EMERGY SYNTHESIS:
Theory and Applications of the Emergy Methodology

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The Hierarchical Pattern of Energy Flow in Ecological-Economic Systems Representing Three Geographic Scales

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ABSTRACT

This paper demonstrates the ubiquity of the hierarchical property of energy flow in ecological-economic systems by evaluating power (energy flow) and empower (emergy flow) spectra for i) the entire state of North Carolina, USA (1E7ha), ii) a mountain county in western North Carolina (Macon, 1E5 ha), and iii) a high-relief watershed within Macon county (Wine Spring Creek, 1E3 ha). Power and empower spectra were found by plotting energy and solar emergy use as a function of solar transformity. Solar emergy is defined as the solar energy previously required directly and indirectly to make a product or service, and solar transformity is defined as the solar emergy per available energy (exergy). The power spectra provided evidence that a log-log relationship of energy use and energy quality was robust across multiple scales. The empower spectra provided a holistic tool for assessing the relative importance of each driving energy and gave the means to uniquely and succinctly identify the systems structure of an ecological-economic system. To gain a better holistic perspective of ecological-economic systems, we suggest that the power and empower spectra become standard for emergy evaluations.

INTRODUCTION

Odum (1996) proposed that energy flow in open systems, such as ecological-economic systems, was hierarchical with large flows of low quality (i.e., low transformity) energy feeding the base of the energy network and less and less high quality forms of energy (i.e., high transformity) being processed at the top of the energy web. This paper demonstrates the ubiquity of the hierarchical property of energy flow in ecological-economic systems using evaluations of systems representing three different geographic scales. The hierarchical energy pattern is depicted with power (energy flow) and empower (emergy flow) spectra developed for i) the entire state of North Carolina (1E7ha), ii) a mountain county in western North Carolina (Macon, 1E5 ha), and iii) a high-relief watershed within Macon county (Wine Spring Creek, 1E3 ha).

The combined systems of nature and humanity have as their common basis and fundamental attribute the processing of energy for development and growth. Emergy evaluation has been developed as a systems analysis tool that allows any system's energy flows to be evaluated on a common basis (i.e., their ultimate source energy) and thus provides holistic overview on how systems organize and assists in identifying the main forces driving a system. Solar emergy, defined as the solar energy previously required directly and indirectly to make a product or service (Odum 1996), and solar transformity, defined as the solar emergy per available energy (exergy), were used to evaluate the energy-flow network structure of three ecological-economic systems. By plotting energy and emergy use as functions of solar transformity, insight into how various forms of energy interact to operate complex ecological-economic systems was gained.

In general there is a search for tools and methodologies that offer holistic overview of systems of all kinds, especially ecological-economic systems. Emergy evaluation has been employed as such a methodology for the past 25-30 years. Here, we stress the utility of the power and empower spectra in capturing, into one picture, the energy dynamics of complex systems and thus provide a much-needed tool for assessing systems in holistic overview. Additionally, the power and empower spectra may prove useful for interpolating and extrapolating for unknown or never-before-calculated solar transformities.

Odum (1996) suggested that due to the dissipation of energy during a system's energy transformations, a log-log plot of energy use versus solar transformity (i.e., a power spectra) would give a straight, negatively-sloped line. The slope is a function of the efficiencies of the series of energy transformations (output per input). A network of high efficiency processes would give a flatter slope than a network of low efficiency processes. This paper gives direct evidence that the log-log relationship is robust across multiple scales, but that the slope varies slightly depending upon the intensity of emergy use.

For the empower spectra (emergy use versus solar transformity) the relationship is a semi-log one. By analyzing the empower spectra of an ecological-economic system an understanding of the relative importance of each type of energy source becomes evident (Tilley 1999). If empower spectra are proven to be unique for each ecological-economic system, then it is a means of quickly and succinctly identifying a system. That is, the empower spectra is a unique identifier of a system.

