Watershed Management Contributions to Land Stewardship: Case Studies in the Southeast

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Abstract.—We describe three examples of watershed management studies, at different spatial scales, that provide approaches and information useful in enhancing natural resource stewardship in the southern Appalachians. A multiple use "pilot" study, initiated 35 years ago at the Coweeta Hydrologic Laboratory, demonstrates that southern Appalachian forests can be successfully managed for water, timber, wildlife, and recreation. Added benefits of this small scale (144 ha) watershed study are the education and on-the-ground demonstration values. A demonstration project of ecosystem management, initiated in the early 1990s on a 1820 ha watershed provides an integrated, interdisciplinary ecosystem approach to research, planning, and management. Organized around themes of ecosystem restoration, forest sustainability, human and economic values, and ecosystem structure and function, the multifaceted studies are providing new knowledge and management benefits. More recently, regional scale watershed research was initiated on two river basins within a 70,000 km^2 area of western North Carolina. The goal is to develop a predictive understanding of the social, economic, and environmental factors that drive land use cover changes and to evaluate the consequences of change for terrestrial and aquatic biodiversity, water quality, and regional carbon cycles. E'm'ergy, a tool for synthesizing the multiple values of watersheds, is applied to the ecosystem management study.

Introduction

As with much of the nation, the mix of forest uses and benefits in the southern U.S. has greatly accelerated in the past several decades. The rapidly changing faces and voices of the South (Cordell et al. 1998) provide exciting opportunities to address complex issues related to planning, policy, and science for the region's natural resources. Interdisciplinary watershed management provides a useful analytical framework for structuring and assessing alternative mixes of forest uses across multiple scales of time and space.

Our objectives in this paper are 1) to illustrate, through case studies in the southeast U.S., the utility of watershed management as a framework for evaluating the conservation and sustainable development and use of resources at several spatial scales and 2) to implement a methodology, emergy analysis, for synthesizing commodity and noncommodity values of watershed values and functions.

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The Regional Setting

The region is characterized by three physiographic divisions: the coastal plain, piedmont, and mountains. Abundant resources, highly diverse and attractive ecosystems, demographic shifts, job opportunities, and other socioeconomic factors contribute to a dynamic changing South. During the past three decades the population has increased 54% and the region (13 southern states) was the only one within the U.S. with net growth from domestic in-migration (Cordell et al. 1998). Forests cover 87 million ha in the region and the 81 million ha classified as timberland (Sheffield & Dickson 1998) accounts for an estimated 40% of the productive timberland in the U.S. Nearly 70% is in nonindustrial private forest ownership. Other timberland ownerships are comprised of national forests (5.7%), other public agencies (4.8%), and the remainder in forest industry (≈ 20%). About 52% of the timberland is classed as a hardwood type and upland hardwoods comprise 37% of the total timberland. The pine forest type occupies about 33% of the timberland with 15% in pine plantations and 18% in natural pine plantations (Sheffield and Dickson 1998). In the past decade the region has emerged as a leader in the world's forest products industry, accounting for about 25 % of world paper production and 35% of solid wood products manufacturing. nationwide, the region provided 50% of the softwood and 42% of the hardwood timber produced in the country in 1992 and the South is expected to supply major future increases in the national timber market (Wear et al. 1998).

The region also encompasses an abundance of water, recreation, and wildlife as illustrated in a comprehensive assessment of the Southern Appalachians, a sub-region of 15 million ha within seven southeastern states (Southern Appalachian Assessment Summary Report 1996). The area contains parts of 73 major watersheds, and nine major rivers that arise in the southern Appalachians provide drinking water to the major cities of the Southeast. The mean main stream and river density is 12 m / ha and when all perennial streams are included, ranges from 48 in the piedmont to 87 m / ha in the mountains. Natural lakes and reservoirs represent about 1.5% of the total area. The southern Appalachians are well known for their scenic beauty and the recreation opportunities they provide. In the past 15 years, there has been a significant increase in the number and diversity of recreationists in the region. Concurrently, demand has increased for specific recreation opportunities such as hiking and white water rafting / kayaking. The southern Appalachians is home to an estimated 80 species of amphibians and reptiles, 175 species of birds, 65 species of mammals and more than 25,000 species of invertebrates. Populations of major game species such as deer, turkey, and bear have increased in the past 25 years while populations of birds such as ruffed grouse and bobwhite quail have declined.

Clearly, the south is a region with a rapidly growing range of public interest and changing views of land and natural resources. This situation is probably most evident and complex in the Appalachians where mixed ownerships, diverse resources, and increasing population pressures offer challenging planning and policy decisions for multiple uses on the landscape. Fortunately, past and current watershed research in the region provides information relevant to decision making processes. The Coweeta Hydrologic Laboratory, a 2185 ha USDA Forest Service research facility located in the Appalachian Mountains of western North Carolina, has a long history of interdisciplinary watershed research. It is this cooperative research program from which we draw our case studies.

Multiple Use Management: A Pilot Program

One of the earliest and most practical demonstrations of the multiple use concept in a watershed context in the eastern U.S. was implemented at Coweeta in 1962 (Hewlett and Douglass 1968). At the time, there was substantial controversy over the Multiple Use Act passed earlier in 1960 because on-the-ground examples of the concept were lacking. The concept was pilot-tested on a 144 ha hardwood-forested watershed (WS 28) in the Coweeta basin for the uses it was judged to be best suited for; water, timber production, hunting, fishing, and hiking. Scientists delineated objectives and prescriptions to evaluate conflicts among uses and to demonstrate potential management practices for the future (Hewlett and Douglass 1968).

Prescriptions

One of the highest priorities was to provide access on the catchment without impairing other resources. Properly planned access is a basic component of watershed management that is essential in achieving other goals and access should be designed to meet current and anticipated future needs. Four classes of roads were specified and included forest engineered roads to specified standards and a network of climbing roads, contour roads, and skid trails using criteria developed from previous research at Coweeta and from some new ideas for design criteria.

Silvicultural conditions of existing stands dictated even-aged management (clearcutting) on the slopes and ridges to regenerate the degraded forest from the previous selective logging in 1923-24 and to produce the maximum yield of water and deer browse. In the cove forest, a thinning was prescribed along with removal of residual poor quality overstory trees remaining after earlier logging, to increase growth of the residual yellow-poplar stand. To enhance the visual appeal of the cove in winter and spring, eastern hemlock (*Tsuga canadensis*) and dogwood (*Cornus florida* L.) were not cut.

