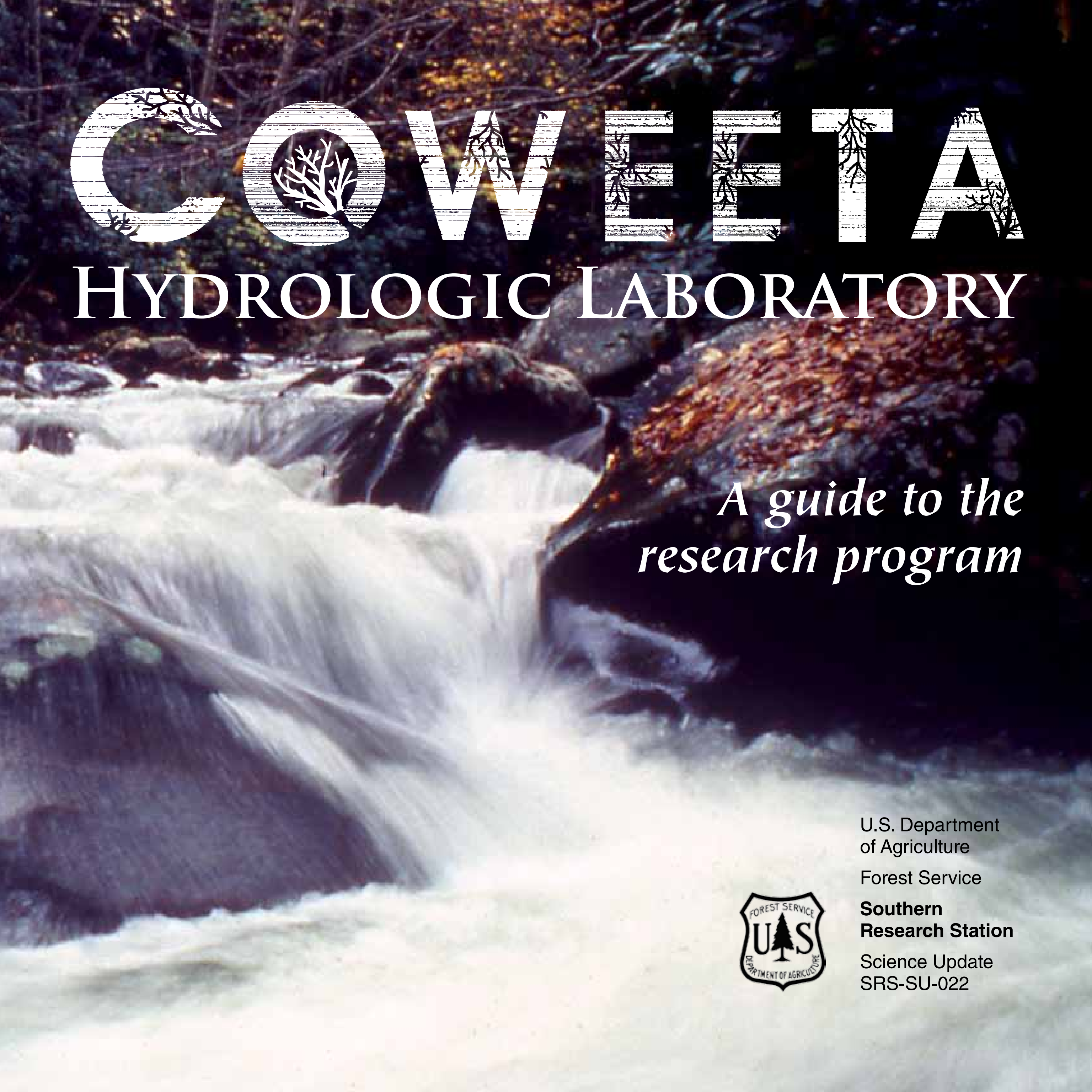

COWEETA HYDROLOGIC LABORATORY

A guide to the research program

U.S. Department of Agriculture

Forest Service

Southern Research Station

Science Update SRS-SU-022

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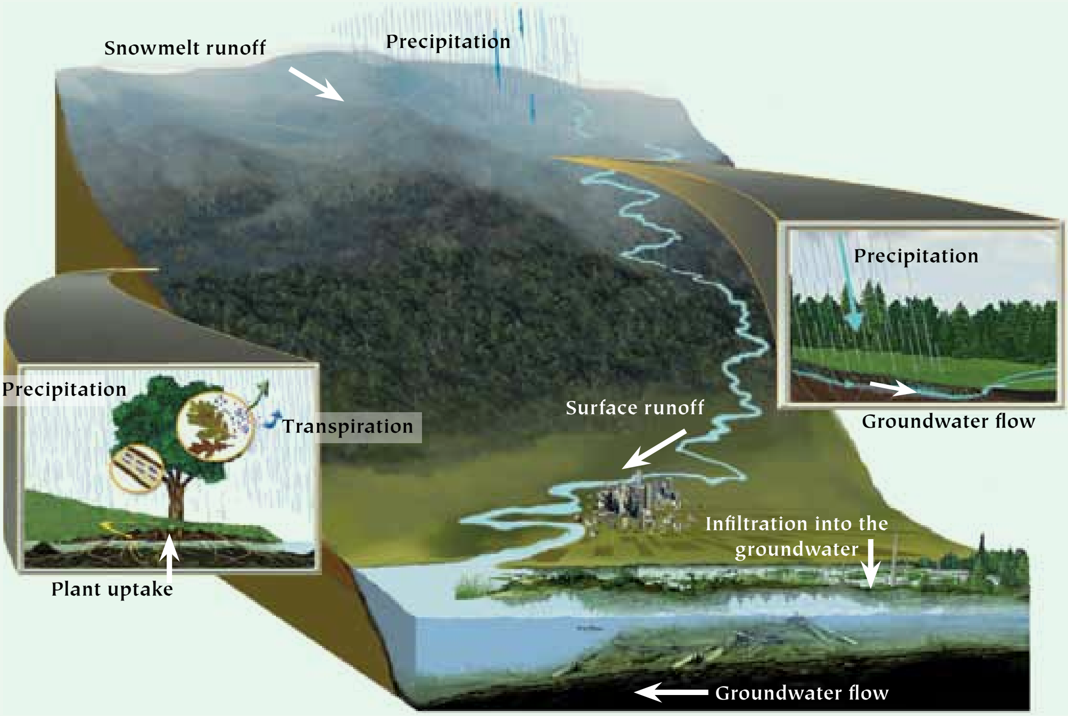
INTRODUCTION

The rains that watered the ground at Earth's beginning are still with us today, falling again from the clouds to soak the soil and flow into streams and rivers, evaporating back into the atmosphere to again form clouds. This endless circling of water is known as the hydrologic cycle, its study known as hydrology.

Much of what we know today about the hydrology of forested watersheds was learned through early research at the Forest Service, U.S. Department of Agriculture, Coweeta Hydrologic Laboratory (Coweeta). Coweeta scientists and partners continue to study the hydrologic cycle, but over the years their focus has expanded to

The Hydrologic Cycle



The Hydrologic Cycle of the Undisturbed Forest

The hydrologic cycle in a forested watershed differs from the street in front of your house or an open field. In the forest, rain first reaches the leaves in the forest canopy high above your head. Only when the canopy leaves are saturated does the amount of water that reaches the ground equal that falling in an unforested area. This is why you can stand under a tree at the start of a heavy rain and you will not get very wet—at least, until the canopy leaves are saturated.

