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WATERSHED ECOSYSTEM ANALYSIS AS A BASIS FOR MULTIPLE-USE MANAGEMENT OF EASTERN FORESTS[1, 2]

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Abstract. There is ever-increasing competition for the many uses and natural resources of forests in the eastern United States. Multiple-use management has long been a stated goal for these forests, but application has been problematic and seldom satisfactory to all users. There is a need to incorporate more science into management decisions for Eastern forests, and thereby convincingly demonstrate to forest managers and the public why certain combinations of uses may or may not be compatible. One proven approach for doing this is to use watershed ecosystem analysis. Small watersheds, usually <100 ha in area, serve as a convenient ecosystem for studying how forests function in terms of cycling energy, nutrients, and water. Results of these studies allow assessments of forest health and productivity, and evaluations of impacts of both natural and human-related disturbances. This paper provides illustrations of how watershed ecosystem analysis can be used to study the effects of current harvesting practices, acidic deposition, and past land use. The paper also shows how recommendations for land use are derived from watershed ecosystem analysis, and how they are put into practice.

Key words: eastern forests; ecosystem; forest harvest; logging; multiple use; "New Perspectives"; watershed; watershed ecosystem analysis.

INTRODUCTION

"The biggest challenge faced by foresters today is the question of multiple use. That is, how can we use our existing forest resources to satisfy many different public needs." These words are from a recent brochure published by the Northeastern Area Association of State Foresters (1989). This statement occurs three decades after Public Law 86-517 directed that National Forests be administered for multiple use and sustained yield. An obvious question thus arises: why, more than 30 years later, are we still struggling with the concept of multiple-use management of our forests?

The forests of the Eastern United States typify the problem and complexities of applying multiple-use management. The land area east of the Mississippi River is $\approx$51% forested and contains 8.6×10^9 dry metric tons or 53% of the nation's total tree biomass, including 6.2×10^9 dry metric tons or 75% of the nation's total hardwood biomass (Cost et al. 1990). So many people and industries depend on these forests for wood products and employment that harvesting receives high priority. However, other public needs must also be recognized, including outdoor recreation, wilderness preservation, water supply, and wildlife habitat management. These mixtures of land use are not always compatible, and attempts by foresters and planners to either make them so, or to exclude one use in favor of another, form the crux of multiple-use management.

The "New Perspectives" program of the USDA Forest Service (Salwasser 1990) calls for decisions about single and multiple uses to be more scientifically based, and further, that the basis for the decisions be carefully communicated to the public. One approach to obtaining a more scientific basis is the use of watershed ecosystem analysis. This approach has evolved over the past few decades to a level where it can be used more aggressively, not only as a scientific tool, but also to foster communications about possible land-use effects and alternatives. In this paper we define and demonstrate watershed ecosystem analysis with the help of examples for Eastern forests, and demonstrate its usefulness in improving multiple-use management.

WATERSHED ECOSYSTEM ANALYSIS—WHAT IS IT?

Watershed ecosystem analysis is based on using a watershed to study impacts of natural and human activities. A watershed is synonymous with "drainage basin" or "catchment," and at its simplest is defined as a land area through which precipitation is distributed into components of the hydrologic cycle (Fig. 1). Watersheds used for ecosystem analysis are usually

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[1] Manuscript received 27 June 1991; revised 5 November 1991; accepted 18 November 1991.

[2] For reprints of this group of papers on forest management, see footnote 1, page 219.

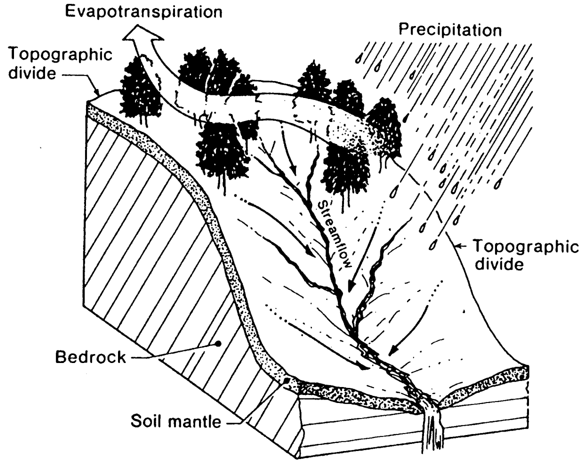

FIG. 1. Small watersheds, <100 ha, are the basis for watershed ecosystem analysis. (Reprinted by permission of John Wiley & Sons, Inc., from Hornbeck et al. 1984.) Precipitation and streamflow are measured continuously and evapotranspiration is obtained as the residual, provided there is no major leakage of water through bedrock.

<100 ha, and are carefully chosen to be representative of regional landscapes.