The Appalachian Trail, which traverses the higher elevations of the watershed, was improved and interpretative signs were placed at strategic locations to enhance recreation. Improvement of trout habitat consisted of removing old logging debris from the lower portion of the main stream and construction of small logs dams to create more riffles and pools.

Responses to Management

Previous papers provide detailed analysis of responses to prescriptions (Douglass and Swank 1976; Swank 1998) and only a review of findings are provided in this paper. An overall summary of resource / use responses is provided in table 1. Based on the paired watershed method of analysis, streamflow on WS28 increased 22 cm the first year after harvest and then declined exponentially over the next 9 years before returning to baseline levels. The cumulative effects of cutting on total flow was an increase > one million m^3 of water. Much of this increased discharge occurred in the autumn season when flows are lowest and both human and aquatic water demands are highest. Analysis of the storm hydrograph showed that, during storm periods, quick-flow volume (direct runoff) increased an average of 17% (Douglass and Swank 1976). During the height of logging activity, peak discharge increased an average of 33% and then declined rapidly following road stabilization and recovery of evapotranspiration.

Table 1. Summary of Watershed Responses to Multiple-Use Management Prescriptions on WS28, Coweeta Hydrologic Laboratory (0 = Minimal Response, + = Positive Response, - = Negative Response)

Resource/Use	Response
Water Yield	+
Storm Discharge	0/-
Sediment	0/-
Nutrient Loss	0
Vegetation	+
Wildlife	+
Recreation (Hunting, Hiking)	+

Sediment delivery to streams was minimal due to proper road locations and construction features. However, increased frequency of cleaning the weir ponding basin clearly indicated an acceleration of bedload movement. Much of the bedload scouring occurred in the stream section where fish dams were constructed and reflects readjustment of the stream energy gradient. Apparently, the impact of management on aquatic resources was minimal because the stream still supported a good native brook trout fishery several years after treatment. Stream chemistry was not measured in the early years but about 10 years after disturbance, net nutrient budgets (compared to adjacent control watersheds) suggested small losses of nutrients from the watershed (Douglass and Swank 1976).

Vegetation responses to cutting are rapid in the southern Appalachians due to both sprout and seedling regeneration. Thirty years after harvesting in the 73 ha of clearcutting prescription, basal area exceeds that of the forest prior to cutting (30 m^2 ha^{-1}). Moreover, the species composition is greatly improved with and abundance of *Quercus, Prunus, Betula, Tilia,* and *Lirodendron* species (Swank 1998). Stand conditions present an array of future management options. Objectives of thinning the cove forest were equally successful. Growth rates of residual yellow poplar were increased about 40% and by age 30, stand basal area had increased to 46 m^2 ha^{-1}. Advanced regeneration and understory diversity has increased over time and there is also a diverse herbaceous layer (Parr 1992).

Responses of other resources and uses to management have also been evaluated or observed. The variety of habitats produced by silvicultural and prescriptions increased species diversity of breeding birds (Tramer 1969; Tramer 1994) and the variety of shrews and mice (Gentry et al. 1968). The varied habitat has been a strong attractant for turkey foraging and the area supports a large turkey population. Other wildlife such as deer and ruffed grouse have benefitted from management and the watershed, with improved access, is still a favorite area of hunters. The road network over the watershed also provides a favorite area for the day hiker. Wild flame azaleas that became established on the edge of roadway clearing and an abundance of flowering dogwood provide outstanding aesthetic value.

Summary

This 35-year-old watershed based study has demonstrated that southern Appalachian forests can be successfully managed for a variety of uses. Although there may be some conflicts among uses, it is important to recognize that ecosystem changes are not irreversible and opportunities are available to meet future goals. Many of the findings from this pilot project have been factored into forest management planing and practice. Moreover, we suggest that another important long-term contribution of the study lies in its demonstration and education values. The watershed provides a setting where management decisions are made, applied, and evaluated. It provides an on-the-ground framework where managers, conservation and environmental groups, policy makers, and students can view and discuss resource issues. This benefit from watershed research has been repeatedly observed from interaction with numerous groups who tour Coweeta and this catchment each year.

Integrated Watershed Ecosystem Management

The Wine Spring Creek Ecosystem Management Project is a recent example of integrated research where the watershed is the basic unit for evaluating management and land stewardship. Ecosystem management is currently an operating philosophy of the USDA Forest Service with the objective of using an ecological approach to achieve broader multiple use objectives (Kessler et al. 1992; Thomas 1996). Similar to when the concept of multiple use management emerged in 1960, there are a wide range of views and opinions about the concept of ecosystem management (Swank and Van Lear 1992; Ecological Applications 1996). We suggest there is no blueprint for implementing ecosystem management; indeed, different approaches will be needed to address the array of issues inherent to varied regions of the country. The real need is for tailored, on-the-ground examples of ecosystem management.

Compared to the earlier demonstration of multiple use at Coweeta, ecosystem management encompasses a broader perspective. Specifically, there is a mixed partnership where scientists, managers, the public, and other groups have a role in the decision making process. As a result, the planning approach is more comprehensive, the science is more interdisciplinary, and tools for synthesis such as modeling and decision support systems are required to facilitate interpretations. However, a common thread of past and present approaches is that the watershed still provides the fundamental framework for evaluating land use issues and alternatives for management.

The Setting and Approach

In 1992 we developed and initiated the ecosystem management project in the 1820-ha Wine Spring Creek Basin which is located in the Nantahala mountains of western North Carolina, about 50 km from Coweeta (Swank et al. 1994). The objective of the project is to use / and or develop ecologically based concepts and technology to achieve desired natural resource conditions. The watershed is comprised of steep slopes with elevations ranging from 918 to 1660 m. Annual precipitation averages 1800 mm and mean monthly temperatures range from 0.5° in January to 21.3° in July. A mix of hardwood forest types, dominated by oak, cover the watershed and McNab et al. (1999) have classified five ecosystem units for the area based on vegetation, soil, and topographic variables. First- through third-order streams drain the basin and Wine Spring Creek flows to Nantahala Lake, an important reservoir in the region. Most of the basin is managed by the Wayah Ranger District, national Forests in North Carolina, but a portion is in private ownership at the base of the watershed near Nantahala Lake. The area supports a diverse fauna and variety of uses, with primary access provided by a paved Forest Service road through the middle of the basin.