Some of the water that passes through the forest canopy wets the leaves of the understory—the younger trees, rhododendron, and laurel growing beneath the canopy. Rain that passes through the various layers of vegetation and reaches the ground is called

(continued on page 2)

THE HYDROLOGIC CYCLE OF THE UNDISTURBED FOREST

(continued from page 1)

throughfall. A portion of the rain also reaches the ground by flowing down the vegetation stems and is called stemflow. Water that evaporates from the canopy and stems without reaching the ground is called canopy interception loss. Additional water is trapped by the litter layer—the blanket of dead leaves and twigs that make up the forest floor. At Coweeta, 13 percent of the annual rainfall is lost through interception. Of the water that reaches the soil below the forest floor, about 30 percent is taken up by plant roots and used in the process called transpiration. The remainder, which amounts to more than half the annual rainfall at Coweeta, moves beyond the tree roots, percolates through the deep subsoil, and reaches the streams.

include all components of the watershed ecosystem. The 5,400-acre Coweeta basin serves as a living laboratory, where teams of scientists from many disciplines and locations study the interactions among water, soils, vegetation, and other organisms that make up the watershed ecosystem. Like other complex systems, watershed ecosystems develop, grow, and respond to disturbances over decades or even centuries. As an experimental forest, Coweeta provides an ideal location to conduct long-term research, to experiment on forest management practices, and to monitor watershed ecosystem responses over decades, even centuries.

Coweeta Basin

COLLABORATION IS KEY TO ECOSYSTEM RESEARCH

For over 75 years, the laboratory has provided scientists the opportunity to measure and record data on rainfall, evaporation, and streamflow. Using these data, Coweeta scientists have been able to describe the cycle and quality of water in an undisturbed forest—as well as how the water cycle links with other important watershed ecosystem processes. Researchers have also studied the impacts of disturbances on water, nutrient, and organic matter cycles. These disturbances can come from nature itself—as insect infestations, tree diseases, droughts, or hurricanes—but they are more often the result of human activities. Climate change, air pollution, harvesting trees for wood, engaging in recreation, clearing land to farm, developing property, and diverting water for industrial and home use are examples.

Forest scientists study the effect such disturbances have on the quantity, quality, and timing of water and on the associated components of the watershed ecosystem. Understanding the complex interconnections within watershed ecosystems requires skills from many areas of expertise. Research at Coweeta ranges from molecular-level studies on genetic variability to large-scale analyses of land use change in the Southern Appalachian region. The current research program encompasses a broad array of cooperative studies, with an average of 30 projects a year involving approximately 50 senior investigators from universities and institutions from all over the world. Over the past seven decades, the Coweeta research team has produced more than 1,700 research papers that have helped establish the foundation of knowledge required for the science-based management of natural resources.

Tour group at Coweeta Lab

The Coweeta Long-Term Ecological Research Program

Sponsored by the National Science Foundation (NSF), the Long-Term Ecological Research (LTER) Program is a national network of 26 field research sites where more than 1,800 scientists work cooperatively and across disciplines on long-term environmental research. The mission of the LTER network is to provide the scientific community, policymakers, and society with the knowledge and predictive understanding necessary to conserve, protect, and manage the Nation's ecosystems, their biodiversity, and the services they provide.

Established in 1980 as one of six original LTER sites, the Coweeta LTER Program is the center piece of long-term cooperation between the University of Georgia and Coweeta. Since 1980, the program has evolved from a site-based to a region-based project. While much of the research is still focused on the Coweeta basin, research objectives have expanded to advance the scientific understanding of the spatial, temporal, and decisionmaking components behind the land use changes that have taken place in the Southern Appalachian region over the last 200 years—and to forecast patterns of change 30 years into the future. By recognizing land use change as a process and following the core research guidelines of the LTER network, we will continue to provide solid science to enhance education and training and to guide future land use planning and policy.

Core Long-Term Ecological Research Areas

- Pattern and control of primary production
- Spatial and temporal distribution of populations selected to represent trophic structure
- Pattern and control of organic matter accumulation in surface layers and sediments
- Patterns of inorganic inputs and movements of nutrients
- Patterns and frequency of site disturbances

Training, Education, and Knowledge Delivery

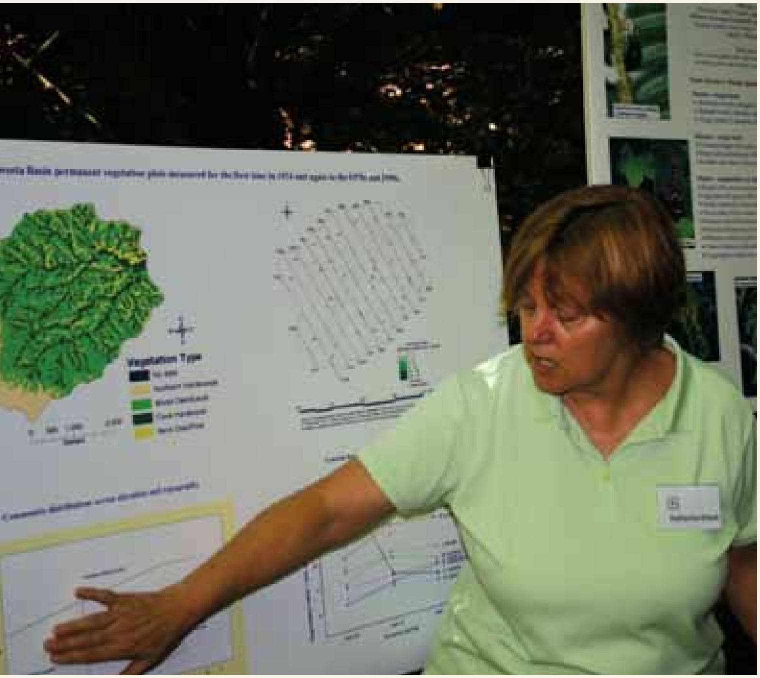
On average, more than 60 groups—over 1,500 people—visit Coweeta each year, where scientists and staff share firsthand knowledge about the experiments conducted in the forested watersheds. Many of the visitors are natural resource managers who use the information to help make decisions about land management activities. The Coweeta Conference Center hosts formal workshops on current issues vital to managing natural resources in the Southern United States with a special focus on Southern Appalachian concerns. The audiences often consist of natural resource specialists from local, State, and Federal agencies. Other frequent visitors include scientists and students from universities throughout the United States, conservation and environmental groups, and policymakers who can view and discuss issues on the ground. Coweeta also hosts numerous international visitors. Examples in recent years include groups from China, Japan, Russia, Turkey, Mexico, France, the United Kingdom, Poland, and India.

Coweeta also serves an important role in training new scientists in many biological fields. Each summer, the laboratory hires four to six undergraduate-level interns to work with scientists on a variety of projects. Students gain hands-on experience in project development, data collection and analysis, and presentation. In addition, graduate students from many institutions conduct research projects at Coweeta in cooperation with staff scientists. As of 2008, more than 250 students had received graduate degrees from research conducted at Coweeta; many of these former students now lead ecosystem research programs at universities and Federal and State agencies throughout the United States.

Field tour presentation

SCHOOLYARD LONG-TERM ECOLOGICAL RESEARCH PROGRAM

Education is also integral to the mission of the LTER Program. Coweeta LTER scientists and staff provide middle school, high school, and community college students “hands-on” field and laboratory research experiences through the Schoolyard LTER Program, which has been funded by a grant from NSF every year since 1998. With the overall goal of building awareness of long-term environmental research into school curricula, the program provides instruction, field research, and data summary and analysis experiences to K through 16 students and instructors. Participants contribute to a wide range of studies that include: monitoring riparian vegetation, examining nutrient content in forest litter, and measuring tree growth on environmental gradient plots.