The forerunner of watershed ecosystem analysis was termed "watershed management research" or "forest hydrology research" and began in the United States at a site in Colorado in 1910 (Bates and Henry 1928). The study involved multiple watersheds, each instrumented with a network of precipitation collectors and a stream gaging station at its outlet. The primary objective was to determine the balance between volumes of precipitation and streamflow for forested watersheds, and how this balance was affected by forest land use. A second objective was to determine impacts of forest use on water quality in streams draining the watersheds, with an emphasis on sedimentation.

Watershed management research expanded in the 1930s with installation of watershed studies at sites such as the San Dimas Experimental Forest in California (Dunn et al. 1988) and the Coweeta Hydrologic Laboratory in North Carolina (Swank and Crossley 1988). Further expansion in the 1950s raised the total number of gaged, forested watersheds across the country to ≈150 (Holscher 1967). Research on these watersheds was largely applied or problem oriented, focusing on ways to increase water yield and reduce flooding, protect watersheds against erosion, and rehabilitate areas that had undergone severe disturbances from fire, mining, grazing, or careless logging. However considerable effort was also devoted to basic research on hydrologic processes, and on relationships among soils, plants, and water. Watershed management research reached a zenith around 1965 with an international meeting of forest hydrologists and a summarization of research results (Sopper and Lull 1967).

Around this same time scientists began to realize that watersheds could be useful in a more holistic approach to studying forest ecosystems. Watershed studies were expanded beyond water quality and the hydrologic cycle to include the cycling of nutrients and pollutants. Measurements of inputs and outputs of chemicals, especially those found in precipitation and streamflow, were incorporated, as were studies of the physical, chemical, and biological processes involved in chemical cycling. Since these studies were conducted on forested watersheds it became convenient to evaluate effects of changes in chemical inputs, or, conversely, impacts of forest disturbances on chemical cycling and outputs. As this approach evolved through the 1970s, it took on the name of watershed ecosystem analysis.

The basic premise of watershed ecosystem analysis is that the myriad of physical, chemical, and biological processes occurring within an ecosystem are interrelated. This approach attempts to understand these processes and relationships as completely as possible and to attach values to pools and fluxes (Fig. 2). The pools, expressed as mass per unit of area, and fluxes, expressed as rates, or mass per unit of area per unit of time, become the basis for assessing impacts of human-related or natural changes upon or within ecosystems. In terms of multiple-use management, watershed ecosystem analysis can be used to evaluate how individual or combinations of uses might affect nutrient cycles and, in turn, the health and productivity of forest ecosystems, or the chemistry and biota of forest streams. The use of watersheds as the ecosystem boundary ensures that effects are integrated over a sizeable landscape. By removing the bias that might occur on smaller areas such as experimental plots there can be greater confidence in extrapolating results to other locations.

Watershed ecosystem analysis increased in popularity in the late 1960s and early 1970s during a controversy over increased use of forest clear-cutting. There was widespread concern that clear-cutting, or the felling of all trees on a harvest site, would lessen species diversity, deplete nutrients, increase erosion, and result in an overall decline in the productivity and health of forest ecosystems (Horwitz 1974). However, many forest managers were insistent that clear-cutting was necessary to regenerate commercially valuable forests, and could be applied without harming productivity or the environment. Watershed ecosystem analysis was just the tool to test the pros and cons of clear-cutting. A number of studies using watersheds were initiated to determine the effects of clear-cutting. In most cases one or more whole watersheds were clear-cut and contrasted with an undisturbed control watershed with regard to nutrient losses, water yield and quality, and stand regeneration. The studies cleared up many of the questions about clear-cutting, and results are now published in the scientific literature where they can be used for

