta can exceed nutrient removal associated with sawlog harvest over a typical rotation period (70–80 yr). However, other research at Coweeta using simulation modeling of nitrogen cycling (Waide and Swank 1977) showed that whole tree harvest repeated for shorter rotations (25–30 yr) leads to long-term reductions in total site nitrogen and nutrient availability Our studies on WS 7 and similar studies at the Hubbard Brook Experimental Forest in New Hampshire suggest that when best forest management practices are used, sufficient residual material is left on site to replenish soil nutrients and that there is little site degradation in terms of nutrient capital loss (see Hornbeck et al., chapter 13, this volume). On the other hand, the time for recovery to replenish large wood in streams would need to be measured in centuries rather than years (Webster et al. 1992).

What Is the Trajectory of Response?

Disturbances during the past 30 years, for example, changes in atmospheric chemistry and the decline or loss of tree species (see Swank and Webster, chapter 1, this **(p.232)** volume), have influenced the response at WS 7 as well as altered the reference forests and streams at Coweeta. Tree-species-composition changes that have occurred include pitch pine decline due to drought and concurrent southern pine beetle infestation (Elliott and Vose 2005; Nowak et al. 2008) and eastern hemlock mortality due to hemlock woolly adelgid (Ellison et al. 2005; Elliott and Vose 2011). The combined effect of natural disturbances such as disease, insects, drought, and fire along with the human-caused disturbances on ecosystem processes mean that the recovery trajectory of WS 7 is proceeding toward a continuously changing target. The ability of an ecosystem to respond in this kind of changing-stability landscape has been referred to as its *adaptive capacity* (Gunderson 2000).

Chemical changes in Big Hurricane Branch also show trends that reflect changing reference conditions. Meyer et al. (chapter 6, this volume) found that the dissolved organic carbon in Big Hurricane Branch followed the expected return toward reference levels for 7 years after the clearcut, but this trend did not continue for the next 20 years due to long-term trends in both WS 7 and the reference steam. Worrall et al. (2003) used time series analysis to examine long-term stream nitrate concentrations on WS 7 and WS 2 from 1971 to 1997. Auto-regressive modeling revealed a significant annual memory effect in both watersheds, but WS 2 responded to drought conditions and WS 7 responded primarily to vegetation changes. Moreover, on WS 7 a significant impulse function was derived for nitrate export in 1989–1997, suggesting the watershed is in a temporary equilibrium (Worrall et al. 2003). This impulse response was again observed in the stream nitrate dynamics in 2002–2007 (see Swank et al., chapter 3, this volume). Worrell et al. (2003) concluded that clearcutting has modified watershed nitrogen dynamics beyond the limit of stability and that reversal of this trend would require "massive management intervention." The long-term NO_3-N budget (see Swank et al., chapter 3, this volume) also continues to provide strong evidence that WS 7 is still in latter stage 1 of watershed N saturation (sensu Aber et al. 1989) as described for earlier years of forest succession (Swank and Vose 1997).

Stability of What?

Is ecosystem resilience based on the return of species composition or on some ecosystem function? Clearly, the two are closely tied, since ecosystem response depends on the functional characteristics of the species involved. In the forest, the species shift from oaks and hickories to tulip poplar, red maple, and black locust has resulted in faster decomposition and higher nutrient content in the litter layer. However, the greater abundance of ericaceous shrubs may moderate this change in litter quality and may also inhibit the regrowth of some late successional species (see Boring et al., chapter 2, this volume). In addition, the shift in species composition has increased transpiration, with a consequent decrease in streamflow in some years (see Swank et al., chapter 3, this volume). Where a single species has a unique functional trait, its abundance may fundamentally affect ecosystem response. For example, black locust (*Robinia pseudoacacia*) is the most important tree species with nitrogen-fixing symbionts in the forests of eastern United States. Its abundance in the first 10–20 years following logging contributes to the long-term elevation of stream nitrate concentrations (see Swank et al., chapter 3, this volume).

