EMERGY BASIS FOR ECOSYSTEM MANAGEMENT: VALUING THE WORK OF NATURE AND HUMANITY

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Abstract

Understanding and accounting for the total contribution of nature to the wealth of a region or state is needed so that national lands can be managed effectively, especially in light of increasingly diverse demands. The natural wealth and production of a high elevation (900m - 1550m) watershed (1130 ha) in the Nantahala National Forest of North Carolina, USA was valued with emergy. Emergy is a system property that relates all flows and storages of energy, materials, and information to the one form of source energy required for their formation and maintenance. Emergy values were converted to emergy-dollars (EM$) so that nature's work could be easily compared with humanity's. The value of species diversity to system operation and performance was investigated using emergy analysis. A measure of system "creativity" was suggested for measuring the contribution of species diversity to ecosystem performance. The emergy evaluation methodology is a quantitative tool, helpful in making decisions about how to manage complex systems such as ecosystems.

Keywords: ecosystem management, biodiversity, valuation, emergy

1. Introduction

At the turn of the 20th century, an important question in natural resource management is how to integrate economic use activities with the supporting ecosystems so as to maximize total performance. A method that allows consequences of various land activities to be compared quantitatively and systematically is needed to aid resource managers and the public in making decisions about environmental management. Here, the potential for emergy evaluation to help in understanding the linkages between the ecology and economy of a forested watershed (1130 ha) in the Nantahala National Forest of North Carolina, USA was explored.

The major ecological functions and economic activities occurring within or because of the existence of the unpopulated, mountain watershed (the Wine Spring Creek basin, WSC) were evaluated based on the flows of emergy. Several ecosystems have been evaluated with emergy (Doherty et al., 1997; Odum et al. 1998). Here, besides presenting a case for the emergy evaluation methodology, the value of species diversity was quantified based on the flow of emergy required for its support. Higher species diversity may increase the long-term productivity of an ecosystem by adding to system "creativity", which was defined as the ability to engage a large number of possibilities during a system's self-organization, self-maintenance, or self-repair. Species-area curves for three forested ecosystems were used to relate emergy to the number of tree species supported and thus quantify the emergy per species-connection supported. The work had some similarity to the work of Keitt (1991). The methodology was suggested for estimating the value of species lost at a local level.

2. Methods

2.1 Emergy, Transformity, and Emdollars

Emergy is the total amount of energy of one form that was used directly and indirectly to make another form of energy (Odum, 1996). For simplicity, presume that to create wood a tree only required sunlight and water. While the sun's light radiation is needed for photosynthesis, the water is used in transpiration. To make 1000 Joules of wood required about 600,000 Joules of sunlight energy and only 600 Joules of water (chemical potential as Gibb's free energy). Therefore, if only the physical energies available were summed, the water seems insignificant. However, with emergy the value of the water is expressed in terms of how much solar energy was required for its formation and delivery to the forest. On a world average, 18,200 Joules of sunlight were needed to create and deliver 1 Joule of Gibb's free energy of water. The ratio of the source energy required to the physical energy available has been named the transformity (Scienceman, 1987.) Therefore, the 600 Joules of Gibb's free energy needed to make the 1000 Joules of wood, represents 10,900,000 solar emergy-joules (sej).

In order that the free work of nature could be compared to the paid services of humans the units of emergy (sej) were translated to emergy-dollars (EMDOLLARS or Em$) by dividing the emergy value of environmental flows by the mean emergy-to-dollar ratio of the state. The emergy-to-dollar ratio was estimated as the total emergy used per dollar of gross state product in an emergy evaluation of North Carolina (Tilley, 1998). Emdollars represent the contribution that "free" environmental resources make to an economy.

Table 1 shows an example of how the energy flows of an ecosystem are transformed into emergy and Em$ units. The mean annual energy input is multiplied by its transformity to derive the annual solar emergy flow. The Em$'s are estimated by dividing the solar emergy flow by the mean emergy-to-dollar ratio of the regional economy. For this study, the majority of the transformities used represent averages for the globe and were taken from Odum (1996).

Table 1. Example table showing how emergy flows are calculated.