METHODS

Description of Systems

North Carolina spans over 800 km from the Atlantic Ocean to the Appalachian Mountains. The state's 135,531 km^2 (52,286 sq. mi.) is situated between latitudes 33.5N and 36.5N, and longitudes 75.5N and 84.3N. Under Koppen's climatological system, the State is humid sub-tropical. The mean annual temperature for the state is 15°C.

Macon County encompasses 134,000 ha of the southern Appalachian Mountains of western North Carolina. Altitudes within the county range from 600 m where the Little Tennessee River crosses into Swain County to over 1660 m at Wine Spring Bald. The mean elevation is 988 m. Climate is marine tropical with abundant precipitation (1350 mm y^{-1}) that includes some snowfall. All energy use data presented here was taken from Tilley (1999).

The 1130 ha Wine Spring Creek (WSC) watershed lies within the Nantahala National Forest of the North Carolina Blue Ridge physiographic province in western Macon County (35° Latitude, 83° Longitude). Elevations in the basin range from 1660m at Wine Spring Bald to 900m at Nantahala Lake. The basin is unpopulated (U.S. Forest Service, 1995), but receives over 10,000 tourists per year (Cordell et al. 1996). All energy use data presented here was taken from Tilley (1999).

Emergy Evaluation

Methods used to evaluate energy and emergy flow were those given by Odum (1996). Data shown in the power and empower spectra and their supporting calculations can be found in Tilley (1999).

RESULTS

North Carolina

The systems diagram of North Carolina (Figure 1) shows the role of externally supplied environmental and economic energies in supporting the interconnections of the state's main ecological and economic units. Beginning on the left of the diagram, the main ecosystems (coastal zone, forests, and agriculture) seized the diverse spectrum of environmental energies—sun, wind (vapor deficit and kinetic energy), rain, tides, waves and geologic uplift—and transformed them to ecosystem goods and services available for economic production and life support. Mineral deposits (phosphate and aquifers) and mountains provided the foundation for such industries as hydroelectric power production, phosphate mining and logging. Continuing rightward in the diagram, the economic sectors of electric power generation, mining, logging, manufacturing and commercial services transformed the goods and services of the ecosystems, with the assistance of imported fuels and services, into products and services for peoples' consumption. Furthest to the right in the diagram, N.C. traded goods and services, and exchanged money with outside markets and the federal government. The state also attracted tourists to its beaches and mountains. At every energy transformation, energy was irreversibly lost to the heat sink, shown at the bottom of the diagram.

Figure 2a shows the power (energy used) spectra for North Carolina, while Figure 2b shows the empower spectra. The spectra demonstrated the hierarchical property of energy use. That is, the vast majority of incoming energy was in the form of low transformity sunlight, while the highest quality energy source (human metabolism for immigrants and tourists) contributed nearly the least amount of energy (Figure 2a). When energies were instead expressed as empower, the numerical differences between the sources were less, but still ranged well over two orders of magnitude (Figure 2b). Interesting to note was how the mid-quality energy sources (1E4 to 1E5 sej/J) vacillated in sequence with increasing transformity (Figure 2b).