(p.233) A similar interplay of the resilience of species composition and ecosystem function has been observed in Big Hurricane Branch (see Webster et al., chapter 10, and Wallace and Ely, chapter 11, this volume). Shifts in the structure and function of benthic invertebrates on WS 7 have been an integrated product of alterations in the physical habitat (e.g., sediment), food base, nutrient dynamics, light levels, and the temperature of the stream. Immediately after clearcutting, macroinvertebrate taxonomic diversity increased in Big Hurricane Branch and was accompanied by a shift in functional benthic groups to those that feed on algae, that is, scrapers and collector-gatherers. Gurtz and Wallace (1984) found that many taxa decreased in abundance in areas of lower stream gradient (sand and pebble habitat); whereas taxa increases were observed in the steepgradient bedrock-moss habitat. Following the rapid growth of vegetation on WS 7, allochthonous litter input to Big Hurricane Branch returned to near pre-logging levels by 1983 (Webster et al. 1992). Consequently, detritus-feeding benthic macroinvertebrates (i.e., shredders) responded rapidly, and 9–10 years after logging their production was greater than that in a reference stream, which was attributed to a greater abundance of early successional leaf litter (Stout et al. 1993). Following 16 years of succession, benthic macroinvertebrate abundance was still 3 times higher, and macroinvertebrate biomass and production were 2 times higher (habitat weighted) in Big Hurricane Branch compared to the reference stream (Stone and Wallace 1998). However, by 2003, abundance, biomass, and production of most macroinvertebrate groups were similar to the reference stream (Ely and Wallace 2010). This apparent recovery of the macroinvertebrate assemblage occurred even though benthic organic matter in the WS 7 stream was still only about half that of the reference stream (Ely and Wallace 2010; see also Wallace and Ely, chapter 11, and Webster et al., chapter 10, this volume). It is evident that despite the similarities in benthic macroinvertebrate structure and function, logging activity continued to influence this group of consumers even 25 years after logging, probably because of enhanced resource quality (Ely and Wallace 2010).

Watershed logging has a multifaceted effect on stream macroinvertebrate assemblages. Probably the most important factors are changes in resources and in sediment, but it is difficult to separate the effects of these two factors. Most interpretations have been based on changes in resources. However, the different responses of the macroinvertebrates in different habitats suggest a possibly important role of sediment. Recovery was most rapid in the more stable, moss-covered bedrock habitat. The slower recovery in the riffle and depositional habitats (see Wallace and Ely, chapter 11, this volume) might be attributable to the negative effects of fine sediment resulting from road building and logging.

The Need for a Long-Term Perspective

The need for a long-term perspective of forest ecosystem response to disturbance is clear. Ecosystems that appear to be in rapid recovery from multiple disturbances may be masking longer-term shifts in ecosystem behavior (Palumbi et al. 2008). For example, the pattern of nitrate export from WS 7 during the first several years **(p.234)** following logging appeared to be exactly what we expected—a rapid increase in nitrate export followed by an asymptotic return approaching pre-logging levels (see Swank et al., chapter 3, this volume). However, beginning around 1990, 13 years after harvest, NO_3 concentrations began rising again, reaching peak concentrations in 1996–1997 that were about 35% above earlier post-logging levels. Subsequently, NO_3 concentrations again declined toward pre-logging levels, showing some short-term elevated concentrations in 2003–2005.

Similarly, the initial water yield increase due to decreased evapotranspiration after cutting and subsequent asymptotic return to baseline flows in the ensuing 10 years were as expected from decades of hydrologic research at Coweeta. However, about 17 years after harvest, annual water yield frequently declined below pre-logging levels, suggesting increased evapotranspiration in WS 7. Possible explanations for the long-term trends in stream NO_3 and water yield are given by Swank et al. in chapter 3 of this volume. The long-term studies of invertebrates in Big Hurricane Branch also illustrate a rapid recovery from initial changes followed by a much longer period of continued change (see Wallace and Ely, chapter 11, this volume). These multidecade responses clearly illustrate significant legacies of the logging disturbance and the need for long-term studies to detect and determine cause-and-effect relationships.

Management Implications

Findings from WS 7 provide important information on the management of southern Appalachians mixed-hardwood forests. At the time the study was initiated, conventional logging was typically conducted by tractor yarding from closely spaced skid roads. In contrast, the high-lead cable logging operation on WS 7 used a 2-drum yarder with a 9-m boom mounted on a truck, with a mainline of 320 m of wire cable and 915 m of haul back line (see figure 1.3 in chapter 1). Operating from a road, the yarder had the capacity to yard whole tree logs a distance of up to 250 m and to suspend them above the ground. Thus, there was minimal forest floor and soil disturbance. Conventional logging would have required more than twice the miles of logging roads that the high-lead system required.