Field presentation

Schoolyard conservation education

HISTORY OF THE COWEETA SITE

Before the first European settlers reached western North Carolina, the Cherokee Indians—and perhaps others before them—inhabited the Coweeta basin. From 1848 to 1900, European settlers cultivated less than100 acres of the 5,600-acre basin, clearing along the main streams and leaving the rest in forest. Timber companies purchased most of the Coweeta basin in 1902, and logged the basin between 1919 and 1923. In 1918, the Forest Service bought the tract that constitutes the present site, designating it part of the Nantahala National Forest in 1923. The site was set aside as the Coweeta Experimental Forest in 1934. Measurements of rainfall, streamflow, climate, and forest growth began almost immediately. Many of the original laboratory buildings, roads, bridges, climatic stations, and stream measurement devices were built by the Civilian Conservation Corps during this period. In 1948, the site was renamed the Coweeta Hydrologic Laboratory, and today is still the only outdoor Forest Service research site to carry the "laboratory" title. Coweeta's commitment to sharing research with scientists worldwide has been recognized by its inclusion in the International Biological Program, the International Hydrologic Decade, and United Nations Educational Scientific and Cultural Organization's Man and the Biosphere project.

Early 1950s entrance sign

THE COWEETA WATERSHEDS

VARIABLE SOURCE AREA STUDIES

Even in dry years, the streams at Coweeta—some of them emerging from watersheds as small as 10 acres—flow year-round. Questioning how this flow is sustained during dry periods, scientists were confronted with the basic question of how water moves from the forest to the stream.

The deep soils of the Coweeta basin can absorb rain at rates of over 10 inches per hour. When there is an intact litter layer on the forest floor to trap rainfall, stormwater does not move over the top of the soil as surface water runoff, but moves down (percolates) through the soil and into streams. To learn more about the mechanics of this process, scientists constructed a large soil model by placing a rectangular box filled with soil on a natural mountain slope. The soil was soaked with water and covered to prevent

(continued on page 9)

A UNIQUE RESOURCE FOR RESEARCH

A watershed is a basin of sloping land surrounded by ridges and drained by a stream. The Coweeta basin, which contains dozens of separate watersheds, is ideal for hydrologic research. The site was strategically selected due to its topography and aspect and the area's unusually high rainfall (70 to 90 inches per year). The solid bedrock underlying the soils permits the hydrologist to account for most of the rainfall that enters the basin. Many of the watersheds in the basin are very similar in terms of size, climate, soils, and vegetation. The relationship between rainfall and streamflow before disturbance has been charted for many of the watersheds since 1934. To test a theory or evaluate a management practice, scientists can manipulate conditions on a watershed and then compare results with those from a similar undisturbed watershed that serves as a reference.

Since the 1930s, 32 weirs, or stream gauging stations, have been installed on streams in the Coweeta basin; 16 of these weirs are currently operational. Streamflow

Coweeta experimental soil model

data has been collected from the weirs since the 1930s using automatic recorders that continuously monitor the height of the water in the weirs, data which is later translated into streamflow using a mathematical formula based on the dimensions of the weir blade. Because the weirs were so precisely constructed, streamflow can be calculated day and night, through storm and sunshine, throughout the year. Sediment that accumulates in the ponding basin constructed behind each weir can also be measured, and streamwater chemistry data has been monitored since 1972.

Weir no. 9

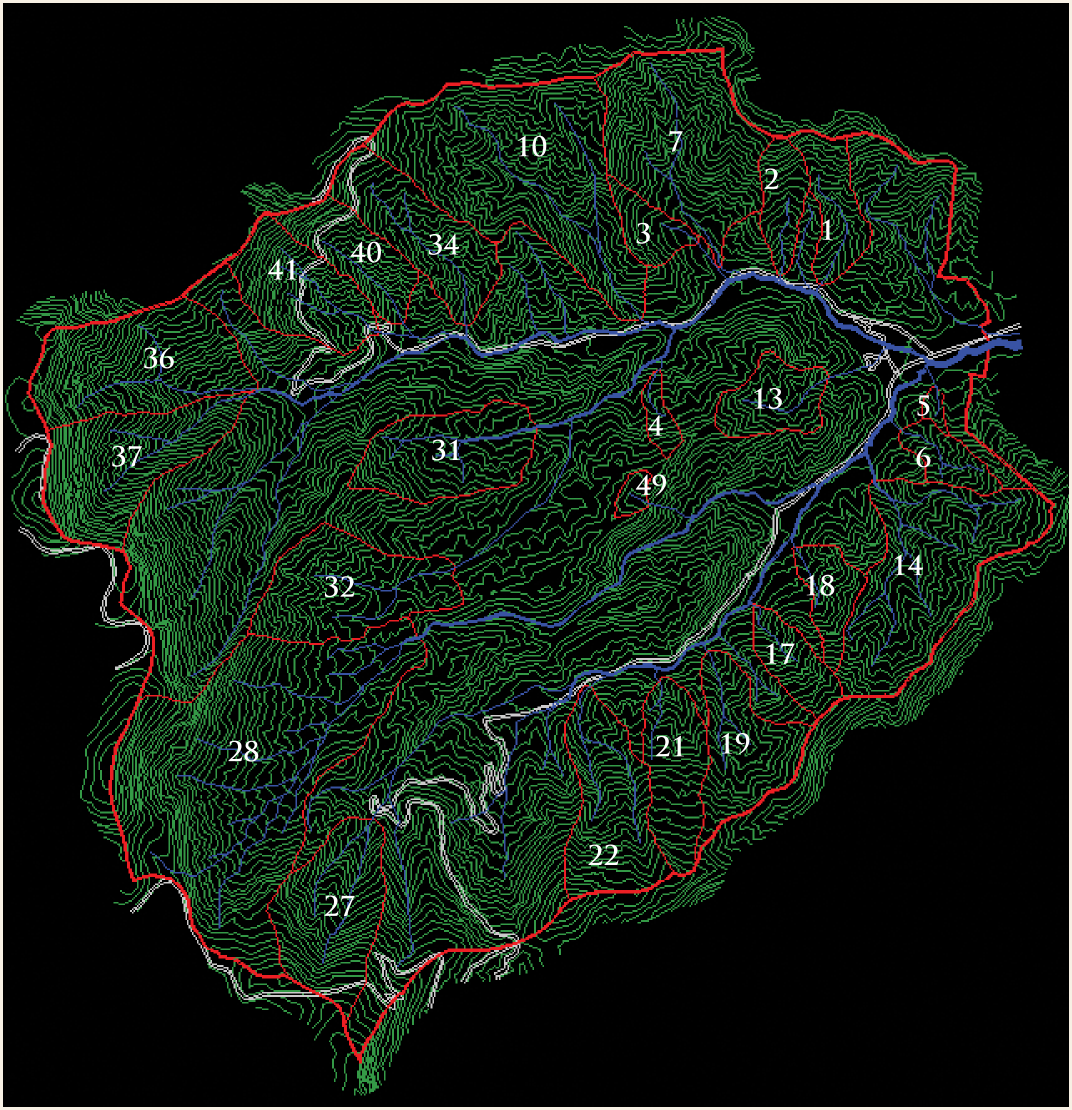
VARIABLE SOURCE AREA STUDIES

(continued from page 8)

evaporation. Water drained continuously from the model for 145 days without the input of additional water. In the first day and a half after soaking, drainage came from saturated waterflow near the base of the model; later, however, water continued to flow from unsaturated soil. From this, scientists learned that water flows through unsaturated soil as individual molecules move downslope in response to the balance between gravity forces and soil moisture. When this hydraulic process occurs on deep soils, it can maintain streamwater levels in the forest even during dry periods.

The concepts of subsurface soil flow developed at Coweeta have been widely used in computer models to simulate the response of streams to storms and dry periods.