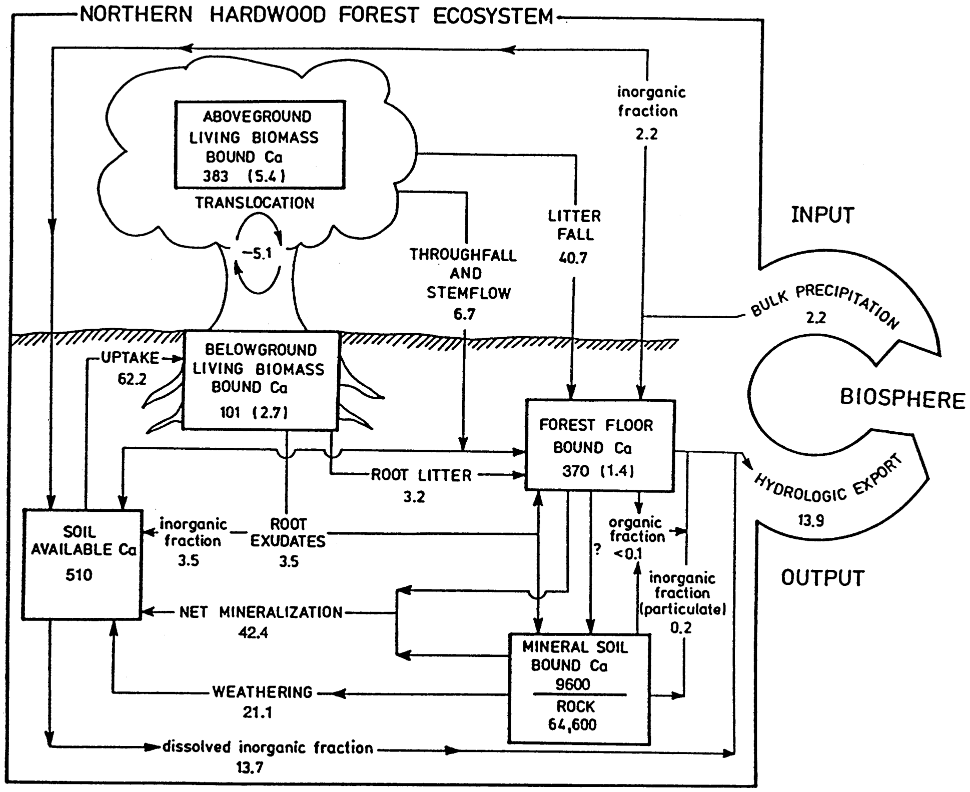

FIG. 2. Annual calcium cycle for a northern hardwood forest (from Likens et al. 1977). The outer border can be considered as the boundary of a watershed. The sizes of calcium pools, shown in boxes, are in kilograms per hectare; the fluxes, associated with arrows, are in kilograms per hectare per year.

making future management decisions (e.g., Hornbeck et al. 1987, Johnson et al. 1987, Brooks et al. 1991).

Watershed ecosystem analysis has also played an important role in studies of atmospheric deposition. Watersheds serve as a convenient unit for measuring amounts and effects of acidic or other types of wet and dry deposition. Knowledge gained through watershed ecosystem analysis has contributed to assessment of how such inputs affect soils, streams, and forest health. The use of watersheds as ecosystem boundaries also offers opportunities for experimental manipulations; for example, acidifying chemicals have been applied to whole watersheds to mimic but hasten effects of acid precipitation on soils, streams, and plants—the goal being to arrive more quickly at strategies for controls and mitigation of atmospheric deposition.

Due to temporal variability in weather and wet and dry deposition, watershed ecosystem analysis is inherently long term. Some parameters must be measured for decades to define variability. On the other hand, long-term data sets from watersheds, many of which now span 30–50 yr, have proved of great value in studying trends and changes in ecosystem fluxes and processes (Strayer et al. 1986, Driscoll et al. 1989, Federer et al. 1990).

In summary, watershed ecosystem analysis establishes cause-and-effect relationships and ecosystem response at the landscape level. This knowledge provides principles that can be used alone or in combination with experimental treatments to evaluate impacts of human and natural disturbances. The results form the needed scientific basis for selecting the most appropriate uses of our forest resources.

APPLICATION OF WATERSHED ECOSYSTEM ANALYSIS

We have chosen two examples involving forest harvest to illustrate the application of watershed ecosystem analysis. Forest harvest is a logical subject area for our illustrations since harvesting is the dominant use in eastern forests, and the major focus of concerns and conflicts.

An example involving impacts of past and present forest uses

During the past decade the rapidly expanding use of biomass harvesting, increased product removals, and shorter rotations have raised legitimate concerns about the depletion of nutrients from forests. Concerns are magnified by the fact that forests in the Eastern United

TABLE 1. Calcium data for mature forests in New England. The data were derived from Hornbeck and Kropelin (1982), Tritton et al. (1987), and Smith et al. (1986).

Forest type and location	Calcium content (kg/ha): Mineral horizons	Forest floor	Above-ground whole trees	Merchantable boles	Roots	Calcium flux ($kg \cdot ha^{-1} \cdot yr^{-1}$): Input in precipitation	Output in streamflow	Net
Northern hardwoods, Success, New Hamsphire	7570	490	360	224	120	1	15	−14
Spruce-fir, Weymouth Point, Maine	10 330	380	540	255	190	1	16	−15
Central hardwoods, Cockaponsett State Forest, Connecticut	3320	100	590	451	240	2	10	−8

States receive acid deposition, which can accelerate losses of nutrients to streams and groundwater. Also, most eastern forests have histories of cropping, grazing, or timber harvesting that involved substantial nutrient removals. A resulting question is: are present-day intensive harvests with potential for substantial nutrient removals an acceptable use of eastern forests, or might they further deplete nutrients to the point of affecting future productivity?