A detailed economic analysis was conducted using data collected on the direct costs per unit of wood volume for cable yarding compared to a conventional logging system on the same area (Robinson and Fisher 1982). From an economic perspective, the cable system was competitive with conventional logging; moreover, the reduced environmental impact on soil and water resources from cable yarding clearly favored this method for logging on steep slopes. Within 2 years, timber sales on National Forest lands typically required cable logging on slopes exceeding 35%. In subsequent years, the technology and expansion of cable logging have advanced and been modified to meet harvesting requirements for a wide range of silviculture prescriptions, and today about 40% of Forest Service timber sales in this region require cable logging.

The WS 7 study also provided an opportunity to conduct detailed research on the effectiveness of previously established best management practices for forest road **(p.235)** construction activities and to evaluate some new road standards meant to reduce erosion and sediment movement (Swift 1988). New information useful to managers included an assessment of the portion of total soil loss that comes from cut slopes, road beds, or fill slopes and the effectiveness of grass and gravel in reducing soil loss. The road research also evaluated filter strip standards downslope from roads, providing techniques for controlling soil loss.

In chapter 3 of this volume, Swank et al. presented sediment yield data showing that roads were the major source of sediment delivered to the streams on WS 7. We also emphasize that the erosion response was due to the storms in May 1976. Because of the record rainfall and discharge during this event, which occurred before the new roads were stabilized, we suggest that the magnitude and duration of sediment yield measured on WS 7 are in the upper limits that could be expected in the region after clearcutting and cable logging.

This unique erosion event and set of conditions provides an opportunity to evaluate the long-term effects of such a major disturbance on stream structure and function. Following the initial pulse of sediment export from the catchment, there was a continued release, over a 15-year period, of sediment from upstream storage that had been primarily deposited during the 1976 storms (see Swank et al., chapter 3, this volume). Concurrent with stream sediment dynamics, stream faunal studies indicated that this storm was a major determinant of macroinvertebrate response and recovery on WS 7 (see Wallace and Ely, chapter 11, this volume).

Water yield responses measured following harvest on south-facing WS 7 support the regional use of a previously derived empirical model for predicting short-term annual flow responses for forest management planning in similar hardwood forests. Water yield increases were distributed throughout the year, with the longest percentage flow increases occurring in the autumn when flows are normally lowest and water demands are high. The effects of the forest management prescription on stormflow parameters was low due to inherent hydrologic factors of the watershed, the low density and proper design of roads, and mineral soil disturbance associated with cable logging. The small initial nutrient losses following logging provide evidence for minimal impact of the management prescription on ecosystem health. High rates of net primary production and storage of nutrients in successional vegetation were mainly responsible for nutrient retention.

Summary: Perceptions of Long-Term Changes in Economic Values and Ecological

Services in a Management Context

In table 14.1 we have attempted to summarize the status of watershed parameters before systematic observations began; the changes the first few years after logging; current conditions; and changes we predict for the next 65 years. Based on this summary, figure 14.1 illustrates changes to economic values (primarily extractive timber values) and ecological services that have occurred. It also shows predicted changes both with and without the influence of human caused environmental changes (such **(p.236)** as climate change, invasive diseases, anthropogenic nutrient deposition). Prior to European settlement, the forest was a highly valuable resource with high timber value and clean water (State 1 in figure 14.1 and column 1 in table 14.1). Douglass and Hoover (1988) quoted Mr. C. E. Marshall in this description of the Coweeta area in the early twentieth century: “For reproduction of desirable hardwoods, there are no better lands in Western North Carolina.” WS 7 also had high ecological value, with attributes such as highly diverse assemblages of trees, wildlife, and stream fauna. It also provided many services, which we recognize today as ecological and economic services, including high quality water and sediment retention. However, the watershed was already impacted by humans; for example, the relatively open understory in the southern Appalachians described by early explorers was probably the result of intentional burning by Native Americans (Mann 2005), so it is likely that WS 7 was frequently burned. Prior to our logging experiment, the watershed was already somewhat degraded from pre-European settlement conditions by fire suppression, selective logging, woodland grazing (by early settlers and experimentally in the 1950s), chestnut death, and perhaps other species losses (State 2 in figure 14.1 and column 2 in table 14.1). We cannot quantify the effects of the loss of formerly abundant species, such as passenger pigeons, and potential keystone predators, such as wolves and mountain lions during this period; however, we know that many ecosystems shifts in predator-prey relationships have a substantial effect on ecosystem, processes. For example, at both Fernow and Hubbard Brook, large animals (deer and moose, respectively) have altered the forest recovery from cutting (see Adams and Kochendenfer, chapter 12, and Hornbeck et al., chapter 13, this volume).