Note	Item	Raw Units	Transformity (sej/unit)	Solar Emergy (1 E12 sej/y)	Emdollars* (US Em$)
1	Sunlight	50 E12 J/y	1 (definition)	50	33
2	Rainfall (chemical)	45 E9 J/y	18,200	819	546

* -- Emergy to $ ratio of North Carolina, ~1992 was 1.5 E12 sej/$ of gross state product

2.2 Research Site

The 1130 ha Wine Spring Creek watershed lies within the Nantahala National Forest of the North Carolina Blue Ridge physiographic province in western Macon county (35° Latitude, 83° Longitude; see Figure 1). Elevations in the basin range from ~1600m at Wine Spring Bald to ~900m at Nantahala Lake. The basin is unpopulated (U.S. Forest Service, 1995). The region averages more than 100mm of rainfall in each month. Mean temperatures in January and July are 3.3 and 22 °C, respectively (Swift et al. 1988).

The University of Florida Arboretum is located in Gainesville, Florida, USA. It was established in 1993 by Dr. Bijan Dehgan, Professor of the Environmental Horticulture. The unit has 135 north central Florida tree species planted on 2 ha. Each species is represented by 3 individuals.

2.3 Species-area Curves and Emergy-species Curves

For the Wine Spring Creek (WSC) watershed, the UF Arboretum and an Indonesian tropical rainforest (Kartawinata et al. 1981), the number of tree species was plotted against the area sampled to develop tree species-area curves. Data reported by Elliott and Hewitt (1997) for elevations greater than 1200m in the WSC basin were used to generate the species-area curve. A map of the tree layout of the UF arboretum was used to develop its species-area curve and combined with results of an emergy evaluation to make the emergy-species curve. For each system the area sampled was transformed to annual emergy flow, since they are proportional.