Watershed ecosystem analysis is a logical approach for obtaining a scientific basis for answering the above question. The example that follows involves direct studies of impacts due to contemporary harvests and extrapolation of data from other studies to evaluate effects of past land use. Long-term data and an understanding of ecosystem processes are used to infer impacts of atmospheric deposition.

Our example focuses on calcium, a macronutrient essential to plant growth and important in soil reactions. Harvests remove a substantial amount of calcium in forest products and also trigger increased leaching of calcium from forest soils to streams and groundwater. A recent paper by Federer et al. (1989) has demonstrated a need to be concerned about depletion of calcium from forests.

Impacts of contemporary harvest.—In 1979–1980 when biomass or whole-tree harvesting (removal of $>90\%$ of aboveground biomass) was gaining popularity in New England, the USDA Forest Service and others began studying impacts using three sets of watersheds, one set located in each of the region's three major forest types (Table 1). Watershed ecosystem analysis was used to study processes and fluxes and assign values to various nutrient pools. Our example concentrates on the pools and fluxes to show impacts of whole-tree harvesting.

Initially calcium capital was quantified for each of the major compartments of the watersheds. The calcium values for the mineral soil horizons and the forest floor given in Table 1 are for material that will pass through a 2-mm sieve. This size fraction is the source of most nutrients available for plant growth. Particles >2 mm, up to and including large boulders, probably contain several times the calcium found in the <2-mm fraction; however, this calcium in larger size fractions is usually tightly bound and is converted by weathering to plant-available forms very slowly, sometimes at rates as low as a few kilograms per hectare per century.

The combined calcium found in mineral soil particles and the forest floor can vary greatly among sites and forest types. For the three sets of study watersheds, total calcium in these two important pools ranged from ≈ 3400 kg/ha for the central hardwoods in Connecticut to $>10\,700$ kg/ha at the spruce–fir site in Maine (Table 1). Calcium in aboveground whole trees ranged from 360 to 590 kg/ha, or 4–17% of the total found in the forest floor and mineral soil. A small amount of calcium, 1–2 kg/ha, is added to forest ecosystems in annual precipitation (Table 1). In turn, 8–15 kg/ha are lost each year as dissolved calcium in streamflow.

Harvesting has two major impacts on calcium capital. First, the calcium incorporated in the harvested products is lost from the watershed. Second, for the first few years after harvest, cutover sites are less efficient than mature forests at cycling calcium. As a result, calcium leaching is enhanced, increasing the amount of dissolved calcium lost from the watershed to streamflow or to groundwater.

From studies on watersheds at the sites in Table 1, calcium in the biomass removed during a whole-tree harvest was 344 kg/ha for northern hardwoods, 494 kg/ha for spruce–fir, and 530 kg/ha for central hardwoods. These removals represent $\geq 90\%$ of the calcium occurring in aboveground biomass of mature forests. Losses of calcium in streamwater approximately doubled in the first year after whole-tree harvesting, ranging from an increase of 10 kg/ha in central hardwoods to 16 kg/ha in spruce–fir. The increases nearly disappeared by the end of the third year after harvest, but the total additional leaching losses for the 3 yr were 30 kg/ha for northern hardwoods, 43 kg/ha for spruce–fir, and 28 kg/ha for central hardwoods.

One way of evaluating these losses is to relate them to capitals of the forest floor and mineral soil. For example, combined leaching losses and removals of calcium in the harvested trees for the spruce–fir site (537 kg/ha) represent a depletion of ≈5% of the capital in the forest floor and mineral soil (10 710 kg/ha). This rather small depletion of a fairly large calcium capital would not seem to present a problem for future productivity. On the other hand, the leaching losses and removals for the central hardwood site (558 kg/ha) represent a depletion of >16% of the capital in the forest floor and mineral soil (3420 kg/ha). The greater depletion of an already-small capital raises a concern regarding future productivity.

Impacts of past land use.—New England states are currently 60–90% forested. Nearly all of this forest is second or third growth arising after past harvests or clearing for crops or grazing. Many early harvests were intensive and followed by wildfire in the logging slash. Thus nearly every harvestable site in New England has a 100- to 200-yr history of human activity that in turn impacted nutrient cycles and capitals. This land-use history can usually be reconstructed in considerable detail using court records, census data, tax records, and physical artifacts.

Impacts of these past land uses can be synthesized and evaluated in the context of watershed ecosystem analysis. For example, Bormann (1982) studied an area in central New Hampshire that had been cleared for agriculture in the early 1800s. The original forest clearing included burning, and had removed an estimated 320 Mg/ha [metric tons per hectare] of forest biomass. Agricultural cropping over the next several decades removed an estimated 2.3 to 3.9 $Mg \cdot ha^{-1} \cdot yr^{-1}$. Using nutrient contents from forest and agricultural literature, we calculate that biomass removed in trees and agricultural crops from the start of land clearing until reversion to forest in the early 1900s would have contained ≈1000 kg/ha of calcium. Bormann's study area was nearby and similar to our whole-tree harvested watershed in New Hampshire, so it does not seem unreasonable to extrapolate this value to our study watershed as an estimate of nutrient removals from past land-use activities.