The existing forest and resource management plan was utilized as the basic framework in an innovative approach for defining desired future resource conditions and specifying prescriptions to achieve conditions (figure 1). The plan identified 8 management areas in the basin, including about 40% of the total area as suitable for timber supply and other traditional forest uses (Swank 1995). Emphases on the remaining area includes animal habitat, recreational uses, scenery, protection of a national scenic trail, and special ecosystems such as high elevation mountain "balds" and riparian areas. Desired future conditions for resources were derived over an 18 month period from a consensus building process entailing a series of workshops comprised of interested stakeholders including managers, user groups, scientists, and the public. A product of this process was the specification of 35 desired resource conditions. Another outcome of the process was enhanced understanding among participants of each others viewpoint in considering the complex trade-offs in-

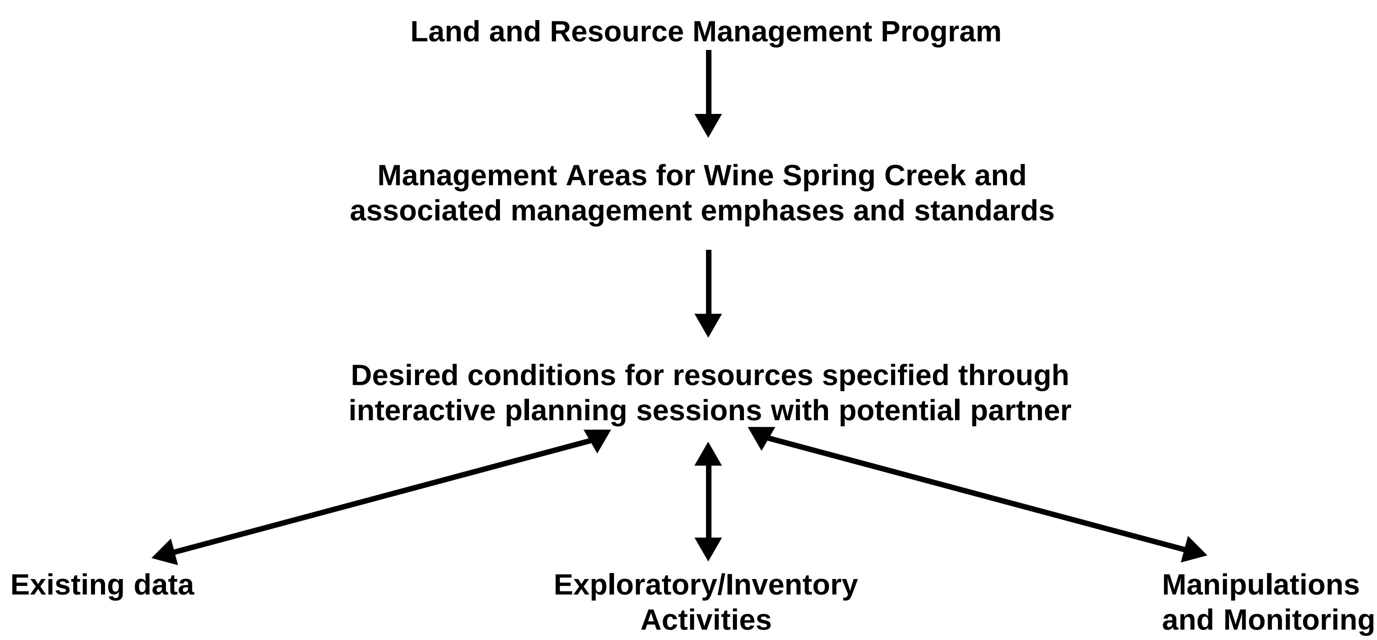

Figure 1. Outline of planning approach for ecosystem management on the Wine Spring Creek Watershed in western North Carolina. Existing forest plans were combined with stakeholders workshops to define desired conditions of resources and subsequent research and management prescriptions.

volved in ecosystem management (Meyer and Swank 1996).

Research

Over the past 5 years a cadre of more than 60 scientists and land managers in 6 research units in the Southern Research Station, National Forest Systems, and 8 universities along with conservation and environmental groups, state agencies, and the public have participated in the study. The 35 desired resource conditions span 8 primary research and management themes (table 2) which thus far, have entailed more than 40 studies. The research process entails the identification of existing data, exploratory and inventory activities, and manipulations / monitoring needed to test hypotheses or achieve goals (figure 1). In Phase I of the project three prescriptions are centered on various habitat manipulations to move the watershed toward desired conditions:

1. Stand replacement fire was prescribed on about 300 ha to restore a degraded pine / hardwood community and to stimulate forage production and promote oak regeneration along a hillslope gradient (Elliott et al. 1999). An interdisciplinary research team assessed initial responses of both terrestrial and aquatic ecosystems to management (table 3) and research continues to determine if desired conditions will be achieved;
2. Four silvicultural prescriptions (three replicates) were applied to the mixed oak stands to regenerate oak and increase biodiversity. Research is evaluating effects on vegetation, soil nutrients, water quality, small mammals and herpetofauna, ruffed grouse, soil invertebrates, stream invertebrates, and fish production;
3. Stream habitat improvement on an impoverished aquatic habitat section of Wine Spring Creek has been implemented through woody debris additions based on research on trout use of woody debris and habitat in Wine Spring the basin (Flebbe 1999).

An example of how research is integrated with management is illustrated in figure 2 where measured effects on resources are linked with adaptive management to provide a continuing process for achieving desired resource conditions. A major strength of the research is simultaneous studies in time and space which facilitates the detection of cause and effect relationships and provides a firmer basis for management decisions. Opportunities for incorporating findings into management are greatly enhanced because of the close planning and on-the-ground partnership between managers, scientists, and other participants in the project.

Additional research in the project also provides valuable information and tools for management. For example, soil erosion and stream sedimentation research are showing the benefits of best management practices associated with forest roads and other management prescriptions. Results have been used to develop a user-friendly, modular based, Geographic Information System for predicting soil erosion and transport to streams (Sun et al. In Press; Swank et al. 1994). This simulation model provides forest managers with a risk-assessment tool for evaluating the impacts of alternative management practices on water quality (Sun and McNulty 1998). An improved basis for management planning was also gained through socioeconomic research. Recreation studies identified human uses of the watershed and customer preferences for future uses (Cordell et al. 1996). A larger scale study of national forests in western North Carolina showed how economic tools can be extended to quantify complex social and biological

Table 2. Major research and management themes derived from enumeration of desired future conditions for resources on the Wine Spring Creek basin.