EXPERIMENTAL WATERSHEDS AT COWEETA



Hydrologic Laboratory

Watershed No.	Treatment Description
1	Entire watershed prescribed burned in April, 1942. All trees and shrubs within the cove-hardwood type (areas adjacent to stream) deadened with chemicals in 1954. This treatment represented 25% of both land area and total watershed basal area. Retreated as necessary for three consecutive growing seasons. All trees and shrubs cut and burned in 1956-57, no products removed; white pine planted in 1957. In subsequent years, pine released from hardwood competition by cutting and chemicals as necessary.
3	All vegetation cut and burned or removed from the watershed in 1940. Unregulated agriculture (farming and grazing) on 6 ha for a 12-year period, followed by planting yellow poplar and white pine.
6	All woody vegetation cut and scattered in the zone 5m vertically above the stream; reduced total watershed basal area 12%. Clear-cut in 1958, products removed and remaining residue piled and burned. Surface soil scarified, watershed planted to grass, limed and fertilized again in 1965. Grass herbicided in 1966 and 1967; watershed subsequently reverted to successional vegetation.
7	Lower portion of watershed grazed by an average of six cattle during a 5-month period each year from 1941 to 1952. Commercially clear-cut and cable logged in 1977.
8, 9, 16	Combination watersheds containing both control and treatment watersheds.
10	Exploitive selective logging during the period 1942-1956 with a 30% reduction in total watershed basal area.
13	All woody vegetation cut in 1939 and allowed to regrow until 1962 when the watershed was again clear-cut; no products removed in either treatment.
17	All woody vegetation cut in 1940 and regrowth cut annually thereafter in most years until 1955; no products removed. White pine planted in 1956 and released from hardwood competition as required with cutting or chemicals.
19	Laurel and rhododendron understory cut in 1948-1949; comprised 22% of total watershed basal area.
22	All woody vegetation within alternate 10m strips deadened by chemicals in 1955; reduced total watershed basal area 50%. Treatment repeated from 1956 to 1960 as required to maintain conditions.
28	Multiple use demonstration comprised of commercial harvest with clearcutting on 77 ha, thinning on 39 ha of the cove forest and no cutting on 28 ha; products removed.
37	All woody vegetation cut in 1963; no products removed.
40	Commercial selection cut with 22% of basal area removed in 1955.
41	Commercial selection cut with 35% of basal area removed in 1955.
2, 14, 18, 21, 32, 34	Controls with mixed hardwoods stands remaining undisturbed since 1927.
27	Control, but partially defoliated by fall cankerworm infestation from 1972 to 1979.
36	Control, but partially defoliated by fall cankerworm infestation from 1972 to 1979.

(Swank and Crossley, 1988)

EARLY EXPERIMENTS

WATER YIELD STUDIES

How does a forest regulate streamflow? At the beginning of the 20th century, some scientists believed that clearcutting forest would reduce the amount of water coming off a watershed, while others thought that cutting trees would cause a watershed to produce more water, but that, due to erosion, the water would be unsuitable for human use. This question was answered definitively by an experiment at Coweeta on watershed 17, which was clearcut in 1941. All felled trees were left on the watershed to avoid disturbing the soil. From 1946 to 1953, all new growth was cut annually. During this period, water yield from the watershed increased 65 percent the first year, with each acre producing nearly a half million more gallons of water; yet water quality remained high, and flood levels were within normal limits. Streamflow actually doubled in the driest month (October), when it is normally at its lowest.

This experiment demonstrated that clearcutting increases streamflow but does not necessarily increase the erosion that affects water quality. Erosion occurs because of the methods used to remove timber. If the forest floor and soil are not severely disturbed, clearcutting can actually increase the supply of pure water. Further research showed that removing the understory, thinning, clearcutting in strips, and clearcutting the entire watershed increased water yields in proportion to the amount of vegetation cut, while effects on water quality were minimal.

Other studies examining harvest effects on water yield showed that cutting mixed hardwoods on a north slope generated over twice the increase in streamflow as south-slope cutting. To explain this difference, scientists studied both the amounts of solar energy reaching these slopes and the percentage of vegetation cut. They developed equations to accurately predict increases in streamflow in the years after cutting. These equations are still used today

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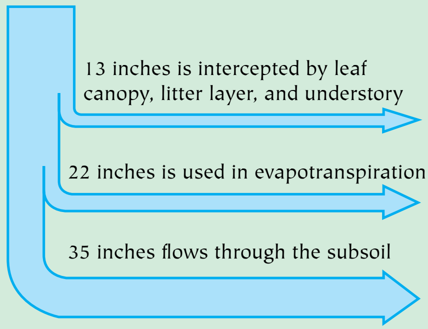


by forest managers to forecast water yield from treatments on forested watersheds.

Scientists also looked at the differences between water use by hardwood and pine forests. Hardwoods are deciduous and lose their leaves in winter, only transpiring water during the growing season, while evergreen pines intercept and transpire water throughout the year. Two watersheds at Coweeta, watersheds 1 and 17, were cleared of hardwood forest and planted in white pine. Measurements revealed that an acre of white pine used 250,000 more gallons of water per year than the same area of hardwood. The conclusion: converting a hardwood forest to pine clearly reduces streamflow.

In another experiment designed to investigate other vegetative types, grass was planted in watershed 6 after the timber was removed. Research found that a dense field of grass used nearly the same amount of water as the hardwood forest it replaced. The grass was not managed; no mowing or grazing occurred on the watershed. As grass production declined streamflow increased, providing more evidence that vegetative type and management affect water yield and quality.

Watershed no. 17

Mountain Farming and Grazing

Scientists never doubted that farming on steep slopes was destructive to soil and water, but they needed data to determine the nature and extent of the damage caused by practices that were commonplace on Appalachian hillsides. Watershed 3 was cleared in 1940. Corn was planted on 6 acres, and 7 acres were planted to pasture grasses that were grazed in alternate years. The remaining acreage stayed in forest.

Expecting a significant increase in sediment runoff, researchers designed a large basin and deep-notch weir to measure erosion. During the 14 years of study, corn yields steadily declined even with the addition of commercial fertilizer because of the loss of topsoil. Eventually crop yields were insufficient to pay for the seed. On the 7 acres planted in grasses and managed for grazing, cattle compacted the soil, reducing its ability to absorb water. By the end of the 13th year, erosion from watershed 3 had resulted in a 215-ton increase in soil

Mountain farming on Watershed no. 3

Mountain farming on Watershed no. 3

loss from the watershed. The stream channel had become wider and deeper, and overflowed from the streambanks, causing frequent flooding.

Control plots were established on watershed 7 in 1941 for another grazing experiment. Half of the plots were fenced to prevent cattle from grazing; half were left open to unrestricted grazing. Due to compaction, the ability of the soil to absorb rain decreased significantly on the grazed plots, and by the end of the eighth grazing season, pasture forage had significantly decreased and there was a sharp increase in the sediment runoff going into the stream. Cattle were forced to browse on hardwood foliage, causing the growth of yellow-poplar (*Liriodendron tulipifera*) to decrease by 50 percent; the growth of other species also decreased.

Together, these experiments demonstrated the damaging effects of improperly managed hillside farming and grazing in the Southern Appalachians.

Cattle grazing

Mountain farming

RESPONSIBLE LOGGING PRACTICES—ROAD CONSTRUCTION

The design standards for mountain forest roads that Coweeta scientists developed to protect water quality have been adopted as BMPs by nearly all Eastern States. Key recommendations include:

1. Construct roads along the contour and avoid steep grades whenever possible.

2. Avoid the older road construction practice of building climbing roads beside streams.

3. Cross streams at right angles and install culverts or bridges.

4. Avoid ditching on the upper side of the road.

5. Break long slopes with gentle dips to trap and discharge water moving down the road, placing brush barriers at runoff points.

(continued on page 17)

TIMBER PRACTICES

Watershed 10 was opened to local timber harvesting practices between 1941 and 1948, long before foresters were aware of Best Management Practices (BMPs) that allowed for responsible removal of logs from harvested areas. Logging roads were located and constructed by traditional methods, horses were used to drag the logs down slopes to loading decks, and trucks hauled the logs out of the forest. As expected, erosion from log trails and roads was extensive. In the undisturbed forest within the Coweeta basin, turbidity—a measure of the concentration of soil particles in the water—routinely averages about 4 parts per million (ppm). During the logging operation, turbidity averaged 94 ppm and reached an alarming 5,700 ppm during a storm event in 1947. Such erosion persisted long after the logging stopped. The soil erosion and impairment of water quality in streams during logging operations resulted from disturbing the soil litter layer by dragging whole logs down trails and across streams, not from cutting trees. Studies at Coweeta on logging practices

Early logging with A-frame

Early logging with four-wheel underslung log cart demonstrated several methods that minimize erosion and water quality effects.