Without the experimental logging and further environmental changes, the system would probably have moved by natural successional processes to a new stable state with higher economic value and different ecological values (figure 14.1, State 3). Perhaps, from a Clementsian viewpoint (Clements 1916, 1936) and a Thoreau system of values (Thoreau 1860; see Foster 1999), there is a state on the right side of the figure that ecosystem function and structure might tend toward, with constant environmental conditions and no human influences (State 0). Because environmental conditions are not constant, State 0 is purely conceptual—pre-European climates were not constant; drought periods and hurricanes happened. Indeed, the fact that our forests respond so quickly to disturbance suggest a long history of disturbances and environmental variation. If State 0 did exist, we might not judge it to have extremely high economic timber value by today’s evaluation standards because it would likely have contained considerable low-quality timber due to insects and disease.

In its current state (column 4 in table 14.1), WS 7 has clearly not reached most of the structural and functional characteristics of pre-European settlement ecosystems, but it may be too soon to tell if it is on that trajectory since this forest is only 37 years old. Indeed, we hypothesize that the ultimate stable state of WS 7 (without further logging, State 5 in figure 14.1) will be considerably different than that of the pre-European settlement state because of the loss of American chestnut and other irreversible changes, such as new climate and disturbance regimes. Chapin and Starfield (1997) used the term “novel ecosystems” to refer **(p.237)**

Table 14.1. Characteristics of watersheds before the European settlement (ca. 1700), just prior to logging WS 7 (1975), the first few years after logging WS 7, at the present time (37 years after logging WS 7), and predicted after 100 years of succession with current management practices and anticipated environmental changes.* Interpretations of the magnitude of parameters (i.e., low, moderate, high) are relative across the five time periods.

Parameter	Before European settlement (ca. 1700); State 1 in fig.14.1	Reference (WS 7 before road building and logging, 1974 (WS 2, WS 14); State 2 in fig. 14.1	WS 7 shortly after logging (1976-1980); State 4 in fig. 14.1	WS 7 now, 37 yr after logging (2010)	WS 7 after 100 yr of succession (2075); State 5 in fig. 14.1
Stand characteristics	Large, old trees	Mature trees	Rapid regrowth, saplings, small trees	Black locust being replaced by tulip poplar	Dominated by large tulip poplar
Tree distribution	Patchy	More uniform	Open, mid-story	Fairly uniform	Increasingly patchy
Tree composition	American Chestnut/ red oak/hickory	red oak/hickory	black locust/tulip poplar/red maple	tulip poplar/red maple/chestnut oak	tulip poplar/red maple/chestnut oak
Woody diversity	Moderate	Slightly reduced	Decreased	Unchanged	Moderate
Herbacious diversity	Low	Moderate			
Net primary production	Low	Moderate	Increasing	Decreasing	Moderate
Vegetation biomass	High, 384 t/ha (Boring et al., ch. 2)	Moderate, 156 t/ha (Boring et al., ch. 2)	Low, 1.4 to 25 t/ha (Boring et al., ch. 2)	Aggrading, > 88 t/ha (Boring et al., ch. 2)	High, approaching old-growth (Vose and Bolstad 2007)