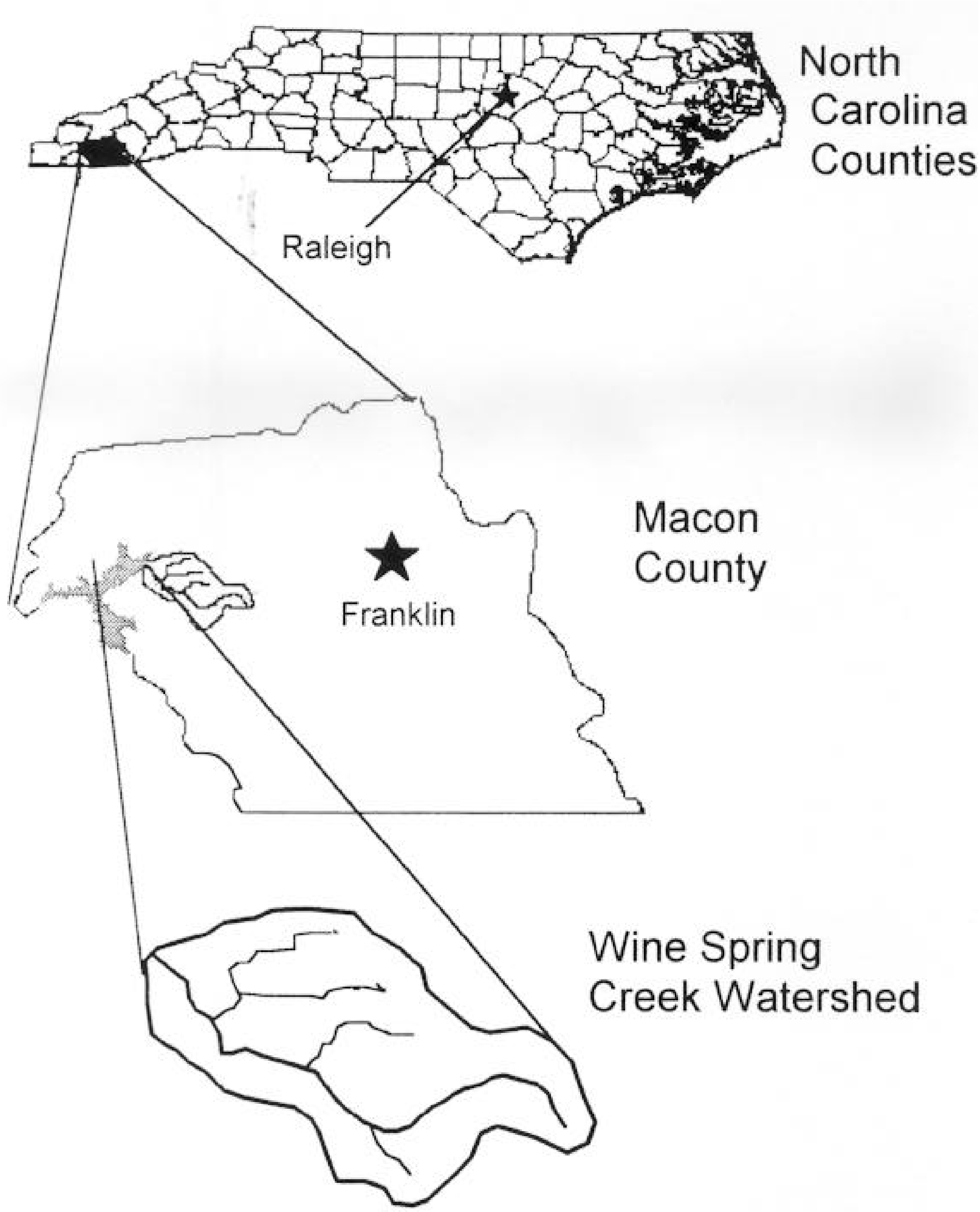

Figure 1. Location of Wine Spring Creek watershed

3. Results

3.1 Systems Diagrams

A general systems symbol language (Odum 1994) was used to describe the important forcing functions, state variables, processes and their relationships in diagrammatic form. Figure 2 shows the diagram for the Wine Spring Creek basin, while Figure 3 displays the diagram for the UF Arboretum.

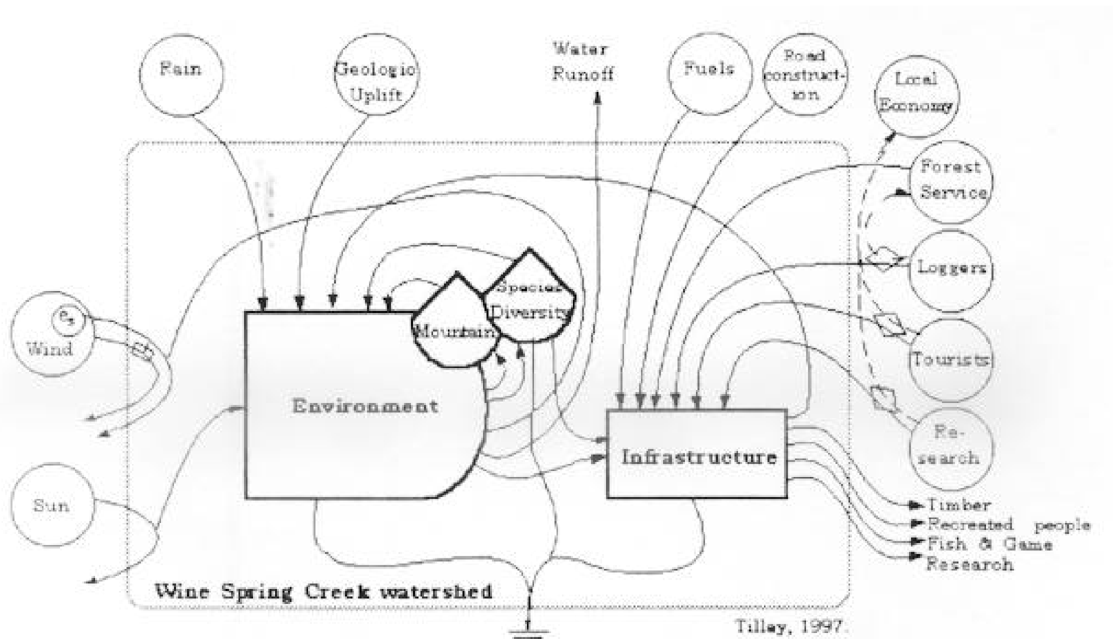

Figure 2. Overview diagram of the environmental-economic interface in the Wine Spring Creek watershed.