The site for the whole-tree harvest study in Connecticut was cleared for grazing sometime prior to 1850, then allowed to revert to forest around the turn of the century. Our calculations suggest calcium removals of ≈900 kg/ha from clearing and grazing, or about the same as estimated for early land uses on the New Hampshire site. The history of the spruce–fir study site in Maine was more difficult to reconstruct. There are no good cutting records, but the forest on the uncut, control watershed shows evidence of logging, most likely from one or more selection cuttings within the past century (Coolidge 1963).

Thus, of the three study sites, the potential for cumulative effects of past land use and present-day intensive harvests would be least for the spruce–fir forest in Maine. In the absence of complete clearing and heavy cutting, past nutrient removals were probably small, and total calcium capital, determined as part of the watershed ecosystem analysis, is substantial (Table 1). The removals from northern hardwood sites in New Hampshire are of more concern. Bormann (1982) found that forest recovery following agricultural disturbance was slower than on sites that had only been logged, possibly because of nutrient deficiencies.

Consideration of past land use is an absolute necessity for sites like the central hardwood forest in Connecticut. Present-day nutrient capitals are small, as evidenced by the total of just over 3400 kg/ha of calcium in mineral soil and forest floor (Table 1), partly because of removals during earlier land uses. Any additional removals and leaching losses could have serious consequences for site productivity.

Impacts of atmospheric deposition.—Mobile anions, such as sulfate and nitrate, associated with atmospheric deposition, raise concerns over calcium depletion beyond those associated with nutrients removed or lost during harvesting. Input–output budgets for mature forests at all three sets of study watersheds show a net annual loss of calcium (Table 1). The mobile anions in acid precipitation are thought to be responsible for these losses (Federer et al. 1989). As the anions pass through the forest ecosystem, the hydrogen ions they are coupled with in precipitation are exchanged for other cations such as calcium, potassium, and magnesium. The hydrogen ions are retained in the ecosystem while the cations are leached to streams and groundwater.

The net losses appear small on an annual basis (Table 1), but assume greater importance when extrapolated over longer times such as a 100-yr rotation. For example, net losses of calcium to leaching over such a rotation may total 800–1500 kg/ha, depending upon location. Slight increases in leaching losses immediately after harvest coupled with removal of another 500–800 kg/ha of calcium in harvested products (over a 100-yr rotation) could mean a total depletion of from 20 to 40% of calcium capital for the rotation. Based on present knowledge of these ecosystems the inputs from rock breakdown, root-zone deepening, and dry deposition would not be sufficient to replace this lost calcium (Federer et al. 1989).

Assessment and recommendations.—The above findings on the calcium cycle, obtained through watershed ecosystem analysis, support concerns about nutrient depletion from forests. The studies suggest that in situations like those at the central hardwood forests in Connecticut, intensive harvesting could have a serious impact on calcium capital, and should be avoided. On the other hand, whole-tree harvesting in the spruce–fir forests of Maine would have little impact because of larger calcium capital.

