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EMERGY-based environmental systems assessment of a multi-purpose temperate mixed-forest watershed of the southern Appalachian Mountains, USA

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Abstract

Emergy (with an 'm') synthesis was used to assess the balance between nature and humanity and the equity among forest outcomes of a US Forest Service ecosystem management demonstration project on the Wine Spring Creek watershed, a high-elevation (1600 m), temperate forest located in the southern Appalachian mountains of North Carolina, USA. EM embraces a holistic perspective, accounting for the multiple temporal and spatial scales of forest processes and public interactions, to balance the ecological, economic, and social demands placed on land resources. Emergy synthesis is a modeling tool that allows the structure and function of forest ecosystems to be quantified in common units (solar emergy-joules, sej) for easy and meaningful comparison, determining 'system-value' for forcing factors, components, and processes based on the amount of resources required to develop and sustain them, whether they are money, material, energy, or information. The Environmental Loading Ratio (ELR), the units of solar emergy imported into the watershed via human control per unit of indigenous, natural solar emergy, was determined to be 0.42, indicating that the load on the natural environment was not ecologically damaging and that excess ecological capacity existed for increasing non-ecological activities (e.g. timbering, recreation) to achieve an ELR of 1.0 (perfect ecological–economic balance). Three forest outcomes selected to represent the three categories of desired sustainability (ecological, economic, and social) were evaluated in terms of their solar emergy flow to measure outcome equity. Direct economic contribution was an order of magnitude less (224×10^{12} solar emergy-joules (sej) ha^{-1}) than the ecological and social contributions, which were provided at annual rates of 3083 and 2102×10^{12} sej ha^{-1}, respectively. Emergy synthesis was demonstrated to holistically integrate and quantify the interconnections of a coupled nature-human system allowing the goals of ecological balance and outcome equity to be measured quantitatively.
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Keywords: Ecosystem management; Watershed assessment; Ecological decision-making; Forest sustainability

1. Introduction

The United States Forest Service (USFS) embraced ecosystem management as its guiding philosophy to balance the ecological, economic and social interests placed upon public forestlands and grasslands in 1992 (Thomas, 1996). Ecosystem management is viewed as a proactive, holistic approach to natural resource management as contrasted to the reactive, species-specific Endangered Species Act (Wear et al., 1996). Managing a complex system, such as a public forest, to achieve multiple objectives with multiple constraints from the varied stakeholders requires the development and application of new integrated assessment and decision-making tools. In the past, when maximizing timber production was a major goal and other forest benefits were treated as constraints, optimization models could be developed based largely on financial indicators. However, now the primary task is to achieve sustainability, which relegates the capture of commodities and amenities to constraints (Christensen et al., 1996).

Ecosystem management has been interpreted and applied in many ways by various organizations and government agencies. Consensus on a strict definition has not been achieved. One alternative approach to conceptualizing ecosystem management is to envision the goal as

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maximizing the 'total combined benefit to nature and humanity,' under the constraints of balanced-use and equitable outcomes. In this type of approach, the goal is to optimize multiple functions, each with its own unique quantifiable units of measure, so that the sum total of the ecological, social, and economic benefits is maximized. A major hurdle to implementing such a decision-making technique is the need to overcome the diversity of metrics used for quantifying forest processes and activities. One approach for overcoming the 'metrics' problem is to normalize all products and services of the maximization function to a unit of measure that represents the quantity and quality of work being created and maintained by the system. In the case of ecosystems, normalization should reflect the inherent system-values that thousands of years of natural selection have created to organize the structure and function of ecosystems. Thus, a complicated issue is to assign transformation values to forest forcing functions, structures, processes, and activities so a maximization function can be developed and solved to aid management decisions. For example, if forest managers were charged to maximize the total benefit from a forested watershed that could only provide three products: timber, water, and species preservation, how do they decide how much wood gives the same benefit as a cubic meter of freshwater?

Emergy synthesis is a modeling tool that addresses the problem of normalizing system properties. In emergy synthesis, solar transformities are used to normalize forcing factors, state variables, and other system attributes to one metric, namely solar emergy. Solar transformities are calculated rigorously and based on scientific principles of system organization and energy flow. Solar transformities represent the position a forcing factor occupies in the hierarchical network of the Earth's biogeosphere (Odum, 1996). Technically, the solar transformity is defined as the solar radiation required directly and indirectly to create and maintain another form of available energy (exergy) (Odum, 1988). It has been calculated for a wide variety of energy forms, resources, commodities, and services (Brown et al., 2000; Brandt-Williams, 1999; Odum, 1996). The Gibbs free energy of precipitation, for example, has a solar transformity of 18,000 solar emergy-joules per Joule (sej J^{-1}), whereas more abundant solar radiation, which is the major source of Earth's energy, is defined to have a solar transformity of 1 sej J^{-1}. Thus, although the abundance of solar radiation can often be two orders of magnitude greater than the Gibbs free energy of precipitation in forested ecosystems, weighting solar radiation and Gibbs energy of precipitation by their solar transformities normalizes them to a common unit, solar emergy-joules (sej), and numerically places their importance to system performance in parity.

Besides providing solar transformities as weighting factors, emergy synthesis forces one to take a holistic view of the combined system of ecology and economy, inventorying all forms of energy and all types of material used to produce and maintain the ecological integrity and economic health of the combined system (Campbell, 2001). Although the system is a complex web of flows, cycles and feedbacks, in emergy synthesis the network is simplified by concentrating attention on the flows that represent greater than 1% of the total solar emergy flow. To quantify the 'system-value' of the energy, material, and information flows of the ecological–economic production network, emergy synthesis uses solar transformities to in effect trace each flow path back to the total solar radiation that was required to generate it. This results in every flow of material, energy and information being expressed in units of solar emergy. The total solar emergy of a resource flow (e.g. vapor deficit, inorganic nutrient uptake) can be calculated, depending on whether the physical measurement is in exergy, mass or money, using one the following equations:

$$\text{solar emergy flow (sej yr}^{-1}) = \text{solar transformity (sej J}^{-1}) \times \text{exergy flow (J yr}^{-1}) \quad (1)$$

$$\text{solar emergy flow (sej yr}^{-1}) = \text{specific solar emergy (sej g}^{-1}) \times \text{mass flow (g yr}^{-1}) \quad (2)$$

$$\text{solar emergy flow (sej yr}^{-1}) = \text{emergy-to-money ratio (sej \$}^{-1}) \times \text{money flow (\$ yr}^{-1}) \quad (3)$$

1.1. Recent applications of emergy synthesis in environmental decision-making

Based on the accelerating rate of scholarly publications centered on emergy synthesis, it appears that the methodology is maturing to a respected form of integrated environmental assessment (Brown et al., 2000, 2003). For example, the net public benefit of reforestation alternatives in Puerto Rico was quantified from an emergy evaluation, finding that natural wealth accumulated to a level 15–25 times the money invested in the 10–20 yr required for canopy closure (Odum et al., 2000). Dam construction projects, which often induce significant ecological and environmental change have been evaluated with emergy synthesis to assess how the functional benefits of water supply, flood control and power production compare to ecosystem and agricultural losses (Kang and Park, 2002; Brown and McClanahan, 1996). Bakshi (2002) explores the feasibility of integrating emergy synthesis with environmental life cycle assessment (LCA) to improve LCA's ability to assess, not only resource consumption and environmental impacts of wastes, but also the indirect support of ecological services, which he believes will overcome a major shortcoming of LCA in its inability to account for ecological services. Ulgiati and Brown (2002), in an attempt to advance the ability of emergy synthesis to account for chemical emissions during production of electricity from coal-fired power plants, included the ecological productivity required to re-incorporate each waste back into its global biogeochemical cycle as an emergy cost. Nelson et al. (2001) used emergy synthesis to compare conventional sewage treatment with wastewater wetland systems as alternatives for developing countries. They concluded that wetland systems were more sustainable based on their much greater use of renewable emergy (60% for wetlands compared to 1% for sewage systems) and much lower use of purchased emergy (e.g. electricity, cement, steel, technical services). Ulgiati (2001) applied emergy synthesis to evaluate the role of ethanol in contributing to the power supply of developed and undeveloped countries, concluding that the net emergy yield was too small in developing countries and that the supply was insufficient in developed countries to make ethanol competitive. Rydberg and Jansen (2002) utilized emergy to compare and contrast the natural and fuel-based inputs to farm traction in Sweden for 1927 and 1996, finding that the emergy of resource inputs had shifted from 60% renewable for horse-traction to only 9% for motorized-traction. Campbell (2000) promoted emergy synthesis as a means for defining, measuring and interpreting ecological integrity and health, explaining that system integrity is a function of the signature of energy forms driving and organizing the system. He concluded that a broader array of energy forms (i.e. higher forcing diversity) increases likelihood of stable ecosystem integrity. Thus, emergy synthesis is frequently used to quantify the structure and performance of environmental systems to aid in environmental decision-making.