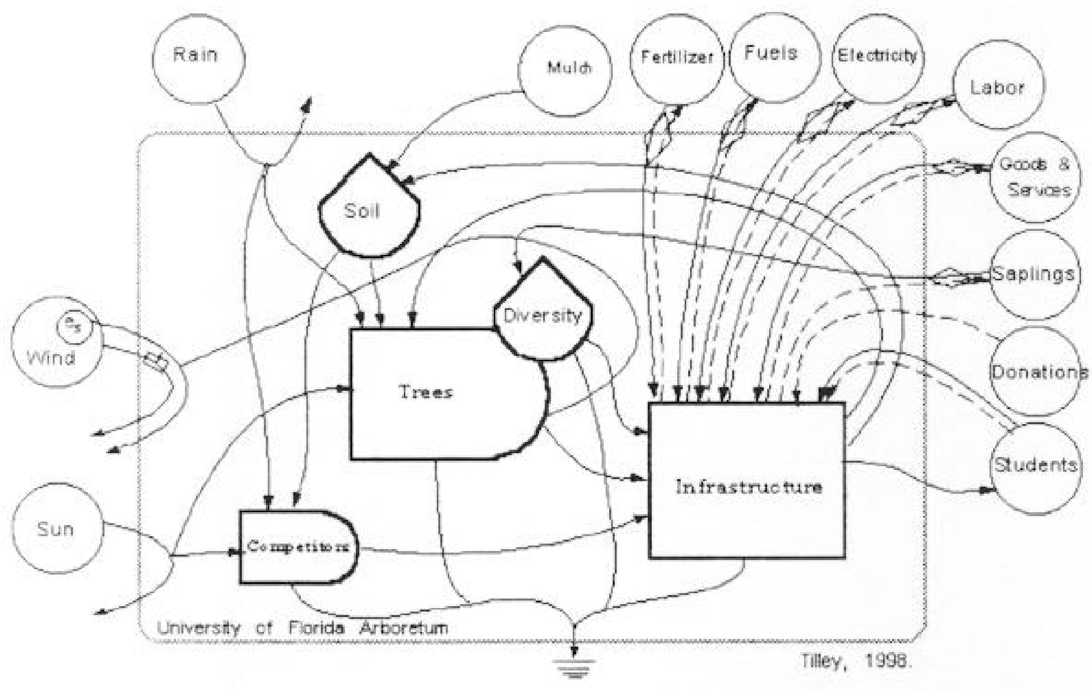

Figure 3. Overview diagram of the environmental-economic interface of the University of Florida Arboretum.

3.2 Emergy Evaluation of Wine Spring Creek Watershed

The WSC basin, by capturing environmental energies and providing ecosystem services, contributed to public welfare at an annual rate of 2,426,000 Em$ based on the rain, earth cycle, and economic imports;

see Table 2). The footnotes which show how the raw energy data were calculated can be found in Tilley (1998). The value of environmental energies captured--sun, wind, precipitation, and geologic uplift--ranged from 32 to 1035 Em$ $ha^{-1} y^{-1}$ (Table 2). The value of ecosystem services estimates for stream discharge, recreation--scenic viewing, net primary production, timber harvesting, soil genesis, and local use of Forest Service Road 711 are shown in Table 2. Stream discharge generated the greatest wealth (1,310 Em$ $ha^{-1} y^{-1}$). As yet to be evaluated are values for hunting and fishing, research activities, and secondary production of birds, fishes, mammals, and arthropods.