Forest floor biomass	High, 27 t/ha (Vose and Bolstad 2007)	High, 26 t/ha (Vose and Bolstad 2007)	High, decreasing	Decreasing to moderate	Moderate
Soil organic C and N	Very high	High	Very high	Decreasing	Moderate
Soil NO_3	Low	Low	High	Still high	
Streamwater NO_3	Moderate	Low (> 10 µgN/L)	Very high (100 µgN/L)	Still high (70 µgN/L)	
Sediment load	Very low	Very low	High	Low, except storms	Low
Evaportranspiration	Low	Moderate	Low	High	Moderate to Low
Peakflows	Low	Low	Increase avg. of 15%	Low	Low
Stormflow volume	Low	Low	Increase avg. of 10%	Low	Low
Canopy insects	Diverse	Diverse	Responding to vegetation changes		Low diversity
Stream invertebrates	Diverse, detritus based	Diverse, detritus based	Low diversity, grazers	Detritus based, reduced production	Detritus based, reduced production
Stream benthic organic matter	High, refractory	High, refractory	Low	Low, more labile	Low, more labile
Stream large wood	Very high	High	High (slash), except low where removed	Low	Still low

(p.238)

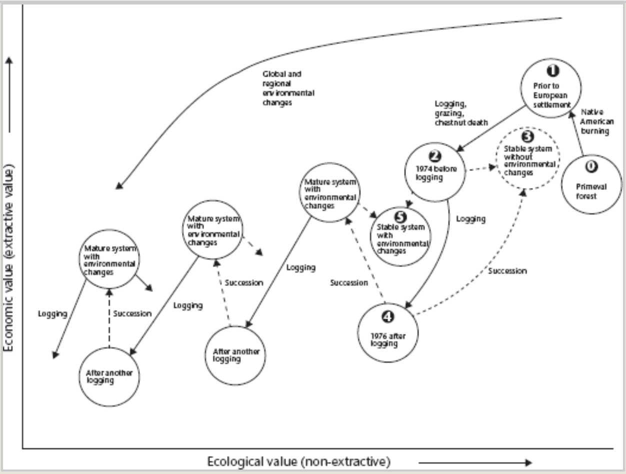

Figure 14.1 Hypothetical trajectories of change in ecological and extractive values of WS 7. Solid lines are human-caused changes; dotted lines represent natural successional changes occurring without global and regional environmental changes; and dashed lines are natural successional changes occurring with global and regional environmental changes. These global and regional environmental changes are predicted to cause decline in both economic and ecological values.

(p.239) to ecosystems responding to global climate change, but Hobbs et al. (2006) and Seastedt et al. (2008) noted that novel ecosystems could result from a broad range of both abiotic and biotic alterations. In that sense, WS 7 in 1974 was already a novel ecosystem.

Immediately after the 1976 clearcut, the watershed had reduced economic value (State 4 in figure 14.1 and column 3 in table 14.1) because there were no harvestable trees remaining. Some ecological service values were likely changed. For example, stream water quality was degraded by sediment even though chemical levels remained well below drinking water standards. There was little reduction in other ecological values, and some values such as improved habitat for early succession-dependent wildlife species and soft mast production were undoubtedly enhanced. Without environmental change, succession would theoretically move the system back towards State 3. In actuality, succession is moving the system towards a new state (State 5 in figure 14.1 and column 5 in table 14.1), though this new state is unknown due to climate change, diseases such as dogwood anthracnose, invasive animals such as earthworms, hemlock woolly adelgid, and perhaps gypsy moths, and invasive plants such as Japanese stiltgrass. Without forward-looking management, we predict that future clearcut logging combined with continuing climate and other environmental changes will reduce both the economic and ecological values of this forested watershed. For example, some evidence can be derived from WS 13 at Coweeta, where a second experimental cutting produced a more simplified stand structure made up mostly of sprout origin *Liriodendron tulipifera* (Elliott and Swank 1994). Also, computer simulations of Coweeta forests suggest loss of nutrient capital and reduction of forest production following multiple cycles of logging (Waide and Swank 1977). The question we pose is whether we can improve both economic and ecological values with appropriate management practices (State 6 in figure 14.2). The answer is clearly yes. The even-aged clearcut prescription for WS 7 has resulted in a forest dominated by *Liriodendron tulipifera* (see Boring et al., chapter 2, this volume). This provides various management options depending on predictions of future timber values. Thinning might be one tool to achieve desired future stand structure and species composition. Proper road construction and logging techniques that minimize soil disturbance cause less deterioration of water quality. With continued road maintenance, future harvest will require very little soil disturbance. In later succession, prescribed fire might be used to encourage more valuable timber species, such as oaks (Arthur et al. 2012). Although we once thought that slash should be removed from channels, we now know that wood in streams is good for sediment retention and animal habitat (e.g., Dolloff and Webster 2000; Gregory et al. 2003). Man-made wood structures placed in streams may further enhance aquatic animal habitat. The construction and maintenance of trails can enhance recreational values.