1.2. Sustainability and equity

A definition of sustainability pertinent to ecosystem management is that it secures the ecological integrity, structure, and function of an ecosystem across multiple generations, balancing the needs of today with the needs of the future. Based on principles from general systems theory (Odum, 1971; von Bertalanffy, 1968), a sub-system must contribute to its larger system in an amount commensurate with parallel sub-systems and in proportion to the feedback it receives from the larger system of which it is a part, if it is to remain a viable component of the system. If, due to non-use or extremely low intensity use, a system provides little value to its larger system, it increases the risk that it will be selected against and discarded (Region 1 in Fig. 1). On the other hand, highly intensive use will likely degrade the system's structure and function, affecting its ability to perform satisfactorily in the future (Region 3 in Fig. 1). Sustainable management aims to be in Region 2 of Fig. 1 where development intensity is neither too low nor too high. The Environmental Loading Ratio (ELR) (Brown and Ulgiati, 1999), the units of solar emergy imported to a landscape via human control per unit of indigenous, natural solar emergy, measures the intensity of land use relative to the natural environment's productive abilities. In other words, sustainable management cannot only be concerned with minimizing the intensity of resource use. It is a balancing act between low intensity use and high intensity use; the former conserves local ecological integrity, while the latter diminishes the risk of being banished from the larger system (Fig. 1).

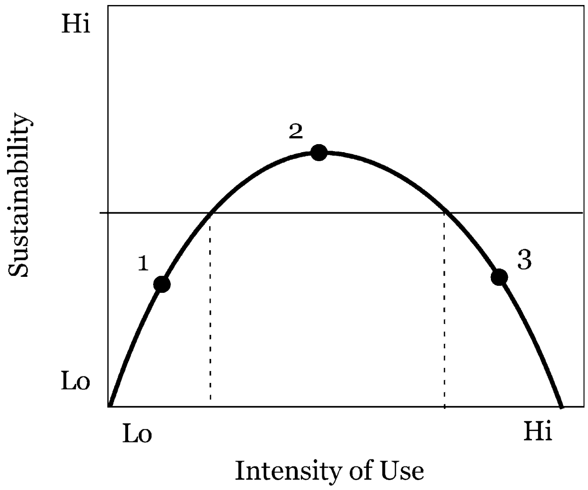

Fig. 1. Likelihood of sustainability is increased when intensity of land use is intermediate.

In addition to finding the development intensity that is sustainable, forest managers must satisfy the needs of stakeholders, who serve as the forest's larger controlling system, providing them with commodities, amenities, and ecological services at a rate commensurate with their own system-value. In an ideal world, all stakeholders would be satisfied with management decisions. In reality, trade-offs are the standard. Emergy synthesis, by measuring the relative value of forest products and services in common units, can provide an indication of whether equity in outcomes is achieved.

1.3. Objectives and plan of study

Our objectives are (1) to demonstrate how emergy synthesis inventories and normalizes the broad spectrum of forest forcing functions, ranging from solar radiation to road construction to tourism, to evaluate their importance to system performance and their contribution to creating and maintaining the flow of forest commodities, amenities, and ecological services (i.e. ecological, social and economic benefits), and (2) show how emergy-based indices can be used to assess the equity of forest outcomes and the ecological-economic balance of human investment in natural systems. The equity achieved in delivering product and service flows such as recreation, species preservation, water yield, timber production, and research information was measured in units of solar emergy. ELR was calculated to assess the balance between economic investment in the forested watershed with the natural productivity of the forest. Two new emergy-based indices, the Ecological

Cycle Load (ECL) and the Emergy Return on Ecosystem Management, are proposed and demonstrated for quantifying human impact on managed ecosystems.

2. Methods

2.1. Description of system

The 1130 ha WSC watershed lies within the Nantahala National Forest of the North Carolina Blue Ridge physiographic province in western Macon County (35°N latitude, 83°W longitude). Elevations in the basin range from 1660 m at Wine Spring Bald to 900 m at Nantahala Lake. The basin is unpopulated, but receives about 12,000 tourists per year (Cordell et al., 1996) who enjoy the forest via the Bartram Trail or a network of paved and unpaved USFS roads. Timbering is present with about 40% of the area designated suitable for timber management. Climate is similar to the near-by Coweeta basin where 1800 mm of annual precipitation is evenly distributed throughout the year with more than 100 mm of precipitation falling each month. Mean temperatures in January and July are 3.3 and 22 °C, respectively (Swift et al., 1988). The main land cover is mixed hardwood forest. The WSC Ecosystem Demonstration project, a research effort to quantify effects of several forest management prescriptions, was begun in 1994 as a collaboration between the managers of the USFS Wayah Ranger District; scientists of the USFS Coweeta Hydrologic Laboratory and other USFS Southern Research Station work units; and scientists from seven US universities (Swank, 1998).

2.2. Emergy synthesis

The general methods for employing emergy synthesis were given fully by Odum (1996, 2000a). Since the emergy value of a flow is the sum of all emergy required directly and indirectly to create it, emergy values for all input items must first be determined (emergy input analysis) and then allocated to internal system pathways and exported items (emergy allocation). The first step is to draw an energy systems diagram that depicts the environmental basis of the ecosystem and its connection to the larger economy. The energy systems language (Odum and Odum, 2000) was used to provide a holistic picture of the ecosystem and specify the main forcing functions, internal components, process interactions, and exported products. The process of developing an energy systems diagram proceeds as follows:

1. Define the spatial boundary as the watershed,
2. Define the temporal boundary as 1 year,
3. Develop a list of the forcing factors and internal units, thought to be important by the project team,
4. Sketch preliminary, complex diagrams of the system with the energy systems language, arranging forcing factors and internal components in order of their solar transformity,
5. Calculate preliminary values of the solar emergy of the forcing factors as a means of filtering out unessential parameters and aggregating others,
6. Draw a final systems diagram, including only those forcing factors which represented greater than 1% of total solar emergy flow.

Step 5 listed above is the emergy input analysis. It proceeds by calculating the solar emergy of each environmental and human-controlled (e.g. fuels, human service) input item by inventorying either its exergy (i.e. available energy), mass or money value and transforming it to solar emergy according to the appropriate equation chosen from either Eqs. (1) and (2) or (3). Table 1 demonstrates how items were transformed from raw units to solar emergy and eventually to emdollars (i.e. emergy-dollars).

Use of emdollars allows contribution of nature to be expressed in terms of the regional currency. In the realm of peopled systems where markets and money are used to exchange goods and services, emdollars are a convenient way to express system-value in terms familiar to people. Emergy is translated to emdollars by dividing emergy flow by the average emergy-to-money ratio of an economic system. The emergy-to-money ratio is found by dividing total emergy use of an economic system by its gross domestic product. For this study, the average solar emergy-to-dollar ratio of North Carolina, 1.12×10^{12} sej $\$^{-1}$ in 1992 (Tilley, 1999), was used.

Unlike the emergy input analysis where the solar emergy of forcing functions was determined as the product of solar

Table 1
Template for inventorying and weighting resource inputs and outputs in emergy synthesis

1	2	3	4	5	6	7
Note	Item	Data	Units	Transformity (sej/unit)	Solar emergy (sej/yr)	Emdollars (Em$/yr)

Column 1 is the line item number, which is also the number of the footnote found below the table where raw data sources are cited and calculations are shown. *Column 2* is the name of the item, which is shown on the systems diagram. *Column 3* is the raw data in joules, grams, dollars or other units. The units for each raw data item are shown in *column 4*. *Column 5* is the transformity used for calculations, expressed in solar emergy joules per Joule or other appropriate units (sej/h; sej/g; sej/$). Transformities may be obtained from previous studies or calculated for the system under investigation. Transformities from other authors will show source reference. *Column 6* is the solar emergy of a given flow, calculated as input times transformity (Column 3 × Column 5). *Column 7* is the emdollars of an item, which indicates its value relative to the economic system.

transformity and available energy (or similary with Eqs. (2) or (3)), the solar emergy of internal processes and exports was determined by allocating incoming solar emergy to a process or product. Allocation adhered to the 'emergy algebra rules' that were stipulated in Brown and Herendeen (1996). For example solar empower of wood growth was the sum of transpiration, land cycle, and atmospheric deposition, which were itemized in the emergy input analysis. Adding the solar emergy of other sources to wood growth emergy would violate the rule to not double count solar emergy. In this case, the rule is to use the larger source of co-dependent sources (Odum, 1996). Sunlight cannot be added along with transpired water because each form of energy was derived from the same energy source within the same time period. The solar transformity of an internal process or export was then calculated as the allocated solar emergy divided by its exergy.

To assess the emergy basis for maintaining natural tree diversity, we converted a developed species-area curve to an emergy-species curve. The tree species-area curve was developed for the high-elevation forests (above 1200 m MSL) of the WSC watershed using unpublished data gathered by K. Elliot (USDA Coweeta Hydrologic Lab). The species-area curve was transformed to a species-emergy curve by multiplying area by the average emergy flow per area (2231×10^{12} sej ha^{-1} yr^{-1}) for the WSC. The species-emergy curve provided an estimate of the solar emergy nature required to maintain a particular level of tree diversity in the watershed.