Ecological Classification
Riparian Zone Management
Aquatic Productivity/Water Quality/Habitat Alternation
Sustainable Productivity (Regeneration, Biodiversity, and Biogeochemical Cycles)
Social Value Assessment
Economic Analyses
Mammal and Bird Population Dynamics
Special Ecosystems ("Balds")

Table 3. Summary of resources examined and related documentation for stand replacement/habitat improvement burning on the Wine Spring Creek Ecosystem Management Project in western North Carolina

Resource	Reference
Vegetation	Elliott et al. 1999
Nutrient pools, soil and stream chemistry, stream sediment	Vose et al. 1999
Small mammals and herpetofauna	Ford et al. 1999
Soil macroarthropods	Crossley and Lamoncha, In Press

values associated with ecological processes (Schaberg et al. 1999). An extensive survey of citizen and special interest group preferences for a variety of goods and services associated with the forest lands showed that water and other ecological services and processes ranked highest across most groups. Other studies are focused on the riparian zone which is dominated by *Rhododendron maximum*, an understory species which is found over much of the stream system (Baker and Van Lear 1999; Laerm et al. In Press). Findings suggest opportunities for additional research in conjunction with management prescriptions to improve the structure, composition, and functional diversity of the riparian zone.

In the short-term, results from this research are reviewed, evaluated and incorporated into management using traditional approaches. However, our approach to ecosystem management includes the development of models that are spatially and temporarily explicit, synthesize and formalize knowledge, and provide an opportunity to view outcomes of proposed management. For example, some research findings from this project (soil erosion model, nutrient cycling, forest productivity) are planned for incorporation into a Decision Support System (Twery et al. In Press). Emergy, is a potentially powerful tool for synthesizing the value of multiple ecosystem components, functions, and outputs. It represents a novel approach to placing value on vastly differing resources (e.g., water, recreation, timber). In the following section, we provide a detailed description of an emergy analysis of WSC and its' potential management applications.

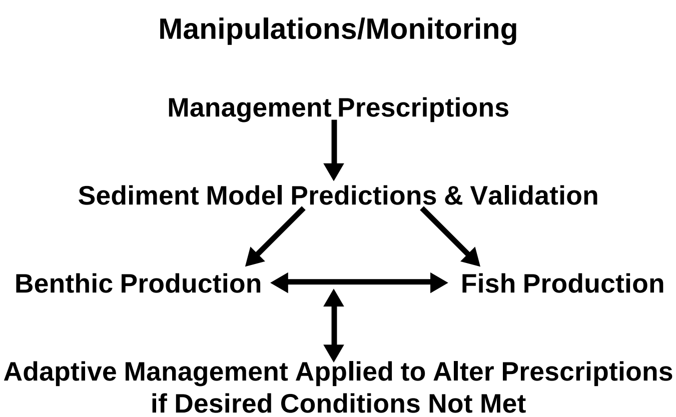

Figure 2. An example of linkages and feedback between management prescriptions, modeling, and stream research to identify the necessity for adaptive management. Wine Spring Creek Watershed, western North Carolina.

Emergy Analysis of the Wine Spring Creek Ecosystem Management Demonstration Project

Evaluation tools must be able to synthesize understanding of an ecosystems' multiple forcing factors, and components and outputs to integrate change across multiple geographic scales, and to predict future conditions. The ecosystem management philosophy adopted by the U.S. Forest Service requires such tools for measuring success in its effort to harmonize the needs of society, economy and ecosystem.

Emergy evaluation, a general methodology for assessing the functional and structural properties of any system, combines systems analysis with energy, material flow, economic and ecosystem analyses for holistic understanding (Odum 1996). For ecosystem management it offers a way of objectively comparing ecological benefits with economic and social benefits (Tilley 1999). It does so by expressing the varied benefits in a common metric, namely solar emergy. Solar emergy is the total sum of solar energy that was used previously in other system processes both directly, and more importantly indirectly, to make a product or deliver a service. It is the memory of energy used in the past. Ecosystem drivers (e.g., sunlight, wind, vapor deficit and rainfall), internal components (e.g., standing biomass, soil moisture, bedrock nutrition and species abundance) and products of an ecosystem (e.g., streamflow, recreated visitors, scientific knowledge and timber) can be quantified in terms of solar emergy for direct comparison of their relative importance to each other and to the larger economic system. The solar emergy per unit of available energy is defined as solar transformity (Odum 1996).

To contrast ecological processes with economic ones in a manner both meaningful and easily comprehended, the units of solar emergy (solar emjoules) for all products and services were translated to an equivalent amount of money. This was accomplished by converting solar emjoules to solar "emdollars" based on the ratio of money flow to emergy flow for the encompassing economy. Emdollars represent the amount of currency (e.g., dollars) being driven by a flow of emergy. In the case of the Wine Spring Creek (WSC) emergy evaluation, the emergy flow to dollar flow ratio was determined from North Carolina's economic activity of 1992.

Emergy evaluation has evolved over the last three decades (Odum 1996). It was applied to evaluate the interactions of man and nature in several river basins, including the Mississippi (Odum et al., 1987), Mekong

(Brown and McClanahan 1996), Amazon (Odum et al. 1986) and Maracaibo of Columbia and Venezuela (Howington 1999). Small watersheds have also been evaluated with emergy, including ones of the southern Brazilian coast (Romitelli 1997), the Coweeta Hydrologic Lab (Romitelli and Odum 1996) and most recently Wine Spring Creek of the Southern Appalachians (Tilley 1999).

We describe the methodology and demonstrate its application in evaluating the ecological-economic system of the Wine Spring Creek Ecosystem Management Demonstration Project (WSC). The multiple benefits of the forested watershed, such as wood, water, tourism and biogeochemical cycling, are compared in terms of solar emergy and emdollars.

Methods of Emergy Evaluation

Applying the emergy evaluation methodology to the WSC involved four steps:

1. identifying the system,
2. creating an emergy evaluation table,
3. determining the energy value of forcing factors and components and
4. converting energy values to solar emergy and emdollars.