Table 2. Emergy evaluation of the resource flows for the entire 1130 ha Wine Spring Creek basin

Note	Item	Raw Units		Emergy per unit (sej/unit)	Solar Emergy (E16 sej/y)	Emdollars (E3 1990 Em$)
RENEWABLE RESOURCES:						
1	Sunlight	6.04E+16	J	1	6.0	36
2	Precip., chemical	1.09E+14	J	18,200	198.5	1,168
3	Precip., geopotential	6.24E+13	J	10,490	65.4	385
4	Evapotranspiration	2.99E+13	J	18,200	54.5	320
5	Wind, kinetic (2)	4.04E+14	J	1,500	60.6	356
6	Hurricanes	4.15E+13	J	41,000	170.1	1,001
7	Earth Cycle	6.76E+08	g	1,000,000,000	67.6	397
8	Deep Heat	1.53E+13	J	34,400	52.7	310
INDIGENOUS RENEWABLE ENERGY:						
9	Stream discharge	7.92E+13	J	31,714	251.2	1478
10	Timber production	1.90E+13	J	17,200	32.6	192
11	Fish production	3.77E+10	J	2,000,000	7.5	44
12	Game production	3.77E+10	J	2,000,000	7.5	44
13	Net prod. live biomass	3.11E+14	J	1,751	54.5	320
14	Wood accumulation	9.08E+13	J	5,998	54.5	320
15	Litterfall	9.51E+13	J	5,726	54.5	320
IMPORTS AND OUTSIDE SOURCES:						
16	Gas, visitors within	2.32E+11	J	66,000	1.53	9
17	Gas, thru traffic	2.32E+12	J	66,000	15.33	90
18	Gas, travel to/fro	1.29E+13	J	66,000	84.85	499
19	Visitors, travel time	3.25E+10	J	8.9E+6	28.92	170
20	Visitors, visit time	9.74E+10	J	8.9E+6	86.68	510
21	Road maintenance	9.98E+04	$	1.5E+12	14.96	88
22	Forest Service Mngmt.	2.82E+04	$	1.5E+12	4.22	25

3.2.2 Economic multiplier effect of environmental wealth

An emergy analysis of N.C. (Tilley, 1998) revealed that the "free" environmental energies of the State attracted external resources for economic production at a rate of 7-to-1 in terms of emergy flows. This is similar to ratios found for the U.S. as a whole (Odum, 1996). This "Ecological-economic Investment

Ratio" represents the multiplier effect of environmental production. Therefore, the free environmental energies captured by the WSC basin (1.5 million Em$ y^{-1}) will likely be matched by 7 times that amount (10.5 million Em$ y^{-1}) in the regional economy.

3.3 Emergy Evaluation of University of Florida Arboretum

Table 3 shows that almost 22,000 Em$ per year of local and imported resources were needed to maintain the 135 species of north central Florida trees at the UF Arboretum. To manage such a high diversity operation, many external resources (fertilizer, herbicide, electricity, gasoline, irrigation, human service) were required. Placing all of these inputs on an emergy basis showed that to maintain the arboretum, 20,000 Em$ y^{-1} worth of goods and services were imported compared to the 1,760 Em$ y^{-1} of local environmental resources (rain + land). The most valuable input was the human services required for administration (13,000 Em$ per year). Fuel for mowing the grounds to exclude weedy competitors and labor for pruning the trees were two other important inputs.

Table 3. Emergy evaluation of the resource flows supporting the 2 ha UF Arboretum (~1997).

Note	Item	Raw Units		Emergy per unit (sej/unit)	Solar Emergy (E14 sej/y)	Emdollars (1990 Em$)
1	Sunlight	91.5E+12	J	1	0.9	61
2	Rain Transpired	7.56E+10	J	18,200	13.8	917
3	Land surface area	2	ha	6.30E+14	12.6	840
4	Water from irrigation	2.99E+09	J	160,000	4.8	319
5	Mulch	4.27E+10	J	17,200	7.3	489
6	Fuel for mowing	3.09E+10	J	66,000	20.4	1,361
7	Fertilizer					
	Nitrogen	5832	g	3.45E+09	0.2	13
	Phosphorus	2592	g	3.90E+09	0.1	7
	Potassium	3240	g	2.96E+09	0.1	6
8	Fertilizer, $ pd.	107	$	1.50E+12	1.6	107
9	Electricity for irrigation	2.79E+09	J	160,000	4.5	298
10	Electricity, $ pd.	120	$	1.50E+12	1.8	120
11	Herbicide, $ pd.	140	$	1.50E+12	2.1	140
12	Start-up costs	600	$	1.50E+12	9.0	600
13	Labels for trees	32	$	1.50E+12	0.5	32
14	Total human service					
	Pruning	1600	$	1.50E+12	24.0	1,600
	Planting, irrigation, start-	900	$	1.50E+12	13.5	900
	Administration	13000	$	1.50E+12	195.0	13,000
	Mowing	975	$	1.50E+12	14.6	975
	Sum of all except item 1, sunlight				326	21,726