A-frame winch and boom, crawler tractors, and cable logging were timber harvest methods developed to help reduce soil erosion and minimize stream turbidity. In the late 1950s, an A-frame winch and boom were used on two sites at Coweeta to skid logs to the log deck. The A-frame cable lifted the larger, butt end of the tree off the soil and skidded it uphill a maximum of 600 feet to the deck. Rarely was more than one tree winched over the same trail. During clearcutting operations on watershed 28 in 1963, crawler tractors were used to winch logs in much the same way. Skidding logs across watercourses was prohibited, and tractors were restricted to roads or ridges to reduce disturbance adjacent to the stream. Cable logging, a method that suspends logs on heavy wire high above the forest floor, was demonstrated in 1977 on watershed 7. Cable logging virtually eliminates skid trails, and requires less road construction, therefore, reducing erosion and sediment transport and deposition.

RESPONSIBLE LOGGING PRACTICES—ROAD CONSTRUCTION

(continued from page 16)

6. Provide a minimum width of undisturbed vegetation, called a filter strip, between roads and streams.

7. Either cut banks vertically, or backslope and immediately seed them with grass.

8. Match the road surface to amount of use. When there will be little traffic, grass is economical and effective.

9. Once installed, BMPs must be maintained periodically in order to remain functional and effective.

Cable logging

Knuckle boom loader

Managing the Land for Multiple Uses

The Appalachian Trail runs along the western ridge overlooking the Coweeta basin and passes through watershed 28, a 356-acre multiresource forest management demonstration site that includes several types of forest cover, sparkling streams, and many species of wildlife. Because of these features, the watershed was divided into compartments for the management of water, timber, wildlife, and recreational resources.

In 1963, a yellow-poplar stand on watershed 28 was thinned to stimulate growth of the best trees, and the mature hardwoods along the upper slopes and ridges were clearcut to increase water yield, regenerate high-quality timber, and produce forage for deer. The roads were carefully designed to permit current and future research access to all parts of the watershed, and to protect soil and water resources and minimize maintenance cost. Roads for these operations were seeded with grass and are still used today; roads retired from use can be reopened at little cost.

To improve wildlife habitat, some debris was cleared from streams and small log structures were installed to create more pools and riffles for trout habitat. Clearings created in forests by timber operations offer good habitat for deer and grouse and also good views for sighting game. In addition, the young vegetation in these openings provides food for animals. Today, hikers on the Appalachian Trail look out over a rapidly growing young forest composed of species such as northern red oak (*Quercus rubra*) and black cherry (*Prunus serotina*). This experiment clearly demonstrates the opportunity for compatible management of forest resources.

Watershed no. 28

ECOSYSTEM RESPONSES TO DISTURBANCE

Effects of Forest Harvest on Ecosystem Processes

Watershed 7 was clearcut in 1977 to determine, among other things, the impacts of forest harvest on vegetation diversity and nutrient cycling processes. Vegetation in permanent plots was measured before cutting and several times over the 30 years since cutting. The results from this study showed that clearcutting favors shade-intolerant woody species such as yellow-poplar and black locust (*Robinia pseudoacacia*), accompanied by numerous early successional forbs and vines. After 10 to 15 years, the shade-tolerant evergreen shrubs rhododendron (*Rhododendron maximum*) and mountain laurel (*Kalmia latifolia*) developed strong dominance in the understory. A substantial reduction in large-seeded and slower growing tree species such as oaks (*Quercus spp.*), hickories (*Carya spp.*), American basswood (*Tilia americana*), and yellow buckeye (*Aesculus flava*) have resulted from clearcutting, competitive exclusion, and lack of time and conditions for seed dispersal. However, in all of these vegetation communities, there was a trend towards increased woody species diversity.

These shifts in species composition had significant effects on biomass accumulation and, ultimately, soil and aboveground nutrients. Soils data showed significant increases in total carbon, total nitrogen, as well as base cations such as calcium, compared to pretreatment levels for up to 3 years following harvest. This increase

Watershed no. 7

was attributed to the decay of slash material remaining onsite following harvest. Increased soil nitrogen availability was evident more than 20 years after harvest.

The stream acts as an integrator of watershed ecosystem responses and, thus, changes in vegetation, soil chemistry, and nutrient cycling patterns in watershed 7 were evident in both short- and long-term stream chemistry data. Stream nutrient export (nitrate, calcium, etc.) increased immediately following harvest, reaching a peak 3 years after harvest was completed. Stream nitrate export then declined from posttreatment highs for approximately 10 years, but never returned to pretreatment levels. After the initial stabilization period, patterns of nitrate losses and water yield became variable compared to the reference watershed (watershed 2). This variability continued with watershed 7 exporting more nitrate and using either more or less water than the reference watershed through 2007. Process-level research such as forest regrowth, alteration of tree species, and shifts in nutrient cycling provide insights into the reasons for the fluctuations in stream nitrate.

This study demonstrates the knowledge gained through the collection of long-term data at the watershed scale coupled with the internal dynamics of basic biogeochemical cycling processes. Further changes are likely as watershed 7 regrows over the next several decades. Coweeta scientists will continue to monitor changes in carbon, nutrient, and water cycling as part of long-term research critical to the understanding of ecosystem response to disturbance.

Soil sampling

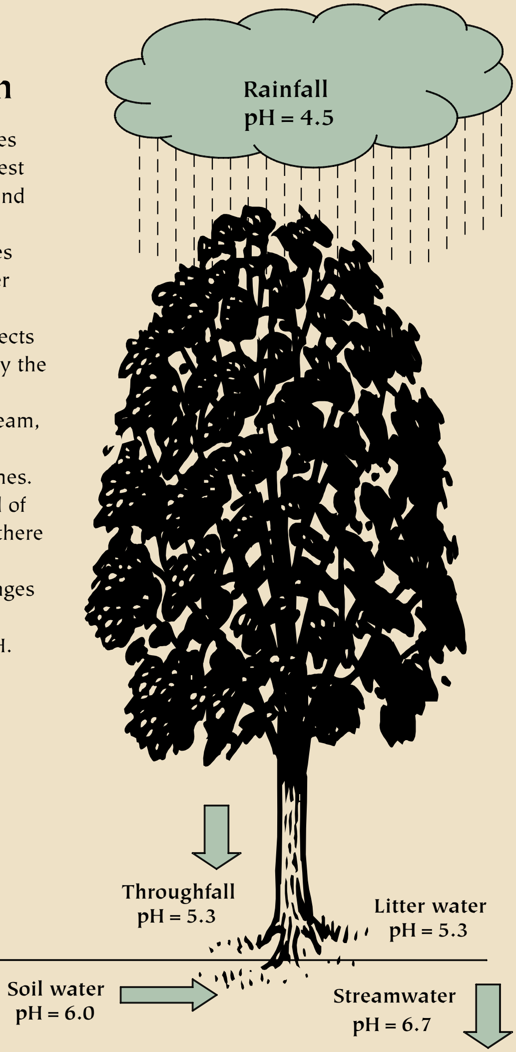
Effects from Atmospheric Chemicals

Some atmospheric chemicals are nutrients that are beneficial to forests, while others such as excess sulfur, aluminum, and lead may be harmful. The chemical inputs from the atmosphere are carefully monitored using deposition samplers to collect rain (wet deposition) and particulates (dry deposition) for chemical analysis. Soil and water chemical analyses reveal the presence and movement of atmospheric chemicals through the forest. The balance sheet of each chemical is called its budget. Coweeta researchers use these budgets to determine how watersheds are impacted by changing atmospheric inputs, natural disturbances, and forest management activities.