The energy systems language (figure 3a) was used to conceptualize the system of the WSC. The diagrams provided a holistic picture of the ecosystem and identified the important forcing factors, internal components and exported products, along with their interactions. The process of developing each energy systems diagram was as follows:

1. The spatial boundary was defined as the watershed,
2. The temporal boundary was defined as a year,
3. A list of the forcing factors and internal units, thought to be important, was developed with input from the project team and other experts,
4. Preliminary, complex diagrams of the system were drawn with the energy systems language, arranging forcing factors and internal components in order of their solar transformity,
5. Rough values of the solar emergy of the forcing factors and state variables were calculated as a means of filtering out unessential parameters and aggregating others,
6. A final systems diagram was drawn, including only those forcing factors and state variables which represented greater than 5% of total emergy flow or stocked, respectively.

Figure 3b explains how the solar emergy values of the forcing factors, internal processes and multiple products of a system were calculated. First, the energy flow of each forcing factor was determined. The energy was transformed to solar emergy by multiplying by the appropriate solar transformity. Unless calculated within this work or otherwise noted, solar transformities used were from Odum (1996). In figure 3b the solar emergy value of the internal pathway Z equaled the solar emergy input Y. The solar emergy of product V was the sum of the two inputs to sector B, Z and U. The solar transformity of input U was determined based on its external transformation (i.e., Y' / U'). The solar transformity of internal pathway Z and the product V were calculated by dividing solar emergy by energy. The emdollars of each flow were found by dividing solar emergy by the average solar emergy-to-dollar ratio of the regional economy. In the case of WSC it was 1.12 E12 sej / $.

Results and Discussion of Emergy Evaluation

Figure 4a is the systems diagram of the ecosystem of Wine Spring Creek watershed. The diagram demonstrates how the energies of the meteorological system—sunlight, wind, vapor saturation deficit and rain—interacted with the mountain geology to create a mixed-hardwood forest with organically rich soils, deep saprolite and plentiful water reserves.

Figure 4b shows the systems diagram of the ecological economic system of the Wine Spring Creek watershed. The details of the ecosystem, which were shown in figure 4a, were aggregated and economic forcing functions were added. The diagram revealed how the capture of environmental energies by forest and mountain supported the ecosystem, which in turn, formed the basis for the human economy.

The diagrams and the process of developing them provide an instrument for focusing the attention of managers, policy makers and other environmental decision makers on the whole system. They help build consensus by identifying the system. If the practice of organizing forcing functions and components from left to right, according to their solar transformity, is followed, then holistic overview prevails and the diagrams clarify understanding.

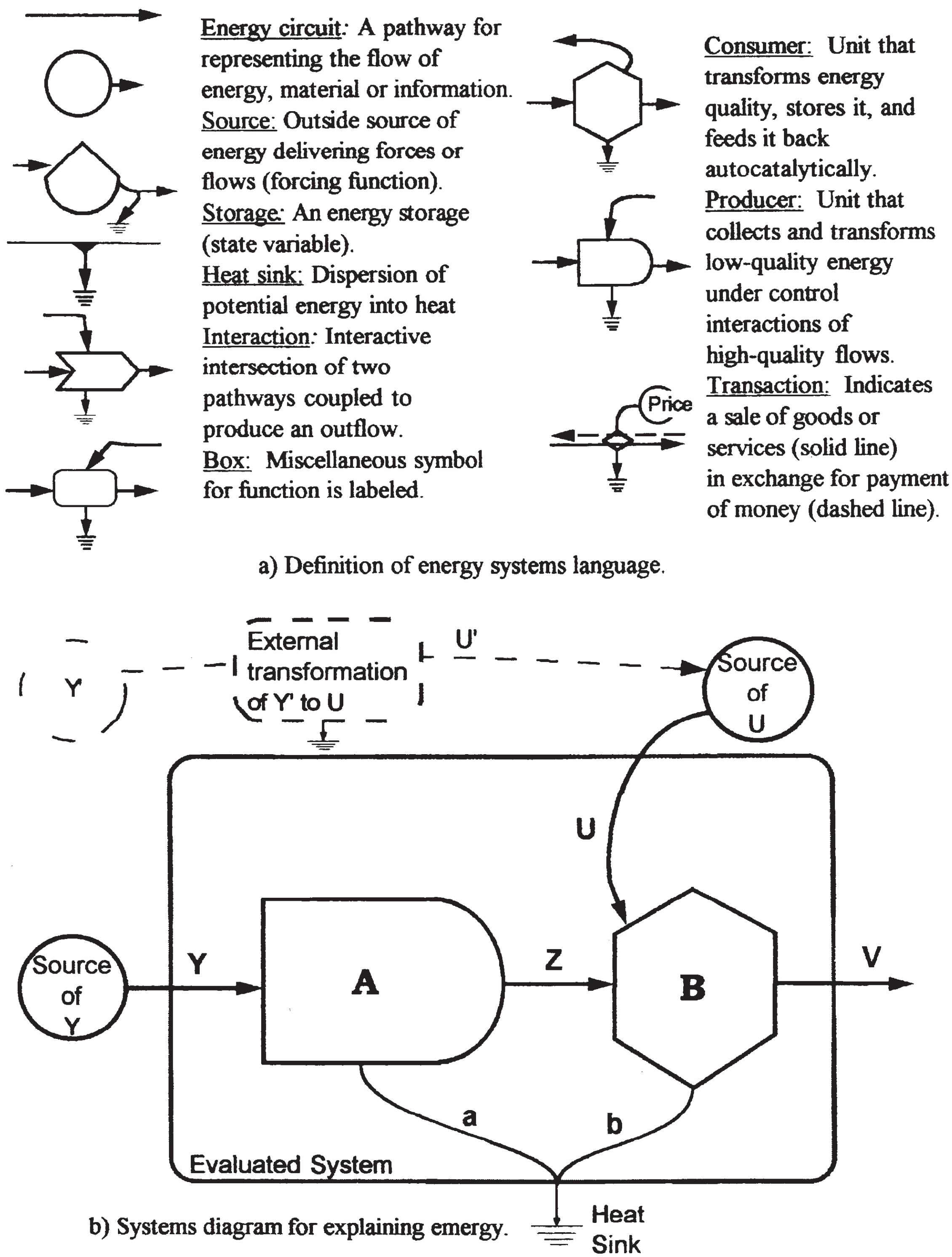

Figure 3. Energy systems language with definitions (a) and an energy systems diagram explaining how emergy flows are calculated (b). Abbreviations: e(X) = energy of X; M(X) = emergy of X; T(X) = transformity of X. The first step is to determine energy values of inputs, Y & U, internal pathway, Z and exported product, V. Next, emergy is assigned based on the total emergy required to make a product. Thus, M(Y)=T(Y)*e(Y), M(Z)=M(Y), M(U)=T(U)*e(U), M(V)=M(Z)+M(U). The waste heat [e(a)+e(b)] does not possess emergy since it is the energy lost in the energy transformation process. Finally, the transformities of the internal pathway and exported product are determined, T(Z)=M(Z)/e(Z) and T(V)=M(V)/e(V). In this example, T(U) is needed in terms of the base energy source, Y. Therefore, T(U) would need to be calculated, T(U)=M(Y')/e(U').