3.4 Species-area Curves

Graphs of the number of tree species vs. the area sampled demonstrated the shape typically observed for forested ecosystems (Figure 4). The species-area curve for the 75 yr. old Wine Spring Creek forest exhibited a lower slope than the UF Arboretum. Both had lower slopes than a tropical rainforest in East Kalimantan (Indonesia, Kartawinata et al. 1981).

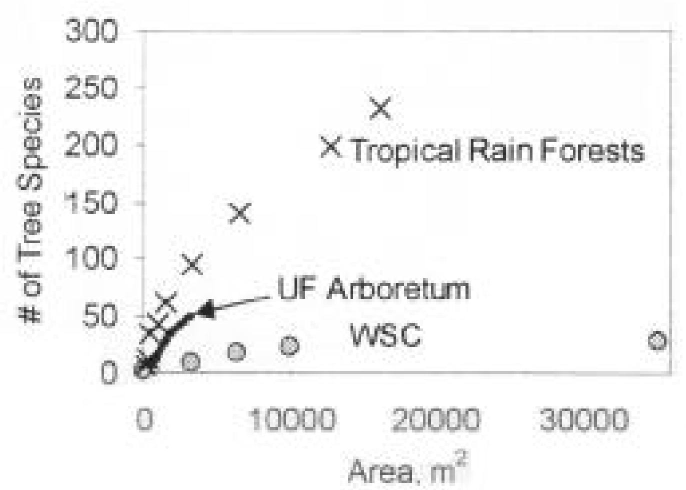

Figure 4. Species-area curves for the Wine Spring Creek watershed (>1200m in the Southern Appalachian Mountains), the University of Florida Arboretum (Gainesville), and a tropical rainforest in East Kalimantan (Indonesia, Kartawinata et al. 1981).

3.5 Emergy-species Curves

The species-area curves for the same three forests were transformed into emergy-species curves (emergy expressed as Em$ y^{-1}, Figure 5). Water used in evapotranspiration was taken as the emergy input to both the Indonesian tropical rain forest and the Wine Spring Creek temperate forest. For the UF Arboretum the mean emergy input per hectare (Table 3) was multiplied by the area sampled to derive the emergy input.

On the emergy-species curve the WSC and the UF Arboretum overlap. The same emergy per unit area per

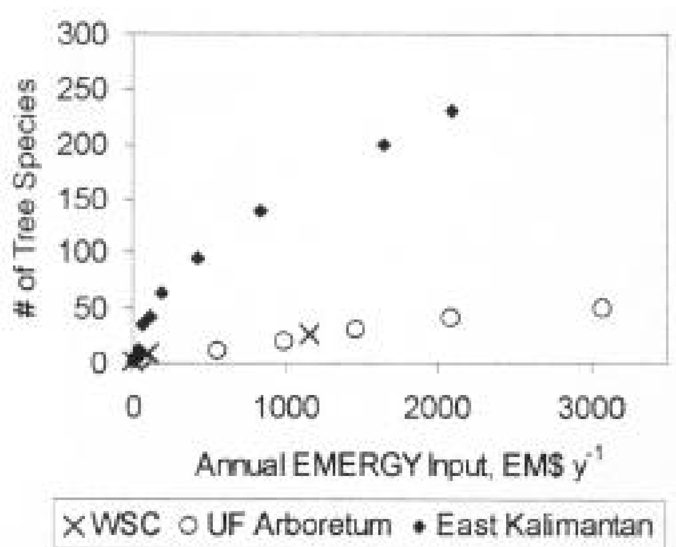

Figure 5. Emergy-species curves for the Wine Spring Creek watershed (>1200m above sea level in the Southern Appalachian Mountains), the University of Florida Arboretum (40 m asl, Gainesville), and a tropical rainforest in East Kalimantan (50m asl, Indonesia.

unit time supported the same number of species. However, the Indonesian rainforest was much more "efficient" in supporting tree species since it had more species for the same emergy input.