Data for the emergy input analysis were gathered from various field studies conducted in the WSC as well as from the long-term monitoring conducted at the near-by US Forest Service Coweeta Hydrologic Laboratory which contained similar watersheds. Transformities for global energies were mainly taken from Odum (1996), while others were calculated by Tilley (1999) (see footnotes to Tables 2 and 3 for details). Estimates of solar transformities and their corresponding variability continue to improve (Campbell, 2003), but need a more concerted effort from a wider cross-section of the scientific community if they are to improve rapidly and assuredly.

2.3. Emergy indices

Representing the free environmental emergy and the human-controlled emergy in similar units allows the balance between the forest's natural capacity and investment in its infrastructure to be gauged quantitatively and fairly. The index employed in emergy synthesis to judge this relationship is ELR (Brown and Ulgiati, 1999), which is the total human-controlled emergy invested in the watershed divided by the annual free environmental emergy input.

We propose two new emergy-based indices for assessing ecosystem impact and management performance. ECL which is defined as the economic emergy imported to an ecosystem per the emergy of the ecosystem's biogeochemical cycle, measures the sustainability of an ecosystem's biogeochemical cycle. The second emergy-based index that may be useful to ecosystem resource managers is the Emergy Return on Ecosystem Management (EREM), which is defined as the total emdollar yield of the ecosystem per the dollars paid for management. It indicates how well the financial expenditures of managing an ecosystem are matched to the total emergy yield of the ecosystem. A high value means that a lot of emergy production is managed with little dollar expenditures, whereas a low value likely indicates that the ecosystem is 'over-managed'.

3. Results

3.1. Emergy of forcing functions

Fig. 2 is an energy systems diagram of the WSC watershed that demonstrates the interconnectedness of the ecosystem and the important contribution of non-indigenous, imported resources. The indigenous, environmental energies—solar radiation, kinetic energy of wind, atmospheric vapor saturation deficit, and precipitation—interacted with the ancient geology to create a mixed-hardwood mountain forest with moderate species diversity. Over the past century, based on the addition of economic forcing functions, the watershed was developed into an ecological–economic system that provides multiple commodities and amenities to society. However, as the diagram emphasizes, the natural environment and the energies that it captures and transforms into forest resources is the basis of the human-built infrastructure and outside attraction. Without the combination of natural energies, the watershed likely would not be as attractive to tourists, nor would it produce as much timber.

The evaluation presented in Table 2 derives directly from the energy systems diagram in Fig. 2. Table 2 lists the indigenous, environmental resources used and the economic resources introduced to the WSC watershed. The chemical potential energy (Gibbs free energy) of precipitation was the largest individual source of solar emergy to the WSC, representing 1763×10^{12} sej ha^{-1} yr^{-1} (1600 Em$ ha^{-1} yr^{-1}). As a temperate forest that receives nearly 2 m per year of precipitation, it may be intuitive that the solar emergy of precipitation is greater than the solar emergy of solar radiation. Part of the difference derives from precipitation having a solar transformity (18,000 sej J^{-1}) that is four orders of magnitude greater than the solar transformity of solar radiation (1 sej J^{-1}). After precipitation chemical energy, the rank list of forcing functions, according to solar emergy flow were: physical potential (geopotential) of precipitation, land cycle (geologic uplift), water vapor saturation deficit used in transpiration, physical kinetic energy of wind absorbed within the ecosystem, solar radiation, and atmospheric deposition of inorganic nutrients (Table 2).

Table 2
Emergy evaluation of forcing functions for the Wine Spring Creek watershed (annual flows per ha, 1995)

Item	Physical unit	Solar transformity (sej/unit)	Solar emergy ($\times 10^{12}$ sej)	Emdollar value (1992 Em$)
Indigenous environmental resource inputs				
Precipitation, chemical[a]	9.69×10^{10} J	18200	1763	1603
Precipitation, geopotential[b]	5.55×10^{10} J	10400	577	525
Transpiration[c]	2.66×10^{10} J	18200	484	440
Land cycle[d]	1.36×10^{10} J	34400	468	425
Vapor saturation deficit[e]	7.17×10^{11} J	590	423	385
Wind, kinetic (annual)[f]	1.88×10^{11} J	1500	282	256
Sunlight[g]	5.02×10^{13} J	1	50	46
Atmospheric deposition[h]	30000 g	1.0×10^{9}	30	27
Imported economic resource inputs				
Scientist's time[i]				
High solar transformity	4.0×10^{6} J	4.5×10^{8}	1825	1661
Middle solar transformity	4.0×10^{6} J	3.4×10^{8}	1377	1252
Low solar transformity	4.0×10^{6} J	2.8×10^{8}	1135	1032
Visitors, length of stay[j]	8.6×10^{7} J	8.9×10^{6}	768	699
Auto-fuel, thru traffic[k]	2.1×10^{9} J	66000	136	124
Road maintenance[l]	8.8×10^{1} $	1.5×10^{12}	133	121
Timbering, services[m]	8.5×10^{0} $	1.5×10^{12}	13	12
Forest Service mgmt.[n]	1.3×10^{1} $	1.5×10^{12}	20	18
Auto-fuel, visitors within[o]	2.1×10^{8} J	66000	14	12
Timbering, fuels[p]	1.6×10^{7} J	66000	1	1

[a] Precipitation@1330 m = 1961 mm/yr; data source: L. Swift, US Fores Service, Coweeta Lab; Gibb's free energy of rainfall (10 ppm vs. 35 ppt), J = (area)(rainfall)(Gibbs no.) = (10,000 m^2) × (1.960 m) × ($4.94 \times 10^6 \times$ J/m^3); energy (J) = 9.69×10^{10}; solar transformity (sej/J): Odum, 1996.

[b] Potential energy@mean elev. (J) = (area)(runoff)(mean elev-min elev)(density)(gravity) = (10,000 m^2) × (1.423 m/yr) × (1318–920 m) × (1000 kg/m^3) × (9.8 m/s^2) Energy (J) = 55.5×10^9; solar transformity (sej/J): Odum, 1996.

[c] Mean rate of transpiration = 538 mm/yr; data source: L. Swift, US Fores Service, Coweeta Lab; Gibb's free energy of rainfall as 10 ppm-salts in rain vs. 35,000 ppm-salt in leaves; Gibb's free energy of rainfall = (area)(transpiration)(Gibbs no.) = (10,000 m^2) × (0.538 m) × (4.94×10^6 J/m^3); energy (J) = 2.66×10^{10}; solar transformity (sej/J): Odum, 1996.

[d] Emergy of land cycle estimated from Earth deep heat flow; heat flow/area = 1.36×10^6 J/m^2/yr, @Bryson City; data souce: Smith et al., 1981; Pollack et al., 1991, 1993; energy (J) = 1.36×10^{10}; solar transformity (sej/J): Odum, 1996.

[e] Energy of vapor saturation deficit used, J/yr = 7.17×10^{11}; data source: Tilley, 1999; solar transformity (sej/J): Tilley, 1999.

[f] Wind energy, J/y = 1.88×10^{11}; data source: Tilley, 1999; equation: elaborate function, see Tilley (1999) for details.; solar transformity (sej/J): Odum, 1996.

[g] Solar radiance@ground = 5.02×10^{13} J/m^2/yr based on Coweeta basin; data source: Swift et al., 1988); solar transformity (sej/J): 1 by definition (Odum, 1996).

[h] Deposition rate, kg/ha/yr = 30 estimate based on Coweeta Hydrologic Lab; data source: Swank and Waide (1988); specific solar emergy (sej/g): Odum, 1996.

[i] At least 52 forest scientist, forest managers, university scientists and graduate students worked on the WSC Ecosystem Project from 1992–1997. Assume they devoted 10% of their total work per year to gathering, analyzing, publishing and sharing their research; Effort, people-hr/y = 10,400; = (10,400 people-hrs/yr) × (104 cal/h) × (4186 J/cal)/(1128 ha); energy (J) = 4.01×10^6; transformity(middle): post-college educated person (Odum, 1988); transformity (high): 494,000 people received advanced degrees (masters, doctoral, professional) in US in 2002 (US Census Bureau, 2003), which at 2500 kcal per d is 1.89×10^{15} J of metabolism per year. Total US expdenditures on all education (elementary thru college) was $572 billion in 1997 (latest year available) which at 1.5×10^{12} sej/$ (Tilley, 1999) was 858×10^{21} sej. ST = 858×10^{21} sej/1.89×10^{15} J = 455×10^6 sej/J; transformity(low): 8.2 million US citizens had advanced degrees (masters, doctoral, professional) in US in 1999 (latest year available, US Census Bureau, 2003), which at 2500 kcal per d is 3.13×10^{16} J of metabolism per year. Total US solar emergy in 2002 estimated to be 8850×10^{21} sej based on update of Odum's 1983 emergy evaluation of US economy using fuels and nuclear electricity from BP-Amoco database (BP, 2003). ST = 8850×10^{21} sej/3.13×10^{16} J = 288×10^6 sej/J.