In managing this ecosystem, we must "not only anticipate change, but we must acknowledge that current systems have already been transformed and are in the process of transforming further" (Seastedt et al. 2008). The species composition and biogeochemical conditions are products not only of current climate change but of other anthropogenic environmental changes, including elevated CO_2, nitrogen deposition, forest diseases, and exotic invasions. We contend that it will not **(p.240)**

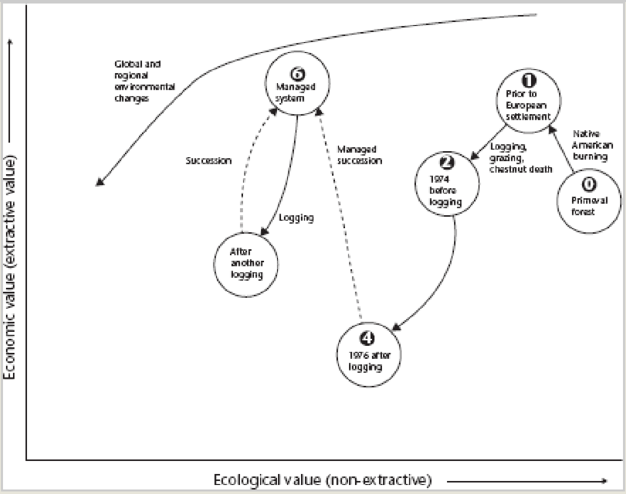

Figure 14.2 Hypothetical trajectories of change in ecological and extractive values of WS 7 with adaptive management of post-logging succession. Solid lines are human-caused changes and dashed lines are successional changes with management based on ecosystem research and predictions of environmental change.

be possible to restore the ecosystem back to some historic or prehistoric state because it has moved beyond the boundaries of the stability of those states. The goal of management cannot be to restore the systems to a past ideal but rather to restore and maintain the ecosystem services provided (e.g., Cairns 1989; Cairns and Heckman 1996).

A research initiatives subcommittee of LTER previously developed a strategic research plan to integrate science for society and the environment in which ecosystems services were emphasized (Collins et al. 2007). Ecosystem services were classified as *provisioning*, *regulating*, and *cultural* services. The roots of multiple-use management (select services) are deeply embedded in USDA Forest Service philosophy and policy, and in its public forests and grasslands management programs. This was true in the early history of the agency and was formally enacted in the Multiple-Use Sustained-Yield Act of 1960. This mandate provided the public with multiple benefits, including clean water, abundant fish and wildlife, a sustainable supply of wood and paper products, and ensured that there would be quality outdoor environments for recreation, wilderness and scenic rivers, supplies of energy and minerals; livestock foraging, and the development of human resources. A pilot program in the multiple-use concept was undertaken in a watershed context at the Coweeta Hydrologic Laboratory, beginning in 1962 (Hewlett and Douglass **(p.241)** 1968) and it continues to provide a valuable example of blending forest benefits for more than 30 years (Swank 1998).

Over the years, the mix of forest uses and benefits evolved in response to changing public needs, new legislative mandates, improved scientific information, and advances in technology. To address changing views of land and natural resources, the Forest Service took a new direction in its research and management programs, adopting an operating philosophy of ecosystem management with the objective of using an ecological approach to incorporate an array of ecosystems services (Thomas 1996). The agency view of ecosystem management is to integrate ecological, economic, and social factors to maintain and enhance the quality of our environment to meet current and future needs.

A compendium of essays on ecosystem management was published in *Ecological Applications* in 1996 (Haeuber and Franklin 1996 and the following papers in that issue), which represented a wide range of view points on the topic. In 1991, a technical symposium was convened at the American Association for the Advancement of Science Annual Meeting that addressed the concept, philosophy, needs, and opportunities related to ecosystem management (Swank and Van Lear 1992). Research at two LTER sites (Hubbard Brook and Coweeta, including WS 7) were used to illustrate how watershed ecosystem analysis can be used to address forest environmental and management issues (Hornbeck and Swank 1992).