The second longest continuous forest study of acid rain in the Eastern United States began at Coweeta in 1972. Acid rain, the input (or deposition) of acidic particles and vapors containing sulfur and nitrogen that collects on leaves and other surfaces, can effect soils and aquatic life, impair water quality, and corrode stone and metal. At Coweeta, scientists determined that, so far, local forests have been able to neutralize the effects of acid deposition by

Acid Rain

As rainfall moves through the forest canopy, litter, and soil the water usually becomes less acid (higher pH) due to the neutralizing effects of the forest. By the time rain water reaches the stream, the acidity is reduced 100 times. Over the period of measurement, there have been no consistent changes in rainfall or streamwater pH.



accumulating sulfur in soil, but scientists caution that the capacity of the ecosystem to effectively continue this process is unknown.

While the element nitrogen is essential for forest growth and productivity, high inputs of atmospheric nitrogen could have negative effects on water quality and forest health. The study of long-term trends of nitrogen and sulfur deposition, transport, and loss in various treated and untreated watersheds at Coweeta has helped to increase understanding of the role of soils, vegetation, and other organisms in mitigating the impacts of atmospheric pollutants on forest ecosystems.

Base climate station

Species-Level Response

Coweeta scientists are modeling forest growth (also called net primary production) and water uptake (also called transpiration) and evaporation in eastern deciduous forests. These models are mathematical representations of the biological processes that occur in nature and allow scientists to make predictions into the future. By measuring fundamental physiological processes such as photosynthesis (carbon uptake by plants), respiration (carbon loss by soil and plants), and sap flow (water flow through the tree roots and stem to the leaves) and applying these data to mathematical models, scientists can then determine ecosystem carbon cycling, net primary production, and water use among species. Researchers have measured many of the hardwood species common to Southern Appalachian forests and determined that rates of photosynthesis, respiration, and water use differ significantly among the species, and that species-based models are needed to accurately estimate forest growth and water demand. This species-level understanding is critical for predicting the potential impacts of changing species composition due to climate change or invasive insects and diseases.

Natural and human-caused disturbances have played significant roles in shaping the present forest composition and diversity in the Southern Appalachians. Disturbances such as timber harvesting or wildfires can change the relative composition of tree species and strongly influence species diversity. Maintaining a diverse landscape requires knowledge of ecosystem dynamics

Sap flow study

as well as an understanding of the ecology of individual species. Scientists have completed studies in Coweeta watersheds that examine temporal changes in tree and herbaceous species composition and diversity following drought, prescribed fire, harvesting, and hurricane blowdown.

For example, past severe droughts have resulted in the death of only certain species of trees. In the mid-1980s, a severe drought that occurred across the Southeastern United States resulted in the elevated mortality of red oak species, particularly scarlet oak and black oak, throughout the southeastern region. This form of forest disturbance is not uncommon even during normal rainfall periods and is the most frequent natural forest canopy disturbance type in these ecosystems. Coweeta scientists have shown that despite the frequency of these small-scale canopy disturbances, they have very little impact on forest structure and composition. What has been learned is that far less frequent catastrophic disturbances such as those associated with tropical storms and hurricanes leave a much longer lasting impact than more frequent smaller scale canopy disturbances.

Soil CO_2 sapflow study

Soil water sampling

Fire in Mountain Ecosystems

Native Americans burned large forested areas for agricultural and hunting purposes for thousands of years before the arrival of Europeans. In the mid-1800s, European settlers started using fire in combination with land clearing.

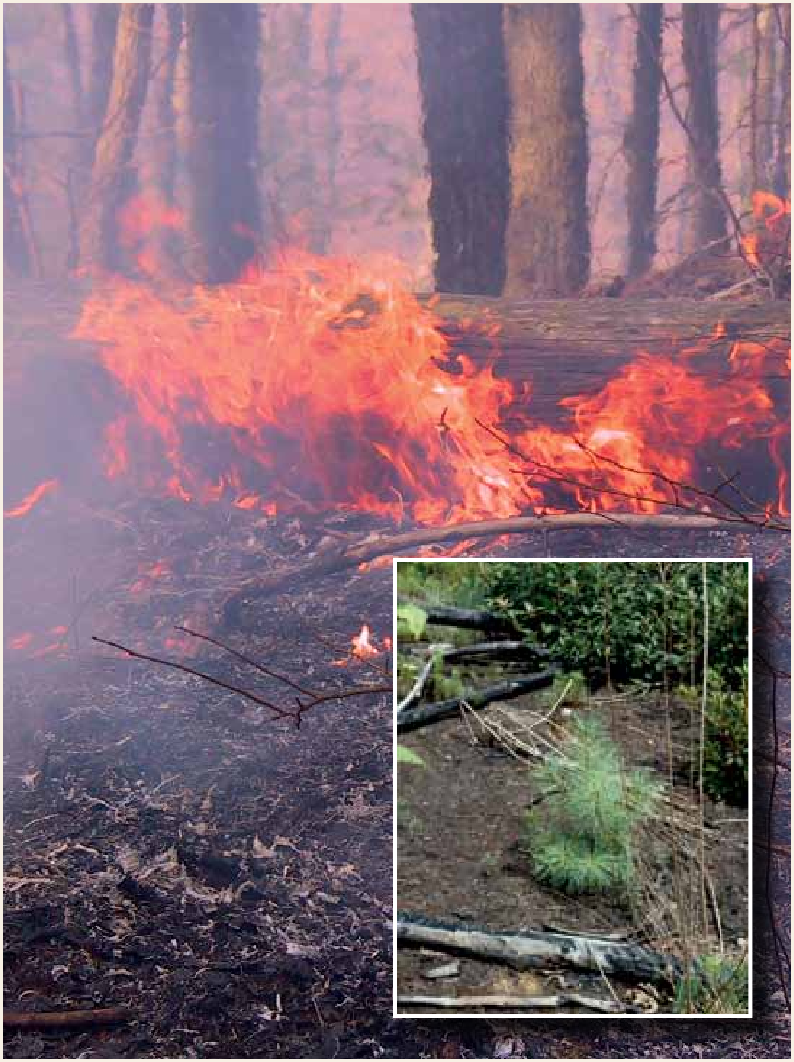
By the early 1900s, timber had been logged throughout most of the Southern Appalachian region. During the same period, chestnut blight decimated the American chestnut (*Castanea dentata*); a majestic tree that once dominated the hardwood forests of the region. Later fire exclusion, smaller scale logging, and reversion of agricultural land to forest further shaped forests in the region. Fire exclusion in the Southern Appalachians has increased fuels and perhaps more importantly, facilitated the expansion of highly flammable shrubs in mid and upper slopes and of tree species such as red maple (*Acer rubrum*) that are considered fire sensitive.

Prescribed burning—the planned and careful use of fire for management purposes—is increasingly used by land managers in the Southern Appalachian region as a tool to both reduce fuel loads and restore ecosystem structure and function. Research conducted by Coweeta scientists has determined that fire can regenerate hardwoods and yellow pine species and enhance biological diversity when applied to certain forests,

Prescribed burning

Prescribed burning in Southern Appalachian forest ecosystems has many potential benefits:

- Reduction of fuel loads to minimize the risk of catastrophic wildfire
- Reduction of the evergreen understory to promote regeneration of desirable species such as oaks
- Restoration of degraded pine-hardwood ecosystems
- Increased diversity of plants, small mammals, birds, amphibians, and insects
- Stimulation of fast-growing new shoots to increase productivity
- Stimulation of nutrient cycling rates to increase site productivity



Prescribed burning and regeneration

but has differing effects on carbon and nutrient pools and nutrient cycling rates. Reintroducing fire into the current forests of the region will have varying effects on ecosystem properties and vegetation structure and composition, depending on fire type (intensity, severity, frequency, timing, and scale) and forest type (current species composition and structure, slope, soils, microclimate, and fuel load).