These findings can be incorporated with information

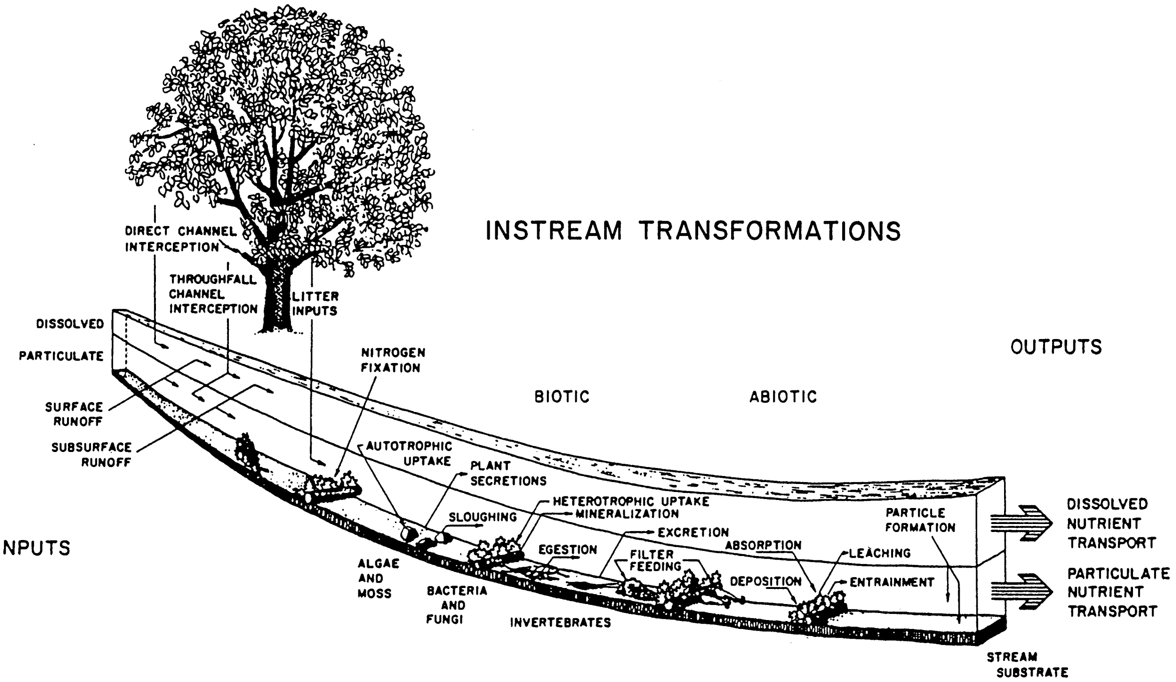

FIG. 3. Factors affecting nutrient dynamics in a forest stream ecosystem (from Webster and Swank 1985).

obtained in other watershed ecosystem studies to form recommendations for forest use. The following are examples of guidelines supported by research at the three sets of study watersheds in New England:

1) Avoid whole-tree harvests on soil types and conditions with low fertility. Examples are coarse-textured sands, and soils that are shallow to bedrock or have high seasonal water tables. These soils have either inherently low total nutrient capitals or low quantities of plant-available nutrients due to slow rates of weathering and mineralization.

2) Plan harvests so that foliage remains on site. Whole-tree harvesting in the dormant season and after leaf fall on a northern hardwood forested watershed reduced nutrient removals by 10% for Ca, 16% for K, and 21% for N and P compared to a growing-season harvest with leaves (Hornbeck and Kropelin 1982). During growing-season harvests, felling should be conducted several weeks in advance of skidding to allow leaves to dry and drop on site.

3) Exercise special caution with logging operations. Whole-tree harvesting has potential for added soil disturbance due to heavier loads, more round trips by forwarding equipment, and the use of new, unfamiliar machinery (Martin 1988). Compaction and exposure of mineral soils may prolong leaching losses by delaying regeneration and plant development. Guidelines for protecting soils during whole-tree harvesting are given in Martin (1988) and Hornbeck et al. (1986).

4) Consider alternative harvesting practices. Whole-tree harvesting is commonly practiced on large, clearcut blocks. A possibility for moderating nutrient leaching losses is to apply a practice known as "progressive strip cutting": the harvest site is clearcut, but over a several-year period, using a series of strips of uniform widths (usually ≈25 m wide). In addition to providing for a seed source and favorable environment for regeneration, strip cutting has been shown to reduce nutrient leaching losses by 40–60% over block clearcutting (Hornbeck et al. 1987).

An example involving stream quality

The myriad of small, low-order streams that drain forested watersheds in the eastern United States are important to a variety of aquatic organisms. Relationships to fish are of particular concern to a variety of interest groups. While many forest streams are too small to support fish populations, they provide the high-quality water needed to maintain downstream fisheries. This quality is maintained through complex chemical, physical, and biological processes (Fig. 3) that are sensitive to disturbances in the stream or on the surrounding watershed. There is frequent concern that forest harvest and logging may disrupt these processes and affect water quality and aquatic productivity. As outlined below, watershed ecosystem analysis can contribute to the understanding of the processes, and provide information to develop management guidelines for protecting aquatic resources.

Most small streams draining forested land are characterized as heterotrophic systems in which much of the energy for the food chain is derived from terrestrial

TABLE 2. Mean annual inputs of litter (ash-free dry mass) to reference streams (WS 14 and WS 18) and disturbed streams (WS 6 and WS 7) at Coweeta Hydrologic Laboratory (North Carolina) (after Webster et al. 1990). Average time since disturbance is 10 yr.

	Lateral transport (g/m)		Litterfall (g/m^2)	
	Leaf	Wood*	Leaf	Wood*
Reference streams	113	10	450	175
Disturbed streams	42	14	343	70

* Wood includes only twigs and small branches.

organic matter. For example, on a hardwood watershed at the Coweeta Hydrologic Laboratory in the Southern Appalachians, litterfall and lateral inputs of organic matter to streams in undisturbed watersheds averaged $\approx 450\ g \cdot m^{-2} \cdot yr^{-1}$ compared to a net primary production rate of $<5\ g \cdot m^{-2} \cdot yr^{-1}$ (Webster et al. 1983).