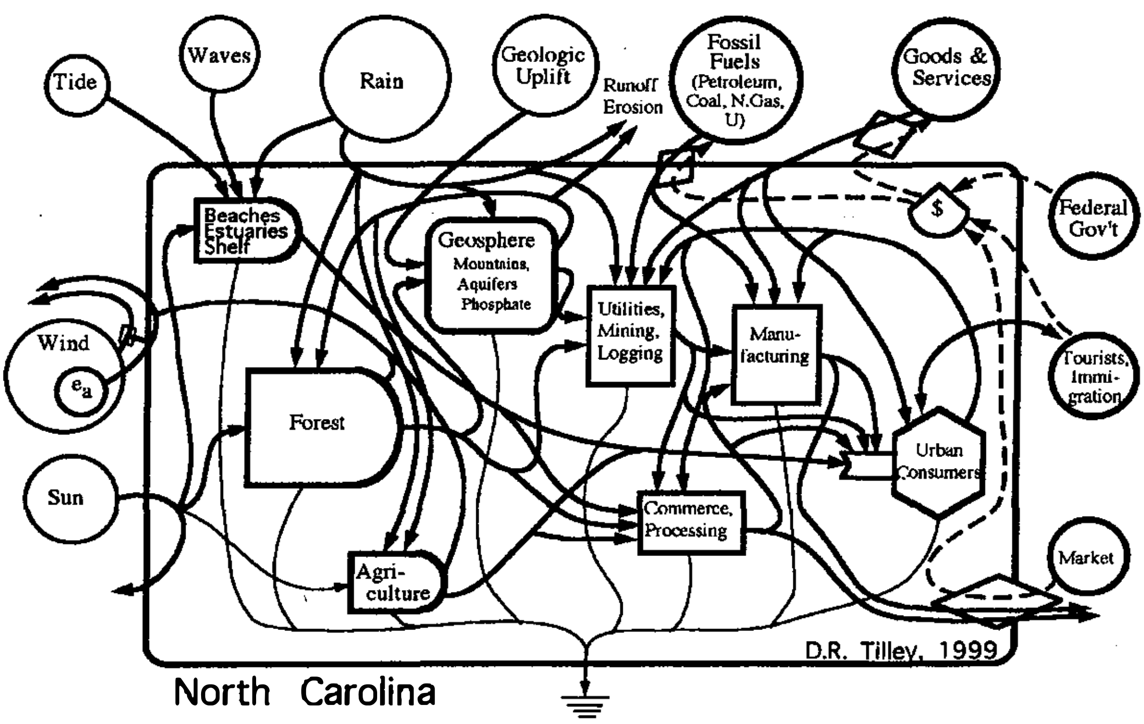

Figure 1. Systems diagram of North Carolina (1992).

Macon County, N.C.

Figure 3 shows the systems diagram of Macon County highlighting the fundamental relationship that existed between forest ecosystems, mountains, and economy. Covering, 84% of the county land surface, forested ecosystems transformed the dilute, low transformity energies of sun, vapor deficit, wind, water, and geologic uplift into ecological commodities. Rainfall in the county, above the state average, was aided by the mountain system. These two main features of the landscape, forests and mountains, together provided the environmental basis for much of the county's economic activities.