Ecosystem management has been interpreted and implemented in a variety of ways by different organizations and agencies. At Coweeta, beginning in 1992, we developed and initiated an ecosystem management demonstration project in the Wine Spring Creek basin in western North Carolina (Swank 1998). The 1130-ha watershed is covered with a mix of hardwood forest types, first- through third-order streams, and diverse flora and fauna. Most of the basin is made up of National Forest land. Participants in this project included an interdisciplinary team of over 55 scientists and managers in five research units in the Southern Research Station, National Forest Systems, and seven universities; state agencies; environmental and conservation groups; and the public. Desired future resource conditions and management prescriptions were determined through a series of workshops comprised of interested stakeholders. During the next decade, a large body of knowledge was derived from research for a wide range of land uses and ecosystem services. This data base was synthesized using an EMERGY-based environmental systems assessment (Odum 1996) of the services provided within the Wine Spring Creek basin (Tilley and Swank 2003). This method of assessment is a mechanism to express ecological and economic benefits with a common metric. The analysis included products and services such as recreation, biodiversity, water yield, timber production, biogeochemical cycles, and research information (Tilley and Swank 2003) and suggested that one of the largest benefits coming into the basin was the large number of scientists and managers involved in the ecosystem demonstrations project and the high value of their research. Christensen et al. (1996) also listed research as one of the services provided by ecosystems. The same is true as a result of the long-term research investment on WS 7; WS 7 has so far provided advanced degrees for more than 20 graduate students, and some 25 senior scientists conducted research on the watershed, publishing over 125 papers (figures 14.3 and 14.4). **(p.242)**

Figure 14.3 Scientists gathered for a three-day Symposium held in Athens, Georgia, in October 1984 to commemorate 50 years of research at the Coweeta Hydrologic Laboratory. The goal of the symposium was to summarize and highlight the major contributions from Coweeta to the hydrologic and ecological understanding of southern Appalachian forested lands. The meeting was attended by over 75 individuals and resulted in a book with contributions from 49 authors/coauthors in 30 papers distributed across 8 topical sections of research. This photo was taken late in the symposium and did not include some of the participants. Keynote speakers included Eugene P. Odum, Jerry F. Franklin, and Hans M. Keller.

(USDA Forest Service photo)

Ecosystem management is based on uncertain knowledge of dynamic ecosystems responding to uncertain predictions of the future (Holling 1996; Lawler et al. 2010). Therefore, ecosystem management must be adaptive (e.g., Walters 1986), changing in response to information provided by studies such as those on WS 7. Examples of this type of forward-looking management include the design of roads and culverts to handle greater rainfall, selection of tree species adaptable to predicted changes in climate and from disturbance regimes. In the Southeast, this might include species that use less water and those that are able to survive extended droughts. Species selection might also mean the choice of species that are resistant to diseases and insects, for example, gypsy moths. The phrase "engineering resistance" has been used in forestry to describe the genetic engineering of trees for resistance to disease. We suggest that the phrase might also be used more broadly to describe the management of forests to include structural attributes and species that may be more adapted to future environmental conditions. Similarly, the role of forests and the options for their management to mitigate greenhouse gas emissions has also been identified (Malmsheimer et al. 2008) and should be considered in any forward-looking research plan. **(p.243)**

Figure 14.4 In November 2009, over 150 scientists gathered for three days in Dillard, Georgia, to commemorate 75 years of research at Coweeta. The focus of this symposium was on the benefits of the long-term research conducted at Coweeta in addressing fundamental hypotheses on hydrologic and ecological processes, as well as practical questions related to science-based land management. Many of the individuals in this picture also participated in the fiftieth anniversary celebration and authored papers in this volume.

(USDA Forest Service photo)

As a site for research to provide guidelines for the adaptive ecosystem management of forested watersheds, WS 7 and other watersheds at places such as Fernow and Hubbard Brook provide an ecosystem service with a value far in excess of other goods and services. Meyer and Swank (1996) concluded that ecosystem management challenges ecologists to test theory in a real-world landscape laboratory. But ecosystem management must also respond to these research findings. As described by Stanford and Poole (1996), research and management policy must involve an iterative protocol—research based on current management strategies and management that incorporates new research findings. Using WS 7 and other watersheds at Coweeta, we will continue to develop hypotheses and test predictions for important ecosystem processes and system-level responses associated with both forest management and natural disturbances.

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