[j] Number of groups/yr = 4361; mean group size = 2.7 people; mean length of stay = 19.0 h; data source: Cordell et al., 1996; energy (J) = (223,720 people-h/yr) × (104 cal/h) × (4186 J/cal); energy (J) = 8.63×10^7; solar transformity (sej/J): Odum, 1996; mean for US citizen.

[k] Gas within WSC = 3.70×10^2 bbl/yr; data source: Tilley, 1999; energy (J) = (370 bbl/yr) × (6.28×10^9 J/bbl); energy (J) = 2.06×10^9; solar transformity (sej/J): Odum, 1996.

[l] Length of unpaved roads = 24 km; Length of paved roads = 9 km; data source: Tilley, 1999; cost to maintain roads: 5000 $/mile/yr; data source: pers. comm., B. Culpepper, USFS Wayah Ranger District; Cost of rd, $/ha/yr = (33 km of rds) × ($5000/mile/yr) × (1 mile/1.609 km)/(1128 ha); cost of rd, $/yr = 88; Emergy-to-$ ratio: Tilley, 1999; mean for state of North Carolina, USA.

[m] Revenue from timber sales from 1973 to 1999 (26 yr) was $250,000; Revenue, $/ha/yr = 8.5; data source: pers. comm., B. Culpepper, USFS Wayah Ranger District.

[n] Expenditures, $/ha/yr = 13; data source: pers. comm., B. Culpepper, USFS Wayah Ranger District.

[o] Gasoline within WSC = 37 bbl/yr; data source: Tilley, 1999; energy(J) = (37 bbl/yr) × (6.28×10^9 J/bbl); energy (J/ha) = 2.06×10^8.

[p] US National average fuel use: 23×10^{15} J/yr to harvest 648×10^6 m^3 of wood; Fuel use in WSC timbering, J/ha/yr = 1.56×10^7; data source: Tilley, 1999.

Table 3
Emergy evaluation of internal processes and exported products of the Wine Spring Creek watershed (annual flows per ha, 1995)

Item	Physical unit	Solar transformity (sej/unit) per hectare	Solar emergy ($\times 10^{12}$ sej) per hectare	Emdollar value (1992 Em$)
Internal processes (transformities calculated)				
Rock weathering[a]	6.0×10^5 g	3.8×10^9	2261	2055
Wood growth[b]	6.2×10^{10} J	1.6×10^4	982[c]	892
Litterfall[d]	6.4×10^{10} J	1.5×10^4	982[c]	892
NPP, total live biomass[e]	2.1×10^{11} J	4.7×10^3	982[c]	892
Maintain tree diversity[f]	30 species	7.5×10^{13}	2250	2048
Develop and maintain Ca cycle[g]	82,000 g	3.8×10^{10}	3083	2803
Exports (transformities calculated)				
Research information[h]	1.2×10^3 J	3.1×10^{12}	3790	3445
Stream discharge[i]	7.0×10^{10} J	3.2×10^4	2261	2055
Recreated people[j]	8.6×10^7 J	2.4×10^7	2065	1877
Timber[k]	4.1×10^9 J	5.3×10^4	220	200
Ca in stream export[l]	7.0×10^3 g	3.8×10^{10}	263	239

[a] Erosion rate, g/m^2/yr = 60; data source: Velbel, 1985, 1988.; Sediment lost, g/ha/yr 6.00×10^5; Specific solar emergy (sej/g): (empower of rain + deep heat + atmos. dep.)/(weathering rate).

[b] Wood growth = 4.20×10^3 kg/ha/yr; data source: Monk and Day, 1985, 1988. Energy (J) = (accum., kg/ha/yr) × (area, ha)(1000 g/kg)(3.5 kcal/g-dry wt)(4186 J/kcal); energy (J) = 6.15×10^{10}; transformity = (emergy of evapotranspiration + deep heat + atmos. dep.)/(wood accumulation).

[c] The annual solar emergy driving each is the sum of transpiration, land cycle and atmospheric deposition.

[d] Litterfall = 4400 kg ha Monk and Day, 1985; data source: Monk and Day, 1985, 1988; energy (J) = (Litterfall, kg/ha/yr) × (area, ha)(1000 g/kg)(3.5 k-cal/g-dry wt)(4186 J/kcal); energy (J) = 64.5×10^9; transformity = (empower of evapotranspiration + deep heat + atmos. dep.)/(litterfall).

[e] NPP, Roots + wood + leaves = 14390 kg/ha/yr; data source: Monk and Day, 1985, 1988. Energy (J) = (NPP, kg/ha/yr) × (area, ha)(1000 g/kg)(3.5 k-cal/g-dry wt)(4186 J/kcal); energy (J) = 2.11×10^{11}; transformity = (empower of evapotranspiration + deep heat + atmos. dep.)/(net production).

[f] From the species-area curve, there were 30 species found within the first ha sampled; data source: Tilley, 1999.

[g] Empower of Ca cycle comes from emergy accumulated during simple turnover time (66 yr) and from new annual input from rain and rock weathering.; Specific emergy (sej/g) for biologically stored Ca = (66 yr, mean turnover time)/2 × (1763×10^{12} sej-rain + 468×10^{12} sej-land)/1.45×10^6 g-Ca stored = 51×10^9 sej/g-Ca, stored. Of the 8.2×10^4 g-Ca cycled annually, 5.9×10^4 g-Ca from stored sources; 2.3×10^4 from new forest inputs (deposition, 0.5×10^4 g; weathering, 1.8×10^4 g). Thus, empower from stored Ca = 51×10^9 sej/g-Ca × 5.9×10^4 g-Ca = 3010×10^{12} sej/yr; Empower from new annual input = (0.5×10^4 g-Ca × 1.0×10^9 sej/g-mineral deposited) + (1.8×10^4 g-Ca × 3.8×10^9 sej-mineral weathered) = 73.4×10^{12} sej/yr. Grand total is $3010 \times 10^{12} + 73.4 \times 10^{12} = 3084 \times 10^{12}$ sej/y; Specific emergy (sej/g) for Ca cycled = 3084×10^{12} sej/yr/8.2×10^4 g-Ca = 37.6×10^9 sej/g-Ca.

[h] Research Information; From 1992 to 1998, 47 publications and 10 reports were produced (Swank and Tilley, 2000); Publication rate over the 6 years was 57/6 = 9.5 pubs/yr. Publications average 10 pages in length; grams of research articles published, g/yr = 9.5 articles/yr × 10 pages × 1 g/page = 95 g/yr; energy of articles, J/yr = 95 g/yr × 3.5 kcal/g × 4186 J/kcal = 1.39×10^6 J/y; energy of articles, J/ha/yr = 1232; transformity = [sum of empower inputs (rain, deepheat, atmospheric deposition, road maintenance, FS management, and research effort)]/[energy of publications, annual rate].

[i] Stream discharge; runoff = 1.42 m/yr, mean 1995–96.; Source: Coweeta Hydro. Lab; energy (J) = (10,000 m^2) × (1.42 m/yr) × (4.94×10^6 J/m^3); energy (J) = 7.03×10^{12}; transformity: [empower of rain + deep heat]/energy.

[j] Same energy as visitor's length of stay in Table 2 item j; transformity = [sum of env. and econ. empower inputs/[metabolism of visitors during length of stay]; 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 management.

[k] Since 1973 (26 yr), timber harvest from WSC watershed was 8623 m^3 sawtimber and 4259 m^3 of roundwood, valued at $251,000; timber harvest rate, m^3/ha/yr = 0.44; data source: pers. comm., B. Culpepper, USFS Wayah Ranger District; Energy (J) = (0.44 m^3/ha/yr) × (5×10^5 g/m^3) × (4.5 kcal/g) × (4186 J/cal); energy (J) = 4.14×10^9; transformity of timber = (emergy of wood + road maintenance + FS management + timbering fuels + timbering services)/energy of timber.

[l] Calcium discharge; annual stream discharge of $Ca^+ = 7.0 \times 10^3$ g; data source: Swank and Waide, 1988; Assume specific emergy (sej/g) of exported Ca same as cycled Ca. Emergy of Ca-export = 7.0×10^3 g-Ca/yr × 37.6×10^9 sej/g = 263×10^{12} sej/yr.

Table 2 also lists the imported economic resource inputs (e.g. fuel, USFS management, road construction material) that were matched to the local environmental energies to build and maintain the forest's transportation infrastructure (i.e. trails, paved and gravel roads, scenic overlooks) and made it possible for the forest's commodities to be extracted and amenities to be explored by scientists, local travelers, tourists, hunters and trout fishermen.