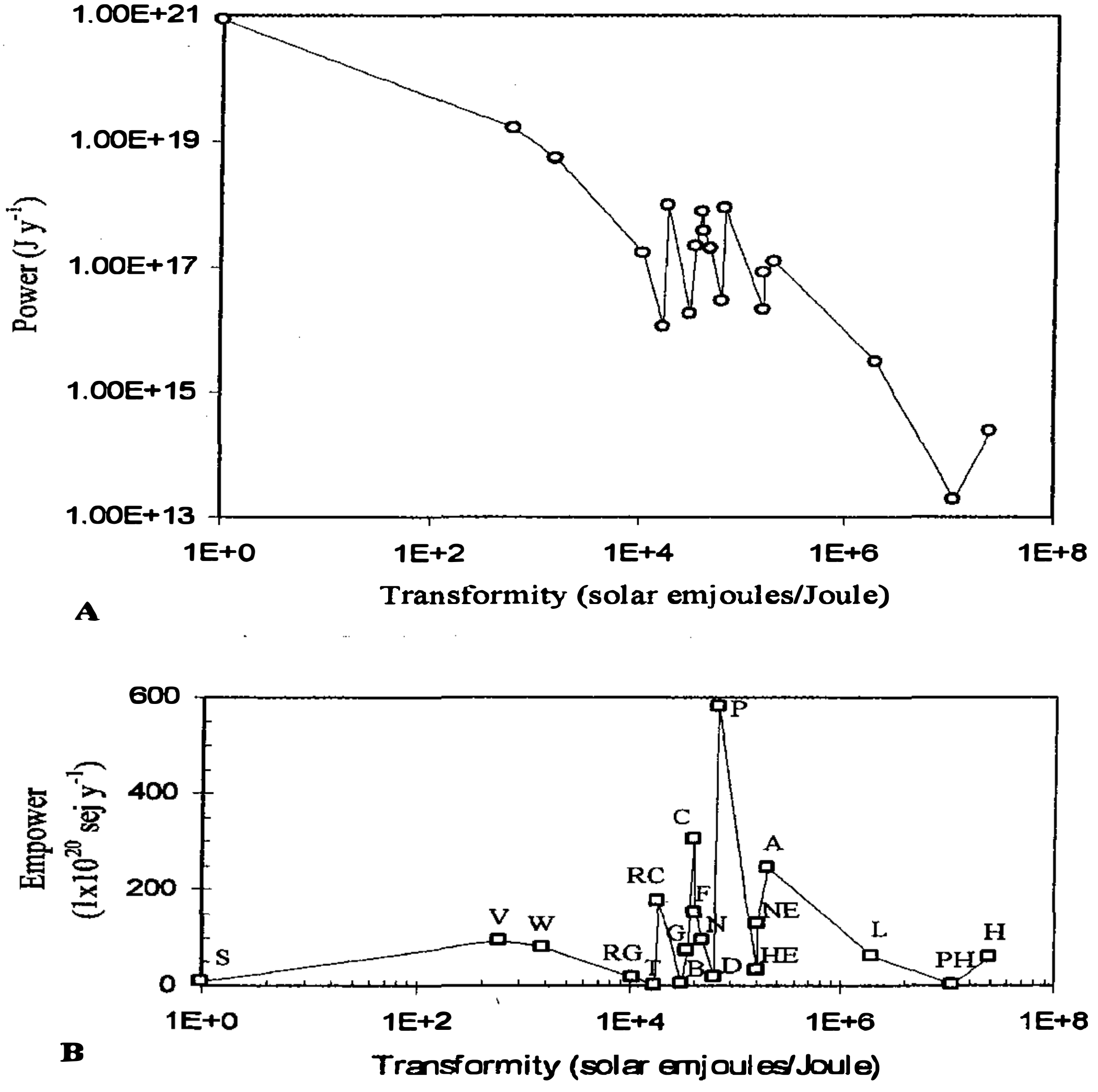

Figure 2. Power (a) and empower (b) spectra of the main resource inputs used in North Carolina, ca. 1992. Abbreviations: S-sunlight, V-water vapor deficit, W-kinetic wind, RG-geopotential of rain, T-tide, RC-chemical potential of rain, B-waves, G-geologic uplift, C-coal, F-wood, N-natural gas, D-soil, P-petroleum, HE-hydroelectricity, NE-nuclear electricity, A-agricultural crops, L-livestock, PH-phosphate mined & used, H-human migration and tourism.