The UF Arboretum had a much higher density of tree species than the WSC (see Figure 4), but only because of the imported economic inputs. Correcting for this resource subsidy by placing both on an emergy-species curve demonstrated that, per unit of emergy input, both systems supported the same number of species.

4. Discussion

4.1 Use of the Emergy Systems Theory in Ecosystem Management

More and more the trend has been for land management agencies to adopt ecosystem management as their guiding philosophy. However, the definition of ecosystem management varies and precise consensus on a methodology to achieve it has not surfaced. The systems science community is in a position to step forward and assert its expertise to help shape this new and increasingly important field of research and management.

Although no one methodology has been accepted, three important criteria for ecosystem management were outlined by the former Chief of the U.S. Forest Service (pers. comm. Jack Ward Thomas). Any method should be able to i) evaluate all forms of inputs to the system, ii) cover multiple scales of space and time, and iii) include humans as part of the ecosystem. By this criteria emergy analysis seems to be the comprehensive tool for forming, implementing, and assessing ecosystem management plans. All inputs can be placed on a common basis for easy comparison, results of an analysis are meaningful and consistent across all temporal and spatial scales, and human efforts and desires can be incorporated into the analysis.

4.2 Measuring System Creativity

If ecosystems have the ability to self-organize, they should possess some creativity in order to do so and not have every ecosystem look alike. Here, system creativity is defined as the ability to engage a broad number of possible connections during a system's self-organization, self-maintenance, or self-repair.

Its theorized that the creativity of an ecosystem is inversely proportional to the mean empower per bit; where empower is emergy per time and a bit is a one-way connection between one species and another or itself. Table 4 shows the mean empower per bit for the three forested ecosystems studied. The Indonesian rainforest with the lowest mean empower per bit is likely the most creative. Each connection is weakly "wired", so the possibilities available are greater and no one connection can dominate the system. The WSC system has a higher empower / bit and therefore, likely less creativity.

Table 4. Mean empower per possible species connection (bit) for three forested ecosystems

Forest Ecosystem	Mean Empower per bit (Em\$ y^{-1} bit)
UF Arboretum	1.33
Wine Spring Creek	1.28
Kalimantan (Indonesian Rain Forest)	0.04

4.3 Valuing the Contribution of Species Diversity of Ecosystem Development

A new area of research using emergy analysis, is in valuing the benefits of species diversity to the ecosystem development. Development of emergy-species curves may be an appropriate way to relate the two. The emergy-species curve exhibited in Figure 5 had a similar shape to the species-area curve in Figure 4, that is, the emergy required for each new additional species increased as the square of the number of species. Presumably, this was due to the fact that each additional species increased the possible connections (bits) between the species at a quadratic rate. If the square of the number of species was plotted instead, then the curves were straight lines (figure not shown). This adds support to the theory that the area required increases as the square of the number of species (Odum, 1994). The cause for this relationship could be that the number of possible connections between tree species increases as the square, thus resources must be devoted to support the connections. The diversion of energy could either be devoted for competition or for a system of behaviors that eliminates competition, both require energy to accomplish.

When species are lost from an ecosystem, the system "creativity" is decreased. Losing five (5) tree species from a system that contains fifty (50) decreases the number of possible connections (bits) by 475, from 50^2 to 45^2. Although the loss of species is 10%, the loss in potential creativity is 19%. If the original system's mean empower/bit was 0.04 Em\$ y^{-1} bit^{-1} like the Indonesian rainforest, then the loss can be quantified as the number of bits lost times the empower per a bit (475 bits x 0.04 Em\$ y^{-1} bit^{-1} = 19 Em\$ y^{-1}). If the species were extirpated for 10 years, then the cumulative loss in creativity would be 10 y x 19 Em\$ y^{-1} = 190 Em\$.

Interpretation of the emergy-species relationships is still in its infancy, but promises new insight to understanding the importance of species diversity so that large land holdings can be managed wisely. Emergy-species curves for forests in other parts of the world need to be developed so that the relationship can be more fully tested. It would also be useful to develop the relationship for the total diversity of ecosystems in order to gain a broader perspective.

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