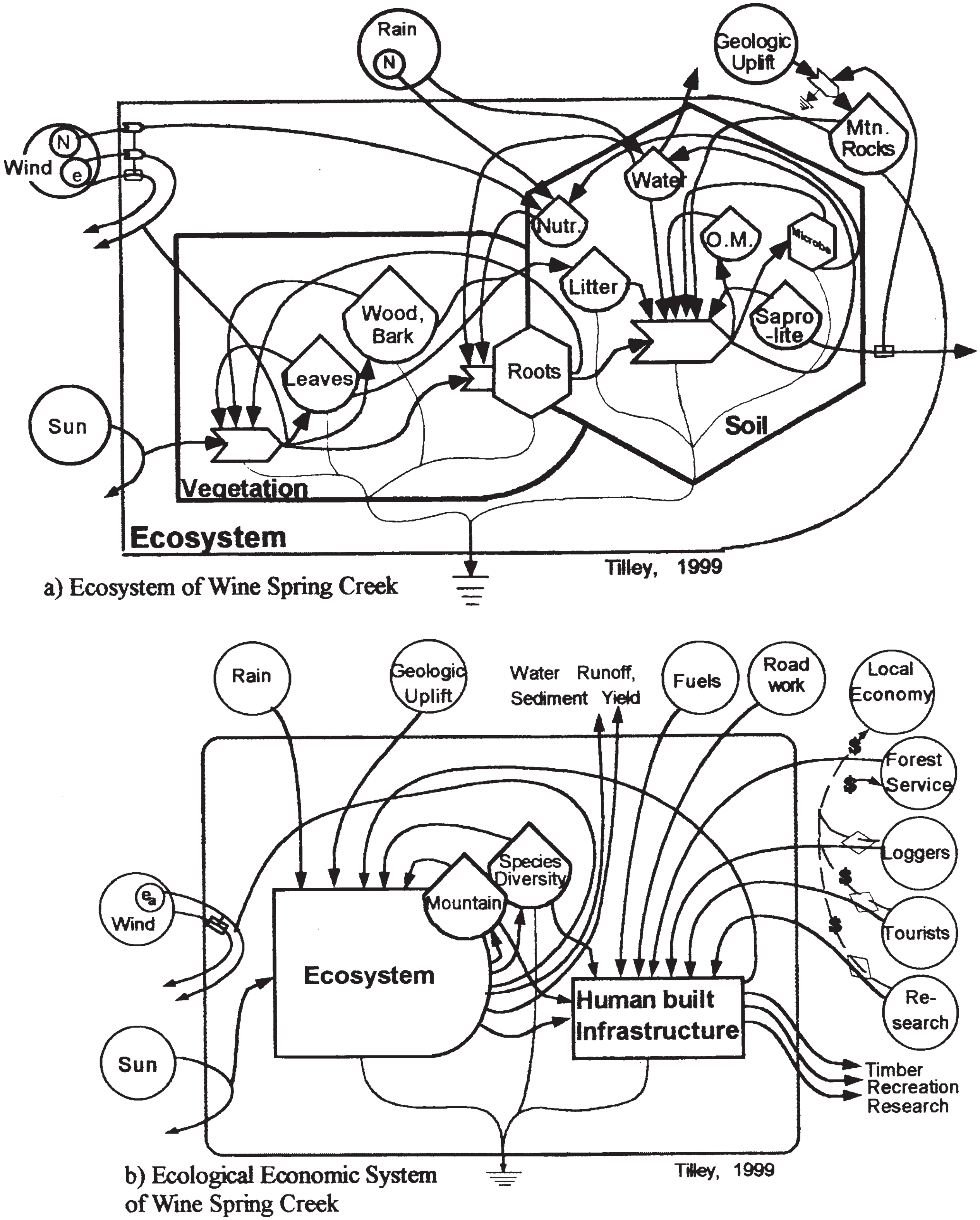

Figure 4. Systems diagram of the ecosystem of Wine Spring Creek watershed (a) and systems diagram of the ecological economic system of Wine Spring Creek watershed (b). Abbreviations: N-nutrients, e-water vapor, O.M.-organic matter.

Table 4 shows the emergy evaluation of the environmental energies used, the economic energies imported, the main internal processes and four important products exported for the WSC watershed.

The chemical energy of precipitation provided the largest input of solar emergy (1603 Em$ / ha / y), environmental or economic. Remarkably, four of the environmental sources (geopotential of rain, chemical potential of water used in transpiration, water vapor saturation deficit and land cycle) contributed a similar amount of solar emergy–between 385 and 525 Em$ / ha / y. The solar emergy of sunlight and atmospheric deposition were the two smallest environmental contributors (<46 Em$ / ha / y). The total incoming solar emergy derived from renewable environmental sources (2055 Em$ / ha / y) was the sum of three independent sources: chemical potential of precipitation, land cycle and atmospheric deposition. Other environmental sources are not added to avoid double counting (see Tilley 1999 for further explanation).

Comparison of the solar emergy contributed by the various ecosystem drivers demonstrated that water was the most important factor and indicates that properly managing water is critical to ecosystem health. The large amount of solar emergy in the land cycle confirms the fact that soil management is also important for a vibrant forest.

Listed next in table 4 (items 9-16) are the non-renewable sources of solar emergy that were imported by humans. The watershed received over 15,000 visitors annually (Cordell et al.1996). Tourists used various energies (automotive fuel and their own services) to enjoy free recreational resources. In one year, visitors utilized 12 Em$/ ha / y of automobile fuel while in the WSC watershed. An additional 124 Em$j / ha / y of auto-fuels were consumed by local through-traffic. The value of the tourists' time, worth 699 Em$ / ha / y, was a major imported resource. The Forest Service, over the last 25 years was paid an average of $9 / ha / y (12 Em$ / ha / y) by loggers. This was an order of magnitude less than the Forest Service expended (121 Em$ / ha / y) to maintain 32 km of paved and unpaved roads, but nearly equal to the value paid for management services (18 Em$ / ha / y). The largest imported source of solar emergy was from scientist's participating in the WSC Ecosystem Demonstration Project (1252 Em$ / ha / y).