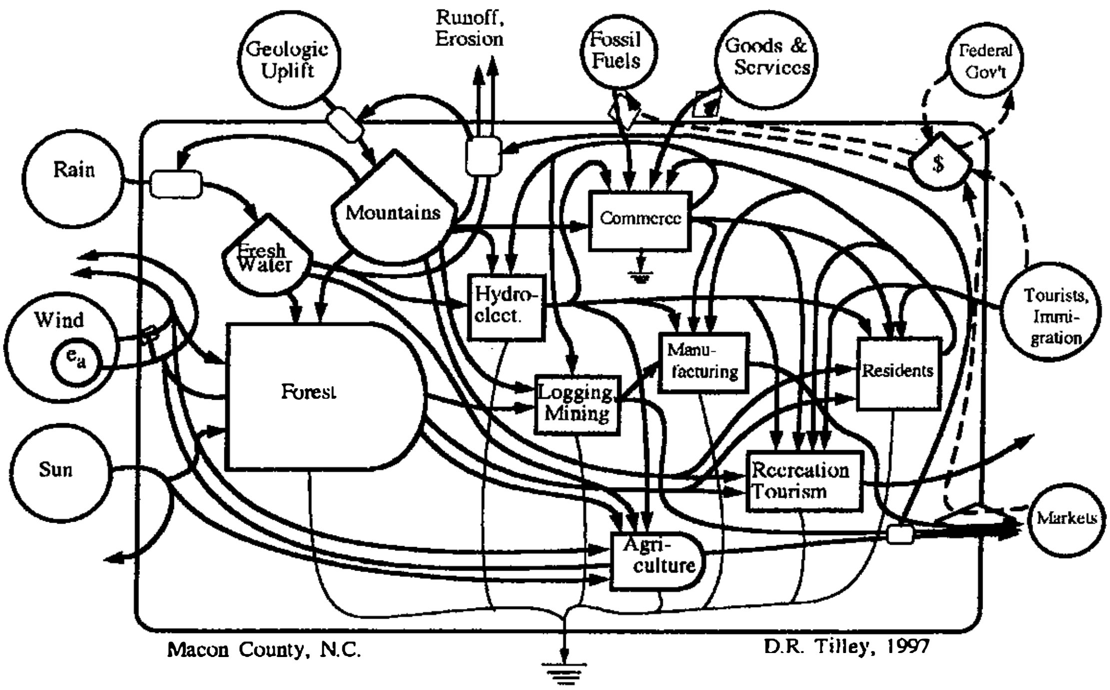

Figure 3. *Systems diagram of Macon County, N.C. (1992).*

Shown in Figure 4 are the power and empower spectra developed for Macon County. The county's power spectrum demonstrated the hierarchical property of energy use, just as the spectra for North Carolina did. The use of low quality energy (e.g., sunlight) was vastly greater than the use of high transformity energies such as that associated with tourists and migrants (Figure 4a). The empower spectrum in Figure 4b highlighted the significance of electricity and tourism in the county. Electricity use (2.2 E20 sej/y) was about four and a half (4.5) times that of transpiration. Total people flux (tourism plus net migration) at 3.2 E20 sej/y was 6.7 times transpiration.

Wine Spring Creek watershed (N.C.)

Figure 5 shows the system diagram of Wine Spring Creek (WSC) watershed. The diagram emphasizes the multi-purpose role of the watershed. In addition to the forest and mountain capturing the energies of the environment the diagram reveals the interconnections of environment and economy, and highlights the fact that the environment is the basis of the human-built infrastructure and eco-tourism.

Figure 6 shows power and empower spectra for the WSC, which highlight the hierarchical property of energy use. Solar energy (solar transformity = 1 sej/J) was five orders of magnitude (10^5) more abundant than human energy (solar transformity = 2.4E6 sej/J). Figure 6b shows the empower spectra of the Wine Spring Creek watershed. Normalizing energy flows to solar emergy flows reduced the vast discrepancies seen in the power spectra; emergy flows were within an order of magnitude of each other in the empower spectra.

Comparison of Power Spectra Across Three Spatial Scales

In Figure 7 the power spectra of three ecological-economic systems (North Carolina—1E7 ha, Macon County—1E5 ha, Wine Spring Creek watershed—1E3 ha) are compared. In addition to