Because of the long period of fire exclusion, thorough analyses of potential negative consequences, such as excessive nutrient losses and decreased water quality, must also be conducted. Since 1990, Coweeta scientists and collaborators have investigated the impacts of prescribed burning with long-term (ongoing), interdisciplinary, ecosystem approaches. One unique aspect under study is the long- and short-term impacts of prescribed fire on ecosystem sustainability, using cycling rates and pool sizes of carbon, nutrients, and water as key indicators of sustainability. Researchers have found that balancing fuel moisture and type with burning technique can optimize results and protect against nutrient losses, thus, ensuring the long-term productivity of the site.

Insects, Disease, and Ecosystems

Numerous studies at Coweeta investigate the interrelationships between insects and ecosystem processes. Recent disturbances and invasions by nonnative species have provided unique opportunities to evaluate the impacts of insects at the watershed scale.

Fall cankerworm *(Alsophila pometaria)*—A study at Coweeta showed that chronic loss of leaves from predation by the fall cankerworm (a native spring defoliator) could be tied to higher levels of nitrate-nitrogen in the streams of several mixed hardwood forests in the Southern Appalachians. The results of this study represent one of the clearest demonstrations of functional, ecosystem-level consequences of the feeding activities of forest defoliators. The significant loss of nitrate-nitrogen is a response to the alteration of nutrient transfer and turnover rates associated with forest defoliation and the consequences of such radical changes may affect long-term processes of the forest ecosystem.

Southern pine beetle *(Dendroctonus frontalis)*—The southern pine beetle, a native pest, is one of the most destructive insects of pines in the Southern United States, Mexico, and Central America. It prefers to feed on southern yellow pines [common yellow pine species in the Southern Appalachians are pitch pine (*Pinus rigida*), Virginia pine (*P. virginiana*), and shortleaf pine (*P. echinata*)]; however, during severe outbreaks the insect will also feed on eastern white pine (*P. strobus*). In the late 1980s and again in 2000, pine forests in the Southeast were severely impacted by southern pine beetle infestations including most of the pitch pine stands at Coweeta (watersheds 1 and 17, the two white pine watersheds). This infestation presented an opportunity to study the insect's effects on an eastern white pine forest community. Researchers located plots in the two watersheds to look at the impact of the beetle outbreak on forest gap conditions (light, soil moisture, and temperature) and on understory herb and seedling diversity and density. Results showed that:

- More light penetrated the canopies over beetle plots than over nonbeetle plots

Fall cankerworm

Pine beetle damage

Adelgid-caused hemlock mortality

Hemlock woolly adelgid

- Litter and soil temperatures were significantly higher in beetle plots than in nonbeetle plots during late summer through early fall months
- Soil moisture was generally higher in beetle versus nonbeetle plots

The forest floor of beetle-infested plots tended to accumulate more litter than the floor in plots that were not infested. A comparison of herb layer composition showed that there was significantly more Virginia creeper (*Parthenocissus quinquefolia*) and violet species (*Viola spp.*) in nonbeetle plots than in beetle plots, while there was significantly more lowbush blueberry (*Vaccinium vacillans*) in beetle plots than in nonbeetle plots. There was greater tree seedling species richness in beetle plots than nonbeetle plots, though herb layer species richness tended to be greater in nonbeetle plots.

Hemlock woolly adelgid *(Adelges tsugae)*—Hemlock woolly adelgid, a nonnative invasive insect that feeds on eastern hemlock (*Tsuga canadensis*) and Carolina hemlock (*T. caroliniana*), was first identified at Coweeta in isolated locations in 2003 and has since spread to most areas of the basin. First reported in the 1950s in Virginia, hemlock woolly adelgid has now spread throughout the Northeastern United States and to the Southern Appalachian region of western North Carolina and northern Georgia. Hemlock trees are prized for their beauty in both forest and urban settings, and they serve an important ecological role in the Southern Appalachians. They are a keystone species in near-stream areas, providing critical habitat for birds and other animals and shading streams to maintain cool water temperatures required by trout and other aquatic organisms. At Coweeta, the research program on hemlock woolly adelgid focuses on four key elements:

- Developing techniques to monitor and predict the spread of the insect
- Evaluating strategies to reduce or stop the spread of hemlock woolly adelgid
- Understanding how the loss of hemlocks impacts the ecosystem
- Developing and evaluating ways to restore function to ecosystems impacted by hemlock mortality

Although hemlocks typically die within 5 to 7 years after infestation in the northeast, Coweeta research has shown that hemlock woolly adelgid is spreading and killing hemlock trees faster than expected in the Southern Appalachians. Assessing impacts of hemlock mortality on ecosystems will require long-term monitoring, but initial results indicate changes in both carbon and water cycling processes.

Chestnut blight *(Endothia parasitica)*—The story of the American chestnut (*Castanea dentata*) is an unfortunate example of how forest diseases can dramatically change the structure and function of forest ecosystems. By the early 1900s, the chestnut blight had decimated American chestnut over most of its range in Eastern North America. Local infestations were first reported at Coweeta in 1926. A basinwide survey in 1934 identified chestnut as the most dominant species at Coweeta; the species occurred in nearly all of the survey plots and comprised 36 percent of the basal area (a combined measured of tree size and density). This early survey noted that most of the chestnut was already dead or dying at Coweeta. Further inventories identified increases in several other species in response to the openings in the forest canopy created by chestnut mortality: eastern hemlock, red maple, flowering dogwood (*Cornus florida*), chestnut oak (*Q. prinus*), sourwood (*Oxydendrum arboreum*), and tulip poplar in the coves. American chestnut had several characteristics that few of these replacement species can duplicate, but it was especially prized for its durable wood and large seed crops that provided food for humans, domestic livestock, and wildlife. As a result, ecosystem processes have likely changed with the demise of chestnut and replacement by other species with different growth rates, litter qualities, and decomposition and nutrient cycling rates.

The cool and moist conditions of the Southern Appalachians are especially accommodating to many other forest diseases. Although not as lethal as the chestnut blight, dogwood anthracnose (*Discula destructiva*) reached epidemic levels in the Coweeta basin during the 1980s. By 1990, it was estimated that 87 percent of the flowering dogwoods were infested with dogwood anthracnose; mortality was substantial in some of the higher elevations.

Blight infested American chestnut

American chestnut burr

As a result of these and other forest health threats, Coweeta scientists keep a vigilant eye on the condition of trees within the basin and in some cases, conduct experiments in anticipation of the arrival of forest pests. In one such study, scientists simulated the impacts of sudden oak death (*Phytophthora ramorum*), a disease that has shown the potential to impact northern red oak and rhododendron, but has not yet been detected at Coweeta. In this way, scientists can begin to develop response and restoration strategies before the forest ecosystems have been impacted.