Logging adjacent to the streams altered both the quantity and quality of allochthonous inputs to the stream. The first year after cutting, leaf inputs were reduced 98%, although regrowth by sprouts rapidly returned part of the allochthonous inputs to the stream. However, quantitative differences were still detectable at least 10 yr after disturbance (Webster et al. 1990); leaf and wood litterfall and leaf lateral transport to disturbed streams were significantly less than to reference streams (Table 2). The quality of leaffall was also greatly altered following removal of streamside vegetation (Table 3) and will probably remain so for may years. Inputs to streams from successional hardwood forests is dominated by leaf material that is more labile (herbaceous plants, birch, black locust, yellow poplar) than that from older, undisturbed forests comprised of oaks and rhododendron (Webster et al. 1988).

Once organic matter and dissolved nutrients pass from the forested landscape into the stream channel, a variety of processes come into play (Fig. 3). Macroinvertebrates and microfauna break down particulate organic matter through their feeding activities and also contribute to nutrient mineralization (Wallace et al. 1982, Meyer and O'Hop 1983). Bacteria and fungi immobilize dissolved nutrients, then gradually return them through decomposition and mineralization processes. Coupled to these biotic processes are important abiotic factors such as ion adsorption by sediments, leaching from organic matter, and deposition and entrainment of mineral and organic particulates. These processes have been studied and quantified within the context of watershed ecosystem analysis for several sites in Eastern forests (e.g., Fisher and Likens 1973, Webster et al. 1990).

Among other things these studies have pointed out the important functions of woody debris in streams, including (1) creation of a more diverse aquatic habitat; (2) reduction of stream velocity; (3) provision of nutrients and substrate for biological activity; and (4) entrapment of sediment (Fisher and Likens 1973, Bilby and Likens 1980, Bilby 1981, 1984, Webster et al. 1983). Forest and stream management programs have been shown to significantly alter the benefits derived from woody debris and other forms of stream organic matter. Logging or cutting adjacent to streams on Coweeta watersheds reduced coarse particulate organic matter, standing crops of benthic organic matter, large woody debris, and the number of instream debris dams (Webster et al. 1992) (Table 4). This in turn reduced channel stability, affected important structural and functional attributes of streams, and altered stream productivity, all of which may persist for decades. These findings have important implications in terms of past and present management practices, which advocate clearing of logging slash from stream channels, and removal of woody debris to allow passage of fish (Froelich 1973, Sedell et al. 1988).

As a result of watershed ecosystem studies in the Southern Appalachians, Webster et al. (1992) have postulated a sequence of at least five phases of stream dynamics following logging or other disturbances (Fig. 4). In the initial phase the energy base is shifted from lowered terrestrial organic matter to increased instream primary production; sediment production is increased due to road construction and other potential soil-disturbance activities; benthic organic matter is reduced due to low input and rapid breakdown; and there is a large phase of wood input associated with logging. In the second phase, sediment transport declines, but remains above predisturbance level due to the redistribution of material entering the stream during disturbance. Leaf inputs begin to increase and approach predisturbance levels in 10–20 yr, although leaf quality may be different. Woody material decreases due to rapid decay and in some cases through physical

TABLE 3. Mean composition of leaffall for selected species to reference and disturbed streams at Coweeta Hydrologic Laboratory (North Carolina) (after Webster et al. 1990). Average time since disturbance is 10 yr.

	Leaf deposition (% dry mass)	
Leaffall source	Reference streams	Disturbed streams
Oaks (*Quercus* spp.)	28	4
Rhododendron (*Rhododendron maximum*)	13	6
Ash (*Fraxinus* spp.)	4	6
Birch (*Betula* spp.)	13	8
Yellow poplar (*Liriodendron tulipifera*)	9	15
Red maple (*Acer rubrum*)	5	10
Dogwood (*Cornus florida*)	1	4
Black locust (*Robinia pseudoacacia*)	<1	5
Herbaceous spp.	<1	7

TABLE 4. Mean values of benthic organic matter in reference streams (WS 14 and WS 18) and disturbed streams (WS 6, WS 7, and WS 13) at Coweeta Hydrologic Laboratory. Average time since disturbance is 13 yr (after Webster et al. 1992).

	Benthic organic matter (g/m²)				
	Coarse particulate* (>1 mm)	Small wood (1–5 cm)	Large wood (>5 cm)	Total†	Debris dams (no./ 100 m)
Reference streams	228	306	4855	5545	2.0
Disturbed streams	169	241	1507	2133	0.4

* Includes wood <1 cm.

† Includes fine particulate organic matter.

removal, and benthic organic matter continues to decline. In the third phase the energy base has fully returned to leaf inputs in 20–30 yr and regrowing vegetation is a source of small woody inputs to the stream. Accelerated sediment loss is suggested 20–30 yr after logging due to loss of debris dams formed by small woody debris undergoing decomposition. The fourth phase, aggradation, begins when relatively large logs fall into the channel and provide the stability necessary to form debris dams, which stabilize sediment movement and collect particulate organic matter. It is postulated that 100 yr may be required to reach the fifth phase of total recovery, including predisturbance levels of debris dams and benthic organic matter.