If ecological sustainability is defined as the condition at which ecosystem benefits are acquired at a rate that does not hinder ability to provide future goods and services, then the ecological sustainability of the WSC system can be measured with the environmental loading ratio (ELR). The ELR was defined as the total imported solar emergy per unit of indigenous, environmental solar emergy (Brown and Ulgiati 1997). The WSC had an ELR of 1.1 indicating that economic activity evenly matched the ecological capacity of the forest. If the WSC was pristine and not used in any way for economic purposes, then there would be no imported solar emergy and the ELR would be zero. Multipurpose ecosystems with ELR's lower than the WSC include the Luquillo National Forest in Puerto Rico (ELR = 0.15; Doherty et al. 1997), where visitation was much higher but spread over a greater area, and the Everglades National Park (ELR = 0.82; Gunderson 1992). Odum and Odum (1980) found the ELR of a New Zealand pine plantation to be 1.4. At this rate of economic activity the ecological sustainability of the pine plantation cannot be assessed with definitiveness, but the ecological sources did provide less solar emergy than economic sources. For further perspective on how the ELR relates to ecological sustainable, consider that the ELR of Charlotte (N.C.), a modern American city, was 134 (Tilley 1999). Increasing the amount of imported solar emergy to the WSC will make the economic "load" much greater and the ecosystem less sustainable.

From a management perspective, the ELR could used for regional forest planning. Multi-purpose lands such as the WSC, could be targeted to maintain an ELR of one (i.e., an even match between economy and ecology), while wilderness lands could be selected to have much lower ELR's, possibly less than 0.10.

In table 4 the solar emergy value of wood growth and forest production (NPP) were each 892 Em$ / ha / y, which was the sum of the solar emergy of transpiration, land cycle and atmospheric deposition. The geologic work that weathered bedrock was the most valuable internal process (2055 Em$ / ha / y).

Water yield, harvested timber, recreationists and scientific data were the exports determined to posses large amounts of solar emergy (table 4). Total solar emergy of all exports was 4292 Em$ / ha / y. Based on this rate, the 1128 ha WSC watershed contributed wealth to the region at the annual rate of 4.8 million Em$.

A goal of ecosystem management is to maintain a balance between the ecological, economic and sociological goods and services provided by the ecosystem. With the emergy model, the balance (i.e., all outputs contribute equal solar emergy) of an ecosystem as well as its total output can be determined for alternative management plans. The WSC is fairly well balanced because it is contributing multiple benefits (water, recreation and information), valued in terms of solar emergy, at similar rates (table 4). If perfect balance is the goal, then timber harvest, which represented only 6% of total solar emergy output, needs to be increased or the other benefits need to be decreased. With all flows (input, internal and output) in the same unit (solar emergy), a sensitivity analysis can easily be performed to determine what happens to the balance of watershed products and ecosystem sustainability (i.e., environmental loading ratio ~=1.0) under various management plans.

Table 4. Emergy evaluation of Wine Spring Creek watershed (

Item	Physical Unit		Solar Transform (sej/unit`
ENVIRONMENTAL ENERGY INPUTS:			
[a] Sunlight	5.0E+13	J	
[b] Vapor saturation deficit	7.2E+11	J	5.9E+
[c] Wind, kinetic (annual)	1.9E+11	J	1.5E+
[d] Precipitation, geopotential	5.6E+10	J	1.0E+
[e] Precipitation, chemical	9.7E+10	J	1.8E+
[f] Transpiration	2.7E+10	J	1.8E+
[g] Land cycle	1.4E+10	J	3.4E+
[h] Atmospheric deposition	3.0E+04	g	1.0E+
Sum of c, g, & h			
IMPORTED ENERGY SOURCES:			
[I] Auto-fuel, visitors within	2.1E+08	J	6.6E+
[j] Auto-fuel, thru traffic	2.1E+09	J	6.6E+
[k] Visitors, length of stay	8.6E+07	J	8.9E+
[l] Timbering, services	9	$	1.5E+
[m] Timbering, fuels	1.6E+07	J	6.6E+
[n] Road maintenance	88	$	1.5E+
[o] Forest Service mgmt.	13	$	1.5E+
[p] Scientist's time	4.0E+06	J	3.4E+
Sum of imports (i - p)			

footnotes follow

Footnotes to Table 4

[a] Solar insolation @ ground 5.02E+13 J/m^2/yr (taken from Coweeta, Swift et al., 1988)

[b] Energy of vapor saturation deficit used, J/y = 7.17E+11 (see Tilley 1999)

[c] Wind energy, J/y = 1.88E+11 (complex function, see Tilley 1999 for details)

[d] Potential energy @ mean elev. (J) = (area)(runoff)(mean elev - min elev)(density)(gravity)
= (10,000 m^2)*(1.423 m/y)*(1318-920 m)*(1000 kg/m^3)*(9.8m/s^2)
Energy, geopotential (J) = 55.5E+9

[e] Precipitation @ 1330 m = 1,961 mm/yr Forest Service (1995-1997)
Gibb's free energy of rainfall (10ppm vs 35ppt), J = (area)(rainfall)(Gibbs no.)
= (10,000 m^2)*(1.960m)*(4.94E6 J/m^3)
Gibb's free energy (J) = 9.69E+10

[f] Mean rate of transpiration 538 mm/y CS301t (pers. comm. L. Swift, Coweeta)
Gibb's free energy of rainfall (10ppm vs 35ppt), J = (area)(transpiration)(Gibbs no.)
= (10,000 m^2)*(0.538m)*(4.94E6 J/m^3)
Total energy (J) = 2.66E+10

[g] Emergy of land cycle calculated as eart
Heat flow / Area = 1.36E+06 J/m^2/y, @ Bryson City, NC
Energy (J) = 1.36E+10 (Smith et al., 1981; in Pollack et al., 1991).
Transformity, 34,400 sej/J was the mean calculated for the continents by Odum, 1996.