Field plot

Analytical lab

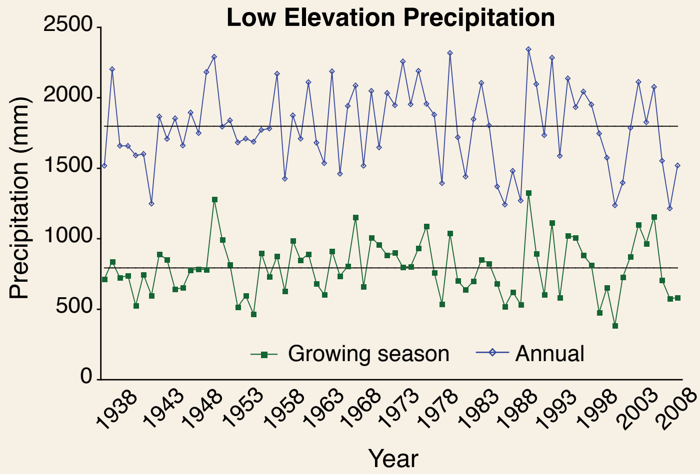
Field data recording

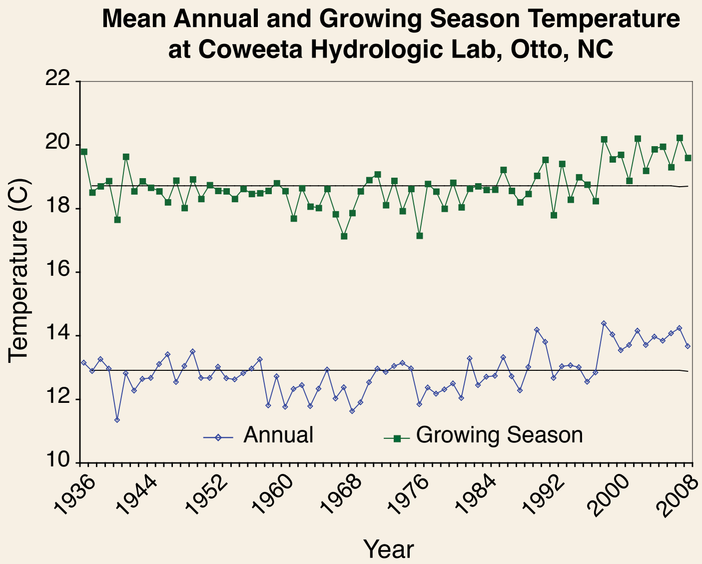
Variation in Climate

Climate has been monitored at Coweeta through a network of climate and rain gauging stations since 1934. Climate parameters such as temperature, rainfall, wind speed and direction, humidity, solar radiation, air quality, and evaporation continue to be measured at different elevations and aspects across the Coweeta basin.

The regions of the world are classified into climate regions; Coweeta is classified as having a maritime, humid, temperate climate. Coweeta weather is strongly influenced by the oceanic atmosphere (maritime); the basin receives high levels of rainfall throughout the year (humid), and daily and seasonal temperatures do not fluctuate widely (temperate). Long-term climatic monitoring is very important because it helps scientists explain current weather in terms of what has happened in the past and what can be expected to happen in the future. For example, long-term Coweeta climate data indicate that the frequency of significant droughts has increased since the mid-1980s and that air temperature (especially during the winter) has been increasing since the 1970s.

Remote precipitation gauging system





Land Use Change and Water Quality

How important are forests to maintaining high quality water in the Southern Appalachians? Coweeta studies show that forests produce the cleanest water among other land uses; forested watersheds have consistently been shown to have lower sediment and nutrients in streamwater. Healthy forests soak up nutrients from the soils as they grow. For example, the lowest levels of nitrogen are usually found in waters draining forested watersheds, while the highest levels are found in water from agricultural and urban uses. One study by Coweeta scientists showed that as the stream flows from a forest water quality is high, but as it flows through a more urban setting, water quality declines from the inputs of sediment and nutrients from nonforest landscapes. However, when intermixed with other land uses, undisturbed forests can improve streamwater quality draining agricultural and urban areas. For example, in a recent study, Coweeta scientists showed that the combination of dilution from clean water draining forested watersheds and instream processes improved water quality in a stream draining an urbanized headwater watershed. With the popularity the Southern Appalachians now have as a retirement destination and for second homes, understanding the impacts of changing land use and a growing population on water quality will only become more critical as demands for high-quality water for human consumption increase.

Sediment from Roads

Sediment is one of the most significant stream pollutants in the Eastern United States. High sediment loads in streams have negative effects on aquatic insects, animals, and plants and can substantially increase the cost of water treatment. Nonpoint sediment from unsurfaced roads contributes to the majority of sediment present in Southern Appalachian streams. One study estimated that unpaved roads, ditches, and road banks were responsible for 85 percent of the stream sediment load in a large watershed in the Southern Appalachians.

Roads in the Southern Appalachians vary from improved paved roads to poorly constructed and maintained dirt roads. Past research has generated a range of Best Management Practices (BMPs) designed to limit the production and movement of road sediment. Despite the development and implementation of these BMPs, road sediment continues to be a major challenge to private and public land managers. To address this challenge, land managers need information and tools to assess the relative differences in sediment generated from a range of existing road conditions, and to evaluate potential improvements after BMPs are put in place.

In one study, Coweeta researchers measured the particulate matter of total suspended solids and total petroleum hydrocarbons (TPH) from an array of typical road conditions found on public and

1950s road construction

private land in the Southern Appalachians. These included paved roads, gravel roads with routine maintenance, gravel roads with sediment control BMPs, and poorly constructed roads receiving minimal maintenance. Results showed the lowest amount of sediment production came from the paved roads and the highest sediment production came from the poorly constructed roads receiving little or no maintenance. Properly installing and maintaining BMPs effectively reduced sediment delivery to streams. TPH was found to be in very low concentrations in paved road runoff, and was not found in nearby streamwater or bottom sediments. These results held for both fresh and older paved surfaces. Since paved surfaces also generate less sediment, paving can be an option to forest managers where critical aquatic habitat may be at risk to sedimentation from unpaved road surfaces. This information, combined with computer-based models that apply these values to the watershed scale, is currently being used by land managers to estimate current sediment yields and evaluate how improved road surfaces (either by paving or using BMPs) will impact future amounts of stream sediment.

Forest road BMPs

Broad-base dip

The Power of the Long Term

Long-term data collection and analyses continue to provide the cornerstone of the interdisciplinary research program at Coweeta. Latest studies addressing criteria for characterizing, managing, and restoring riparian zones; expanding analyses of the impacts of land use change on terrestrial and aquatic resources to the regional level; and evaluating the effectiveness of ecosystem restoration practices such as prescribed burning and riparian zone restoration on ecosystem sustainability all build on the foundation of long-term basic hydrological and ecological data collected over decades at Coweeta. Continued long-term monitoring of experimental and control watersheds provides key insights into the relationship between forest management, natural disturbances, and susceptibility of forest ecosystems to factors such as climate change, land use change, and invasive species. These recent areas of research emphasis address some of the most important and emerging issues in natural resource management worldwide. Long-term studies at Coweeta show how forests can be managed to provide sustained watershed benefits to society; the work of scientists at Coweeta provides information citizens need to make informed decisions about future land use and management.

Coweeta stream

FACILITIES

Coweeta facilities have been expanded and upgraded considerably between 1999 and 2003 to support the growing research program and expanding collaborations. The newest building, the Coweeta Conference Center and Office Complex, was completed in 2003 and houses an 80-person capacity conference center, visitor reception area, and administrative and scientist offices. The Ecosystems Ecology Building, constructed in 1980 by Job Corps participants, holds additional offices. The Data Processing and Hydrology Building is the focal point for data storage and processing at Coweeta. Built by the Job Corps in 1989, it contains data processing equipment, a vault for storing long-term data, and office space for technicians and scientists.

The original section of the Coweeta Dormitory Building was built in 1937 and once served as headquarters for the laboratory. This building was first expanded in 1987 to house 14 visiting researchers; further renovations and expansions were initiated in 1999 and completed in 2003 to provide much improved accommodations for up to 24 researchers. The Analytical Laboratory, established in 1974, renovated in 1980, and expanded and renovated in 2001, provides a state-of-the-art facility for chemical determinations of water, soil, and vegetation in support of the research activities at Coweeta.

The real focal point of Coweeta is its outdoor living laboratory. You are invited to visit several of the accessible experimental sites. Because the roads are gravel, steep, and narrow, please drive carefully and be prepared to share the right-of-way at all times.

Main office and conference center

"The strength of the Coweeta Research Program is based on a long-history of employees deeply committed to its core mission of evaluating watershed ecosystem responses to natural, management, and other human disturbances of Southern Appalachian forests"

Past and present Project Leaders (l. to r.):
Jim Douglas, 1964 to 1984
Wayne Swank, 1984 to 1999
Jim Vose, 1999 to present

SRS
Southern Research Station

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