The watershed received about 12,000 visitors annually as part of the regional southern Appalachian tourist attraction (Cordell et al., 1996). People used various energies, notably automotive fuel and their own metabolism, to enjoy the recreational opportunities. In 1 year, visitors consumed 14×10^{12} sej ha^{-1}-watershed (12 Em\$ ha^{-1}) of automobile fuel traveling around inside the WSC watershed. An additional 136×10^{12} sej ha^{-1} yr^{-1} (121 Em\$ ha^{-1}) of auto-fuels were expended by local through-traffic. Cordell et al. (1996) determined that the average length of stay for visitors was 19 h. This represented about 200 people-h ha^{-1}, the equivalent of 768×10^{12} sej ha^{-1} yr^{-1} (686 Em\$ ha^{-1}) assuming that the solar transformity of a recreating individual's metabolism was equal to that of a typical US citizen on an average day.

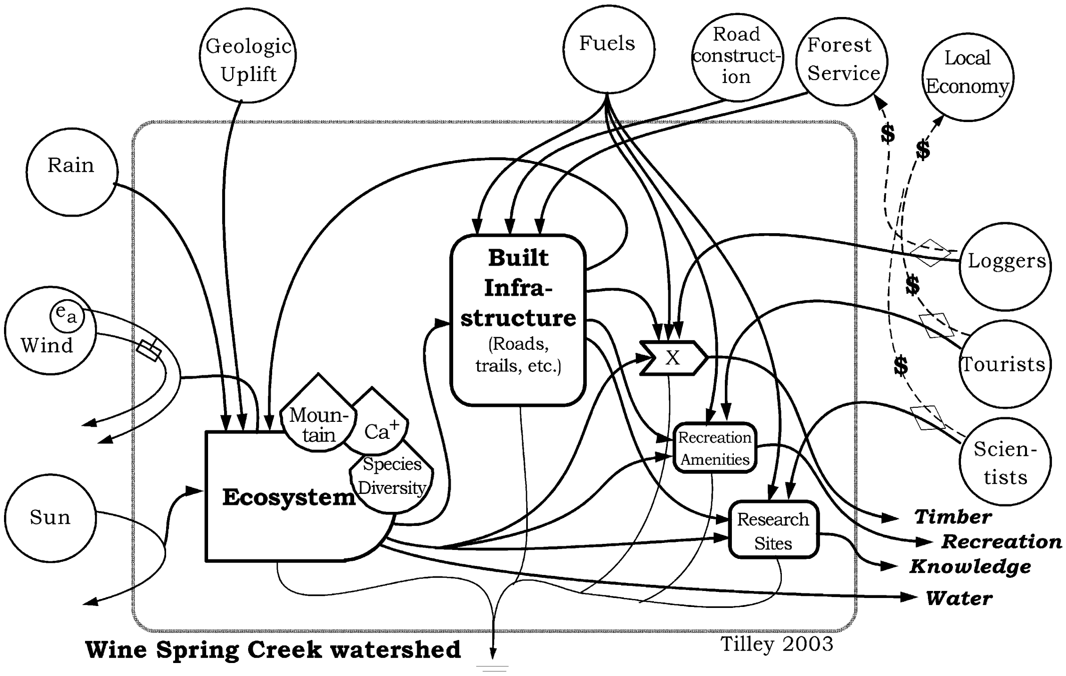

Fig. 2. Systems diagram of the ecological–economic interface of Wine Spring Creek watershed.

The USFS, over the last 25 yr was paid an average of $\$9\ ha^{-1}\ yr^{-1}$ (13×10^{12} sej $ha^{-1}\ yr^{-1}$) by logging companies to harvest timber (B. Culpepper pers. comm., Table 2). The engine fuels used to harvest timber represented only 1×10^{12} sej $ha^{-1}\ yr^{-1}$ (0.89 Em\$ $ha^{-1}\ yr^{-1}$). Together these were an order of magnitude less than the USFS expended (133×10^{12} sej $ha^{-1}\ yr^{-1}$, 119 Em\$ $ha^{-1}\ yr^{-1}$) to maintain 32 km of roads-9 km of paved road and 23 km of unpaved service roads.

The largest imported source of solar emergy was the personnel participating in the WSC Ecosystem Demonstration Project (1377×10^{12} sej $ha^{-1}\ yr^{-1}$, 1229 Em\$ $ha^{-1}\ yr^{-1}$), which was due to the large number of scientists and managers (52) and their relatively high solar transformity. The high solar transformity of scientists and managers, in this case, derives from the vast amount of high transformity energy required to create and maintain the institution of academia which produces a relatively small number of professionals with advanced degrees. We used Odum (1988) estimate of the solar transformity of work conducted by scientists (340×10^{6} sej J^{-1}), which he calculated by taking the entire United States' solar emergy flow of 1987 and dividing by the combined annual metabolism (exergy) of the population holding advanced degrees (i.e. masters, doctoral, professional) in that year.

Due to the work of the scientists representing the largest input of solar emergy to the Wine Spring Creek (WSC) project, we performed a sensitivity analysis of their contribution by calculating new estimates for the solar transformity of the work performed by people holding advanced degrees. One estimate was calculated using Odum (1988) method, but with newer data. In 1999, the number of people holding advanced degrees was 8.2 million (US Census Bureau, 2003). Our estimate of solar emergy use in US in 2002 was 8850×10^{21} sej. Thus, the newer data gave an estimate of the solar transformity for scientist as 283×10^{6} sej J^{-1}, which was 83% of Odum's 1987 calculation. While this estimate was based on the solar emergy required to maintain a population of scientists at the top of the nation's education hierarchy, our other estimate evaluated the annual solar emergy directly used (i.e. \$ expenditures) to produce a specific number of advanced degree graduates in a single year. Using 2002 data, we determined that the \$572 billion spent by all funding sources (i.e. public and private) on US education (i.e. elementary through college) to produce 494,000 advanced degrees (US Census Bureau, 2003) gave a mean solar transformity of 455×10^{6} sej J^{-1} (133% of Odum's 1987 estimate). The former approach (Odum's) assumes a steady-state system with highly educated people located near the top of the nation's hierarchy and captures the mean solar transformity of all (new and old) US advanced degree holders. The latter approach is a recent 'snap-shot' of a dynamic system and partitions the national solar emergy budget according to the flow of money, thus representing the mean solar transformity of new advanced degree recipients. Since the two new estimates were above and below Odum's 1987 estimate, we used his original solar transformity for our particular case of valuing the work of scientists on WSC project. Arguably, our lower estimate was more appropriate, but given the uncertainty in our estimate of the US emergy budget of 2002, we place more confidence in Odum's 1987 value. The higher estimate corresponds to a group of recent graduates, rather than seasoned scientists.

The total indigenous environmental resource inputs to the WSC watershed (2260×10^{12} sej ha^{-1} yr^{-1}; 2060 Em$ ha^{-1} yr^{-1}) was found by summing the three resource inputs which were derived from independent sources of solar emergy (chemical potential of precipitation, land cycle, and atmospheric deposition). Precipitation was included because it was the largest source of solar emergy. Adding the solar emergy of the land cycle was justified because its solar emergy came from a storage with a much greater turnover time than 1 year. Atmospheric deposition was added because its solar emergy was simply moved from another location; thus spatially, it was independent of the solar emergy that went into providing the other local energies.

3.2. Internal processes

Table 3 lists the solar emergy values of the internal processes and exported products of the WSC watershed. Unlike the emergy input analysis in Table 2, where the solar emergy of forcing functions was the product of solar transformity and available energy, the solar emergy of an internal process or export was determined by allocating incoming solar emergy to it. For example solar empower of wood growth (982×10^{12} sej ha^{-1} yr^{-1}) was the sum of transpiration (484×10^{12} sej ha^{-1} yr^{-1}), land cycle (468×10^{12} sej ha^{-1} yr^{-1}), and atmospheric deposition (30×10^{12} sej ha^{-1} yr^{-1}), which are itemized in Table 2. Therefore, the solar transformity of wood growth was 1.6×10^4 sej J^{-1} (Table 3, 982×10^{12} sej ha^{-1} yr^{-1} divided by 6.2×10^{10} J ha^{-1} yr^{-1}).

3.2.1. Biogeochemical cycling

Weathering of the parent bedrock to create regolith, which supplies the majority of the mineral nutrition for tree growth and soil formation, requires the solar emergy contributed by precipitation (1763×10^{12} sej ha^{-1} yr^{-1}) and the land cycle (468×10^{12} sej ha^{-1} yr^{-1}, Table 2). Since inorganic material is better characterized by its mass, rather than its energy, the specific solar emergy (sej g^{-1}) was calculated. At WSC, there were 3.8×10^9 sej required per gram of rock weathered (Tilley, 1999), which is 3.8 times the global average of 1.0×10^9 sej g^{-1} (Odum, 1996). When the same methodology was applied to seven sub-basins of the Coweeta watershed, the total emergy flux (precipitation + land cycle) per mass of rock weathered ranged from 3.8×10^9 to 8.7×10^9 sej g^{-1} (Tilley, 1999).