The preceding ecosystem perspectives of linked terrestrial–aquatic processes provide a basis for management practices. It is obvious that the moist areas immediately around stream channels, called riparian zones, are directly linked to stream trophic levels and are critical to protecting water quality. Leaving a strip of trees, termed buffer strips, in the riparian zone to separate streams from roads and harvest areas is often recommended to protect stream banks and channels, provide shade, and prevent logging slash and eroding soil from entering streams. However, the decision to use buffer strips is not always straightforward. Riparian zones are frequently the most productive sites, and harbor trees of high quality and value. Also, felling of all trees except a narrow buffer strip can make trees left in the strip vulnerable to windthrow.

Based on watershed ecosystem studies, some guidelines for the use of buffer strips are as follows:

1) Buffer strips are usually necessary only along perennial streams. However, reduced evapotranspiration after forest harvest may result in increased streamflow (Swank et al. 1988) and temporary expansion of perennial stream channels.

2) The width of buffer strips can vary depending upon slope, climatic factors, and soil erodibility. A variable width of 13–30 m on each side of the stream (more in steeply sloping terrain) is recommended.

3) Haul roads and skid trails through buffer strips should be kept to a minimum.

4) Crossings of stream channels should be on closed culverts or bridges.

5) It may be desirable to make a light selection cutting in the buffer strip to remove larger trees or those susceptible to windthrow. In such instances, care should be taken to avoid soil disturbance and to prevent logging debris and slash from plugging the stream channel (Hornbeck et al. 1984).

PUTTING WATERSHED ECOSYSTEM ANALYSIS TO PRACTICE

Knowledge and guidelines obtained through watershed ecosystem analysis have a varied audience, including the scientific community, the general public, environmental interest groups, planners, forestland owners, practicing foresters, and loggers. Several approaches are used to reach these groups. Publications in peer-reviewed journals are the initial outlet for watershed ecosystem studies. A follow-up step, termed "technology transfer," is accomplished by rewriting material from the scientific publications in forms suitable for trade journals, magazines, newspapers, and information brochures. This step, which seeks to put

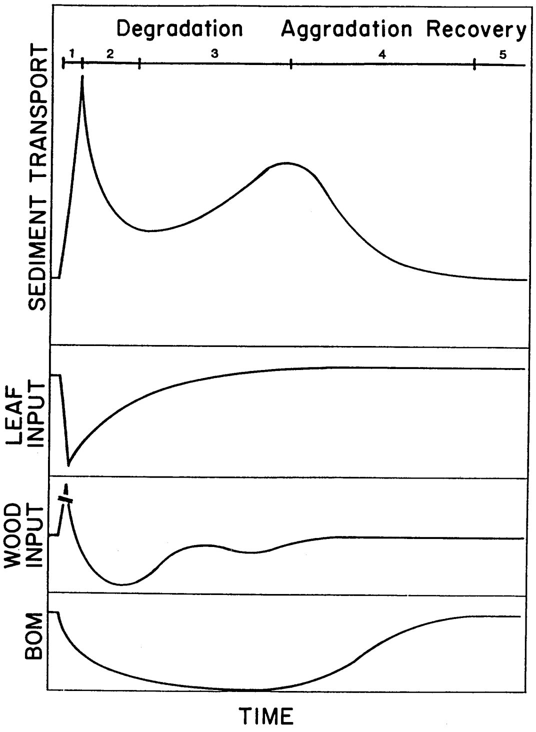

FIG. 4. Trends in stream processes following streamside forest disturbance. (Reprinted by permission of John Wiley & Sons, Ltd., from Webster et al. 1992.) BOM = benthic organic matter.

information directly in the hands of on-the-ground users, has traditionally been a weak link. The "New Perspectives" program calls for renewed and improved efforts at technology transfer.

National legislation provides a different path for results of watershed ecosystem analysis to become practice. For example, the Forest and Rangeland Renewable Resources Planning Act, amended by the National Forest Management Act, requires that all National Forests develop a Forest Plan. Assessment of the environmental impacts of these plans is required by the National Environmental Policy Act. Watershed ecosystem analysis, by virtue of evaluating forest uses, provides information for both preparing Forest Plans, and for assessing environmental impacts.

CONCLUSION

Watershed ecosystem analysis is a useful approach for obtaining the scientific basis to make decisions about land use. The approach provides integrated data for forested landscapes that can be used to: (1) address concerns about impacts of particular land uses, (2) demonstrate the basis for permitting or denying land uses, and (3) develop guidelines for managers and others responsible for implementing land uses.

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