[h] Deposition rate, kg/ha/y = 30 estimate based on Coweeta Hydrologic Lab

[i] Gas within WSC = 3.70E+01 (bbl/yr; see Tilley 1999)
Energy(J) = (____bbl/yr)*(6.28e9 J/bbl)
Energy(J/ha) = 2.06E+08

[j] Gas within WSC = 3.70E+02 (bbl/yr; see Tilley 1999)
Energy(J) = (____bbl/yr)*(6.28e9 J/bbl)
Energy(J/ha) = 2.06E+09

[k] no. of groups/yr = 4,361 Cordell et al., 1996.
mean group size = 2.7 people
mean length of stay = 19.0 hours
Energy(J) = (_____people-hrs/yr)*(104 Cal/hr)*(4186 J/Cal)
Energy(J/ha) = 8.63E+07
Transformity of 8,900,000 sej/J is the avg. for a U.S. citizen during avg. day.

[l] Revenue from timber sales from 1973-1999 (26y) was $250,000 (Wayah Ranger District).
Revenue, $/ha/y = 8.5

[m] U.S. National average fuel use: 23 E15 J/y to harvest 648 E6 m^3 of wood
Fuel use in WSC timbering, J/ha/y = 1.56E+07

[n] Length of unpaved roads = 24 km (GIS database)
Length of paved roads = 9 km (GIS database, FS 711)
Cost to maintain roads 5.000 $/mile/y (B. Culpepper, Wayah Ranger District)
Cost of rd, $/ha/y = (length of rds, km)x($5000/mile/y)x(1 mile/1.609 km)/(1128 ha)
Cost of rd, $/y = 8.84E+01

[o] Expenditures, \$/ha/y = 13

[p] At least 52 forest scientist, forest managers, university scientists and graduate students worked on the WSC Ecosystem Project from 1992-99. Assume they devoted 10% of their total work per year to gathering, analyzing, publishing and sharing their research

Effort, people-hr/y = 1.04E+04

Energy (J/ha) = (____people-hrs/yr)*(104 Cal/hr)*(4186 J/Cal)/(1128 ha)

Energy (J/ha) = 4.01E+06

Transformity: post-college educated person (Odum 1996)

[q] Roots+wood+leaves 14390 kg/ha/y; Day and Monk, 1977.

Energy(J) = (NPP,kg/ha/y)x(area, ha)(1000 g/kg)(3.5 kcal/g-dry wt)(4186 J/kcal)

= 2.11E+11

Transformity = (empower of evapotranspiration + deep heat + atmos. dep.) / (net production)

[r] Wood growth 4.20E+03 kg/ha/y; Monk and Day, 1977.

Energy(J) = (accum.,kg/ha/y)x(area, ha)(1000 g/kg)(3.5 kcal/g-dry wt)(4186 J/kc

= 6.15E+10

Transformity = (empower of evapotranspiration + deep heat + atmos. dep.) / (wood accumulation

[s] Erosion rate, g/m^2/y = 60 Velbel, 1985.

Sediment lost, g/ha/y 6.00E+05

Empower-to-flux (sej/g) = (empower of rain+deep heat+atmos. dep.) / (weathering rate)

[t] From the species-area curve, there were 30 species found within the first ha sampled. See Tilley 1999 for details

[u] Stream discharge

Runoff = 1.42 m/y mean 1995-96. Source: Coweeta Hydro. Lab

Chemical Energy(J) = (10,000 m^2)*(1.42 m/y)*(4.94E6 J/m^3)

Chemical Energy(J) = 7.03E+10

Transformity: [empower of rain + deep heat] / energy

[v] Since 1973 (26 y), timber harvest from WSC watershed was 8623 m^3 sawtimber and 4259 m^3 of roundwood, valued at \$251,000 (Wayah Ranger District, courtesy of Bill

Timber harvest rate, m^3/ha/y = 0.44

Energy(J) = (m^3)*(5 E5 g/m^3)*(4.5 Kcal/g)*(4186 J/Cal)

Energy(J) = 4.14E+09

Transformity of timber = (emergy of wood + road maintenance + FS management + timbering fuels + timbering services)/energy of timber

[w] Same energy as visitor's length of stay above (#24)

Transformity = [sum of env. & econ. empower inputs /[metabolism of visitors during

Environmental inputs were taken as half the annual flow of rain+deepheat+atmospheric deposition since the main road is only opened from Apr. to Nov.

Economic inputs were sum of auto-fuel use, visiting time, road maintenance, and FS managemen

[x] From 1992 to 1998, 47 publications and 10 reports were produced (Swank 1999)

Publication rate over the six years was 57 / 6 = 9.5 pubs/yr. Publications average 10 pages in len

Grams of research articles published, g/y = 9.5 articles/y x 10 pages x 1 g/page = 95 g/y

Energy of articles, J/y = grams x 3.5 kcal/g x 4186 J/kcal = 1.39E6 J/y

Energy of articles, J/ha/y = 1,232

Transformity = [sum of empower inputs (rain, deepheat, atmospheric deposition, road maintenance, FS management, and research effort)]/[energy of publications, annual rate]

[y] Total Export was rain + deep heat + atmos. deposition + all imported sources (items 10-18)

Regional Scale Analyses in Progress

Watersheds also provide a useful framework for evaluating land stewardship at larger landscape scales; i.e., river basins. However, the complexities of planning and assessment increase substantially at a regional scale with mixed ownerships and multiple land uses.

As part of the Long-Term Ecological Research program at Coweeta, regional scale research was initiated to assess the effects of human caused disturbances on ecological processes. The effort encompasses a 15,000 km^2 area of western North Carolina with a focus on the Little Tennessee and French Broad river basins. Interdisciplinary research is being conducted by more than 30 co-principal investigators including social and economic scientists, as well as aquatic and terrestrial ecologists. The overall research goal is to develop a predictive understanding of the social, economic and environmental factors that drive land use cover changes and to assess the ecological consequences of changes for terrestrial and aquatic biodiversity, water quality, and regional carbon cycles (Swank 1998). Regional land use change models (Wear and Bolstad 1998) will be linked to socioeconomic and environmental models to forecast the consequences of future land use practices and policy. Initial research shows that whole watershed land use in the 1950s (compared to 1990s) is the best predictor of present day diversity of stream invertebrates and fish (Harding et al. 1998). Findings indicate that past land use, particularly agriculture, may result in long-term reductions in aquatic diversity, that persist even with reforestation of the watershed.

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