Fig. 3a shows an overview systems diagram highlighting the energy basis of the simplified calcium cycle. Atmospheric deposition of calcium enters the soil solution, is used by vegetation, falls to the ground as litter, and is mineralized by soil processes. Acidic runoff waters percolate through the soil, down to the regolith, weathering the bedrock. Calcium ions from the weathered bedrock and organic matter are placed in soil solution to complete the cycle. Growth of forest biomass accelerates recycling processes due to the addition of carbonic acid from soil respiration. Thus, the calcium cycle evolves over time, maturing with the forest.

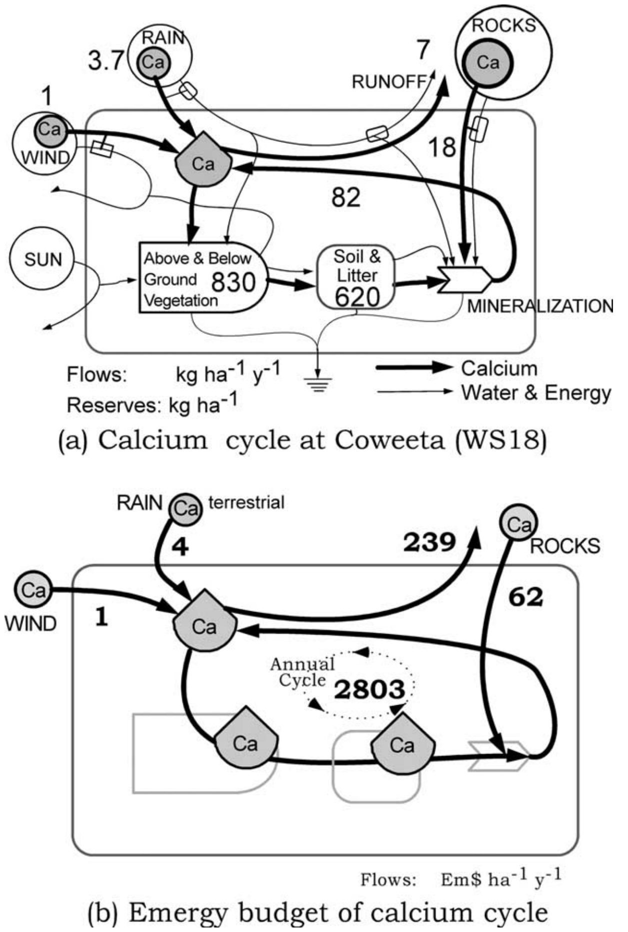

Fig. 3. Systems diagram of calcium cycle at the Coweeta forest (a) and its emergy budget (b).

Three sources of calcium—atmospheric dry deposition, precipitation, and bedrock-were estimated to provide 1.0, 3.7, and 18 kg-Ca ha^{-1} yr^{-1}, respectively, to the WSC, based on data collected from watershed #18 of the Coweeta Hydrologic Laboratory (Fig. 3a). The rate of internal cycle, measured as plant uptake, was 82 kg-Ca ha^{-1} yr^{-1} (Monk and Day, 1988), ~3.5 times the annual input. The watershed exported 7 kg-Ca ha^{-1} yr^{-1}. The internal reservoir of calcium was 1450 kg-Ca ha^{-1}, (830 kg-Ca ha^{-1} in live above and below ground vegetation; 620 kg-Ca ha^{-1} in soil and litter, Monk and Day, 1988).

The emergy budget of the WSC calcium cycle is shown in Fig. 3b. Calcium, which entered the forest via dryfall and wetfall, contributed 1×10^{12} (0.91 Em$ ha^{-1} yr^{-1}) and 4×10^{12} sej ha^{-1} yr^{-1} (3.64 Em$ ha^{-1} yr^{-1}), respectively, to the forest assuming a specific emergy (i.e. emergy-to-mass ratio) of 1×10^9 sej g^{-1}-Ca, which is the global average for the land cycle (Odum, 1996). The weathered bedrock contributed 68×10^{12} sej ha^{-1} yr^{-1}, (62 Em$ ha^{-1} yr^{-1}) which was found as the product of the 18 kg-Ca ha^{-1} yr^{-1}

weathered and the specific emergy of weathered rock determined for the Coweeta basin (3.8×10^9 sej g^{-1}, Tilley, 1999).

The internally cycled Ca was determined to have an emergy value of 3083×10^{12} sej ha^{-1} yr^{-1} (2803 Em\$ ha^{-1} yr^{-1}) according to the following rationale. After 80 yr of post-harvest succession, the forest had stored 1.45×10^6 g-Ca ha^{-1}, equivalent to 66 yr of annual Ca input (2.3×10^4 g-Ca ha^{-1} yr^{-1}). Based on this annual addition, 5.9×10^4 g-Ca ha^{-1} yr^{-1} of the 8.2×10^4 g-Ca ha^{-1} yr^{-1} cycled internally must be derived from previously accumulated stores of Ca. Each independent source of Ca has an associated amount of solar emergy that is contributed to the cycle. Previously stored Ca, which accumulated solar emergy over the forest's development period, contributes emergy to the Ca cycle as the product of the specific emergy of stored Ca and the mass of cycled Ca derived from forest reserves. The specific emergy of the stored Ca was the sum of annual emergy flow (1115×10^{12} sej ha^{-1} yr^{-1} = 2231×10^{12} sej ha^{-1} yr^{-1} divided by 2 as an estimate of the mean rate over the 66 yr accumulation period) accumulated over the mean turnover time of the forest Ca (66 yr) divided by the Ca stored (1.45×10^6 g ha^{-1}), which equaled 51×10^9 sej g^{-1}. The emergy value of the portion of Ca derived from internal reserves was 3010×10^{12} sej ha^{-1} yr^{-1} (51×10^9 sej g^{-1}-Ca $\times$ 5.9×10^4 g-Ca ha^{-1} yr^{-1}, Table 3). New Ca that entered the forest Ca cycle on an annual basis contributed emergy at a rate equal to the specific emergy of the source Ca (i.e. atmosphere or bedrock) multiplied by the mass of the source. New sources contributed 2.4% (73.4×10^{12} sej ha^{-1} yr^{-1}) of the emergy to the total emergy of the Ca cycle (3083×10^{12} sej ha^{-1} yr^{-1}, Table 3).

3.2.2. Maintenance of tree diversity

Fig. 4 shows the tree species-area curve for the high-elevation forests of the WSC watershed. The graph is a typically shaped curve of species found per area sampled (Whitmore and Sidiyasa, 1986; Kartawinata et al., 1981; Paijmans, 1970). The number of tree species found increased as area searched increased, but at a decreasing rate. Thirty-two (32) tree species were found in the 3.5 ha searched; 29 were found in the first hectare (Fig. 4a).

The species–emergy curve (Fig. 4b) provides an estimate of the emergy that nature requires to maintain a certain level of tree diversity in the watershed. Maintenance of the 30 tree species required a minimum of 2250×10^{12} sej yr^{-1} (Fig. 4b), which translates to an average of 68 Em\$ yr^{-1} for each tree species. By comparison, the University of Florida Arboretum, which maintained 135 southeastern US tree species (3 plants each) required 161 Em\$ yr^{-1} per tree species (Tilley, 1999). In the maturing, fairly undisturbed WSC forest, nature maintained a few species for less solar emergy input, whereas in the heavily managed arboretum more than twice as much solar emergy was required per species. Additionally, the shape of

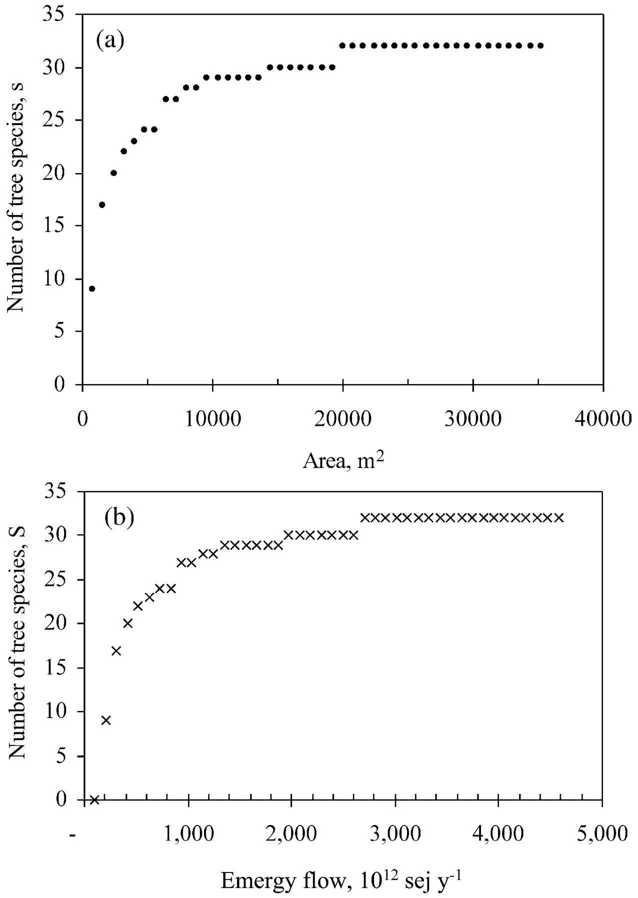

Fig. 4. Species–area curve (a) and species–emergy curve for trees at elevations above 1200 m in the Wine Spring Creek watershed. (Species data provided by K. Elliot, USDA Forest Service Coweeta Hydrologic Lab, Otto, North Carolina).

the species–emergy curve indicates how much additional solar emergy flow would be required to successfully support another tree species.

3.3. Emergy of forest exports

Evaluated exports included not only commodities (e.g. water, wood, macronutrients) that were transformed within and subsequently exported from the WSC forest, but also included amenities, such as the pleasure found strolling along a forested mountain trail. Although many forest functions meet this definition of an export, this study concentrated on four categories of export: ecological (stream discharge), economic (timber), scientific (research information), and social (recreation) services. Of these four, the research information produced by the team of scientists, staff, and graduate students, represented 3790×10^{12} sej ha^{-1} yr^{-1} (Table 3) over the length of the study. The WSC research team, during the period 1992–1998, generated 47 scientific papers and 10 reports with a mean emergy value of 409,800 Em\$ per paper (Table 4). The emergy required to create these publications came from the environmental emergy (precipitation chemical potential,

Table 4
Public value of annual forest production processes based on emergy synthesis

Production process	Product value
Research on the WSC Ecosystem Management Demonstration Project that resulted in 60 published manuscripts[a]	EM$ 409,800 per manuscript
Develop and maintain Ca cycle (a limiting nutrient)[b]	EM$ 34,200 per MT
Weathering of parent rock material into saprolitic clay[c]	EM$ 3425 per MT
Extraction of timber[d]	EM$ 909 per MT
New wood growth added to forest[e]	EM$ 212 per MT
Forest annual litterfall[f]	EM$ 203 per MT
Recreation by tourist[g]	EM$ 180 per person
Maintain tree diversity[h]	EM$ 68 per species
Net Primary Production (NPP) of total live biomass[i]	EM$ 62 per MT
Stream discharge from watershed[j]	EM$ 0.14 per MT

[a] 3445 Em$ per ha per year × 1130 ha/9.5 manuscripts per year.
[b] 2803 Em$ per ha per year/0.082 MT-Ca per ha per year.
[c] 2055 Em$ per ha per year/0.600 MT-mineral per ha per year.
[d] 200 Em$ per ha per year/0.88 MT-wood per ha per year.
[e] 892 Em$ per ha per year/4.20 MT-wood per ha per year.
[f] 892 Em$ per ha per year/4.40 MT-organic matter per ha per year.
[g] 1877 Em$ per ha per year × 1130 ha/11,700 visitors per year.
[h] 2048 Em$ per 30 species (midpoint emergy flow to support 30 tree species in Fig. 4b
[i] 892 Em$ per ha per year/14.40 MT-NPP per ha per year.
[j] 2055 Em$ per ha per year/14200 MT-water per ha per year.

land cycle, atmospheric deposition) and the imported human emergy (road construction, USFS management, and respiration of the team members).

Second in rank of exports was stream discharge (Table 3). The 1.42 m yr^{-1} of runoff had a solar emergy value of 2250×10^{12} sej ha^{-1} yr^{-1} (2055 Em$ ha^{-1} yr^{-1}), which was found by summing the emergy of precipitation and land cycle. None of the economic emergy was added to stream discharge because its flow and quality was not significantly affected by human activities. Stream discharge, as an integrated measure of the watershed's total environmental production, represents the natural value of the entire forest. The naturally endowed value of the water was 0.14 Em$ per MT (Table 4).

In terms of emergy value, people recreating in the watershed ranked as the third highest export (Table 3). The 12,000 people who visited the WSC watershed annually enjoyed 2065×10^{12} sej ha^{-1} yr^{-1} (1877 Em$ ha^{-1} yr^{-1}), which was a combination of environmental and economic inputs. Environmental inputs were taken as half of the annual empower of precipitation, land cycle, and atmospheric deposition, since the watershed was only open to the public from April to November. Economic inputs were the sum of fuel, human respiration of tourists during their visit, road maintenance, and USFS management. The value received per tourist was 176 Em$ (Table 4).

In the 26 yr period leading up to 1998, 12,880 m^3 of sawtimber and roundwood were harvested in the WSC watershed for payments to the USFS totaling $251,000 ($39 per MT, nominal dollars). The emergy dollar value of the timber, on the other hand, by accounting for USFS management (20×10^{12} sej ha^{-1} yr^{-1}), road maintenance (133×10^{12} sej ha^{-1} yr^{-1}), fuel-use and other timbering services (14×10^{12} sej ha^{-1} yr^{-1}), was 909 Em$ per MT (Table 4). Thus, the USFS was paid $0.043 per 1 Em$ of timber value. This difference indicates how much greater the natural wealth was than the payment. It also indicates how much net emergy the timber retains after harvest which can then be realized in the wood products industry.

Calcium, due to its role as a potential limiting factor in long-term forest productivity, was chosen for evaluation to represent the solar emergy associated with biogeochemical export. The Ca exported from the forest had a solar emergy value of 263×10^{12} sej ha^{-1} yr^{-1} (239 Em$ ha^{-1} yr^{-1}, Table 3), which was determined as the specific emergy of the internally cycled Ca (38×10^9 sej g^{-1}) times the mass of Ca exported (7 kg-Ca ha^{-1} yr^{-1}). Using the same specific emergy assumes that the exported Ca is similar in quality to the cycled Ca from which it was derived.

3.4. Equity in services

As previously argued, one goal of ecosystem management could be to achieve equity across the ecological, social, and economic service categories of the forest. Theoretically, if the total benefit derived from the forest is a linear function of the product of these three categories, then maximum benefit is achieved when the three are equal in terms of solar emergy. Additionally, generation of one category of benefits, hinders the production of the others. For example, unsustainable logging accelerates soil loss reducing a benefit categorized as ecological and decreases aesthetic appeal reducing a social benefit. In this study, the services found to have the greatest solar emergy in each category were chosen to represent that category. Biogeochemical cycling of Ca was used as a measure of ecological value, recreated people were chosen as a measure of social value, and timber production was taken as the best indicator of economic value. Based on the emergy value of these three services, the current management of the WSC watershed was not perfectly equitable across all categories because economic value (200 Em$ ha^{-1} yr^{-1}, Table 3) was only 7% of the ecological (2803 Em$ ha^{-1} yr^{-1}) and 11% of social (1877 ha^{-1} yr^{-1}) value. To achieve perfect equity to maximize total forest benefit (i.e. all services contributing equal solar emergy), production of economic value needs to be increased by a factor of 14 and social value by a factor of 1.5. This seemingly large increase in economic production (14 times) starts from a small base (i.e. timber production is highly restricted in the WSC watershed), and thus, does not represent an overwhelmingly large absolute increase in timbering. These proposed increases in timbering and social activities would result in all three services having a solar emergy value of 3083×10^{12} sej ha^{-1} yr^{-1} (2803 Em$ ha^{-1} yr^{-1}).

3.5. Balanced investment in forest capital for sustainability

As pointed out with Fig. 1, sustainability of forest capital can be framed as a balance between low and high intensity use of land. Too little investment increases the risk that the forest will not be able to contribute to its larger system (e.g. economy and society) at its full potential, creating a sub-optimum situation. Too much investment, however, increases the risk that the ecological capital will be depleted faster than it is naturally generated, which will create a sub-optimum situation in the future.

ELR (Brown and Ulgiati, 1999), which is the total human-controlled emergy invested in the watershed divided by the annual free environmental emergy input, provides a quantitative means of assessing forest balance. Since an ELR of 1.0 indicates that human use of an ecosystem is well-balanced (Brown and Ulgiati, 1997), the WSC's ELR of 0.42 (863 Em$ ha^{-1} yr^{-1} per 2055 Em$ ha^{-1} yr^{-1}) indicated that there was excess natural capacity to absorb more external investment without hindering the forest's ability to function properly. The solar emergy of the scientists, which was the single largest external source of solar emergy (3445 Em$ ha^{-1} yr^{-1}), was not included in the ELR since it was considered rare and atypical of land management on USFS land. Excluding it gives an indication of how intensely the average forest unit is managed. However, if it were included in the ELR, the ELR would equal 1.03, indicating that nearly perfect balance had been found between ecological capacity and external investment. On the other hand, an ELR of 0.42, which excluded scientific investment, indicates that externally-induced, human-controlled activity needs to be increased by a factor of 2.4 to achieve a perfectly balanced system with an ELR of at least 1.0.

The new emergy based index that we called ECL was calculated for the WSC forest's biogeochemical cycle of Ca. The ECL was 0.31 (863 Em$ ha^{-1} yr^{-1} per 2803 Em$ ha^{-1} yr^{-1}).

Emergy Return on Ecosystem Management (EREM) for the WSC EM Demonstration Project was 39.2, indicating that the ecosystem services provided by the forest were worth a great deal more than the money spent on its management.

4. Discussion

4.1. Allocating solar emergy to biogeochemical cycles

The rationale for allocating solar emergy to the Ca cycle follows a methodology modified from the guidelines proposed by Odum (2000b) for allocating emergy to biogeochemical cycles. Briefly, Odum (2000b) proposed that if an element (e.g. Ca, P, K) or chemical compound (e.g. NO_3^-, PO_4^-) were highly essential (i.e. a limiting factor) to a particular ecosystem's productivity and overall functioning, then the emergy of any particular chemical cycle should be allocated the entire incoming solar emergy. However, if an element or compound was non-essential to productivity (e.g. Pb, As, Au), but was taken up by vegetation and cycled to some extent, then the driving emergy should be allocated according to the mass-fraction the element represented of all biogeochemical cycles. The former case is similar to allocating input emergy to co-products, whereas the latter resembles splitting emergy (Brown and Herendeen, 1996). The modification used here accounted for the emergy accumulated over the development period of the forest's Ca cycle to derive the specific emergy of the internal reserve of Ca. This appeared to be an important modification since over 97% of the internally cycled Ca came from Ca previously accumulated. To avoid the issue of double counting solar emergy when evaluating multiple biogeochemical cycles, it is recommended that the biogeochemical cycle determined to carry the greatest amount of solar emergy be used as the indicator of the value of the ecosystem's biogeochemical cycle.

4.2. Value of total benefits

Benefits provided by the WSC forested watershed were based on the rate of use of solar emergy from environmental and economic sources. Annually, the WSC watershed processed solar emergy at the rate of 4300 Em$/ha of watershed, indicating that its 1130 ha contributed wealth to the economy and benefits to society at an annual rate of 4.9 million Em$. Of the total solar emergy flow, just under half (49%) was directly attributable to the natural environment, whereas the other 51% came from human-directed, externally introduced sources of solar emergy.

4.3. Equity in services

The emergy synthesis of the WSC EM Demonstration Project revealed that equity in services, as represented by ecological, economic and social categories, was not achieved due to a low generation of economic value. Better equity could be achieved by increasing the timber harvest by a factor of 14 employing such sustainable harvesting practices as two-stage shelterwood or uneven-aged improvement cut, not clear-cutting. The increase would raise the economic contribution to equal that of the ecological services (2803 Em$ ha^{-1} yr^{-1}). However, if the analytical boundary were broadened to include the subsequent economic activity that would be promoted by the timber (the representative economic product), the WSC watershed's contribution to the regional economy via timber would appear greater. Once timber is harvested, it serves as the base material for the forest products industry, where the solar emergy of fuels, electricity, labor, etc. add value to the wood as a commercial product. For example, timber that is processed into plywood attracts an additional 200 Em$ ha^{-1} yr^{-1} based on multipliers developed from the emergy evaluation of the US forest products industry (Tilley, 1999), doubling timber's solar emergy value to 400 Em$ ha^{-1} yr^{-1}. At an aggregated scale, using North Carolina's average solar emergy investment ratio of 3.8–1 (i.e. human-controlled solar emergy invested per the sum solar emergy of natural renewable and locally non-renewable resources) as a multiplier to measure eventual economic value, timber harvested from WSC could attract an additional 760 Em$ ha^{-1} yr^{-1} on top of the timber's environmental value of 200 Em$ ha^{-1} yr^{-1} for a total value of 960 Em$ ha^{-1} yr^{-1}. This places timber's economic benefit closer to the value of the ecological services. Thus, if this more encompassing analytical boundary for timber were used and perfect equity was the goal, timber harvest needs to be increased by 2.9 (2803 Em$ of ecological service/960 Em$ of timber value).

Recreation, as an indicator of social value, should be raised by 1.5 so it equals ecological services. This could be achieved by increasing the ability of people to utilize the many amenities of the forest. However, since the forest is an intricately connected, dynamic system, any change to one or more forcing factors (e.g. logging, recreating) has the potential to alter the state and function of several forest components (e.g. biogeochemical cycling, quality and quantity of stream discharge). Although these dynamics are not reported here, Tilley (1999) developed an emergy-based simulation model (MULTIBEN) to evaluate these type of trade-offs, reporting that maximum sustainable emergy flow to and from the ecosystem could be achieved if, simultaneously, recreation were increased by a factor 2.5 (e.g. 37,500 annual tourist visits, 3150 Em$ ha^{-1} yr^{-1}) and logging by a factor of 15 (3.3 MT-wood ha^{-1} yr^{-1}, 3000 Em$ ha^{-1} yr^{-1}). Additionally, these increases in recreation and logging decreased the flow of renewable solar emergy by less than 0.5% to 2815 Em$ ha^{-1} yr^{-1}.

An apparent limitation to the assessment of equity in services of the forest was the use of only three outcomes as representative of the whole watershed. However, the three chosen forest outcomes were selected based on the fact that each had the highest solar emergy value in its class (i.e. ecological, economic, and social).

4.4. Balanced investment

According to energy hierarchy theory, which serves as the basis for emergy synthesis, different forms of energy possess unique qualities that allow them to interact with system components with varying levels of effectiveness. One measure of an energy form's quality is its solar transformity (Odum, 1988), whereas solar emergy is a measure of the total equivalent amount of solar radiation required to create and deliver a certain form of energy. The basis for using the ELR as an indicator of land use intensity is derived from the equivalency that can be measured for the various forcing factors driving forest processes. A wilderness area, impacted lightly by anthropogenically controlled resources, relies solely on the natural energies and thus, would have an ELR near zero. A modern-day US city, on the other hand, has very little natural productivity relative to the imported emergy resources; it may have an ELR greater than 100 (Tilley, 1999). Therefore, the ELR is an index for measuring land use intensity.

The WSC watershed, excluding the solar emergy of the scientists, had an ELR of 0.42. By comparison, a New Zealand pine plantation (Odum and Odum, 1983), a Texas, USA cotton field (Odum and Odum, 1987), and North Carolina, USA tobacco crop (Tilley, 1999) had ELR's of 1.4, 9.6, and 20.0, respectively. Thus, management of the WSC was approximately one-third (1/3rd) as intense as plantation pine, 1/23rd as intense as cotton and 1/48th as tobacco. Therefore, the relatively low ELR of the WSC indicates that it was much more ecologically sustainable than other agricultural land uses and likely possessed a reserve capacity for attracting more external investment that would not decrease its capacity to deliver ecological services.

4.5. Emergy-based ecological decision-making

Forest managers are increasingly forced to make difficult decisions about how forest resources (i.e. timber, recreational opportunities, wildlife, etc.) are allocated to satisfy the various interests of forest stakeholders. We have demonstrated how two emergy-based indices, the ELR and ECL, can be used to quantify the ecological capacity of the forest to withstand human use, thus quantifying a total limit for the various types of human activities that can take place in the forest and maintain a sustainable and balanced system. If forest managers take an ecosystem management approach, generally defined to balance ecological, social and economic benefits, then emergy synthesis affords them the ability to quantitatively assess how well they are meeting all three categories of benefit.

5. Conclusions

To fully appreciate the social and economic benefits of forest lands, the new philosophy of ecosystem management must take a systems viewpoint which considers the importance of the multiple forcing factors over varying scales of space and time, and relates these forcing factors to the forests' services and products. Doing so will provide a better understanding of the basis of forest wealth and the consequences of management decisions.

The goals of ecosystem management to achieve balance between the ecology and economy of its integrated system and to foster equity among the diverse outcomes of the forest were assessed with emergy synthesis. The ELR, an emergy-based index which was calculated to measure balance, was found to equal 1.03, when the investigative efforts of scientist's were included, indicating that there was a great amount of balance between the natural productivity of the watershed and the level of human-controlled resource investment in the watershed. Excluding the solar emergy of scientists reduced the ELR to 0.42, indicating that land under similar management absent the scientific research, would have excess natural capacity for further economic investment. Outcome equity, which was assessed by evaluating the solar emergy flow of three services (biogeochemical cycling, timber and recreation) representing three categories of sustainability (i.e. ecological, economic and social), was not achieved for the WSC watershed. Economic and social values contributed by the watershed's ecosystem need to be increased to be equitable with the ecological value generated.

Emergy synthesis, by comparing the multiple functions of forest systems, can lend valuable insight into the consequences of meeting the public's increasingly diverse set of goals for natural resource use. Emergy synthesis can also elucidate the significance of ecological services, which were shown to be worth 40 times the money spent on management. Further more, emergy synthesis can aid in determining forest policies that are ecologically, socially and economically sustainable.

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