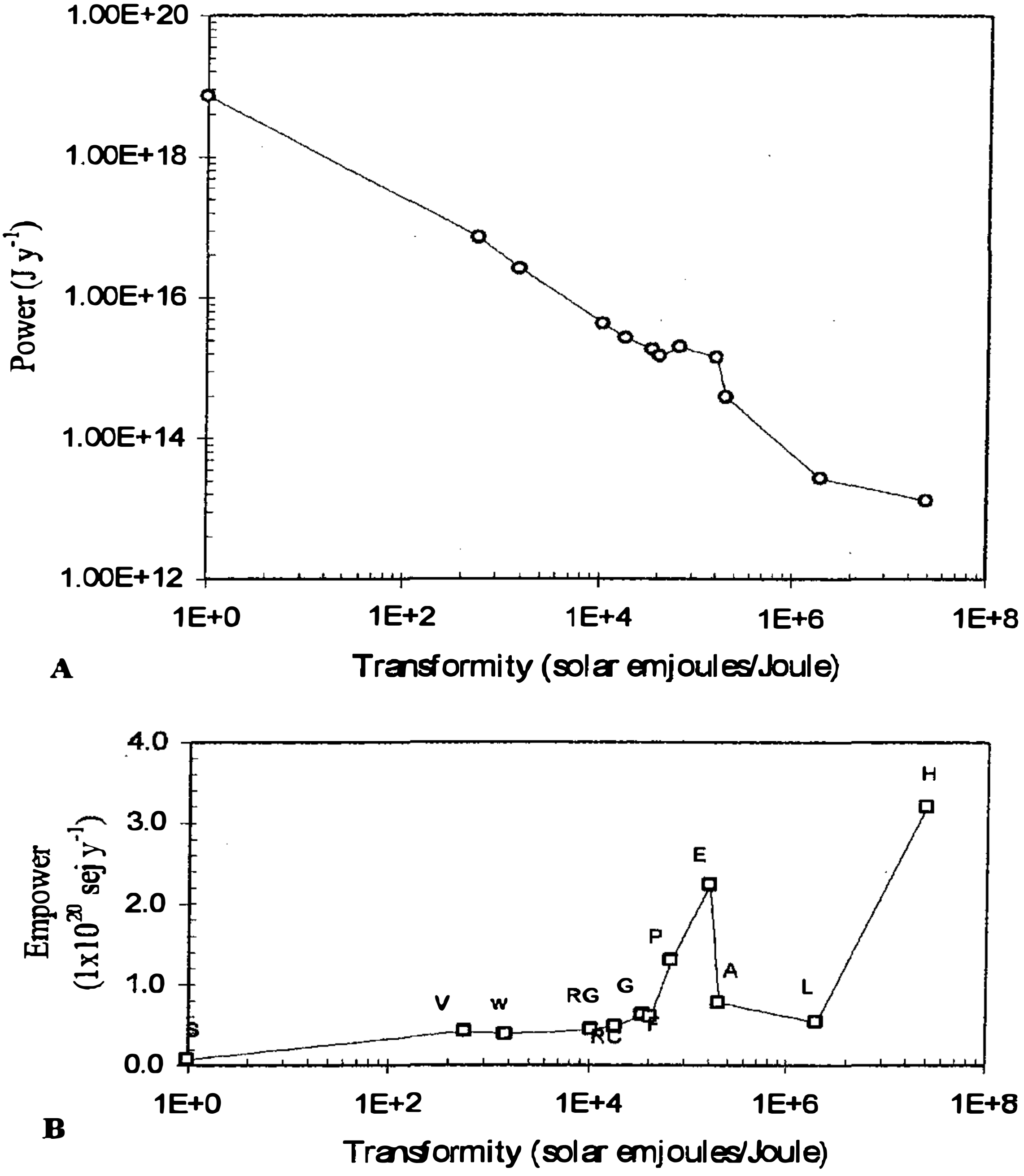

Figure 4. Power (a) and empower (b) spectra of the main resource inputs used in Macon County, N.C. (1992). Abbreviations: S-sunlight, V-water vapor deficit, W-kinetic wind, RG-geopotential of rain, RC-chemical potential of rain, G-geologic uplift, F-wood, P-petroleum, E-electricity, A-agricultural crops, L-livestock, H-human migration and tourism.

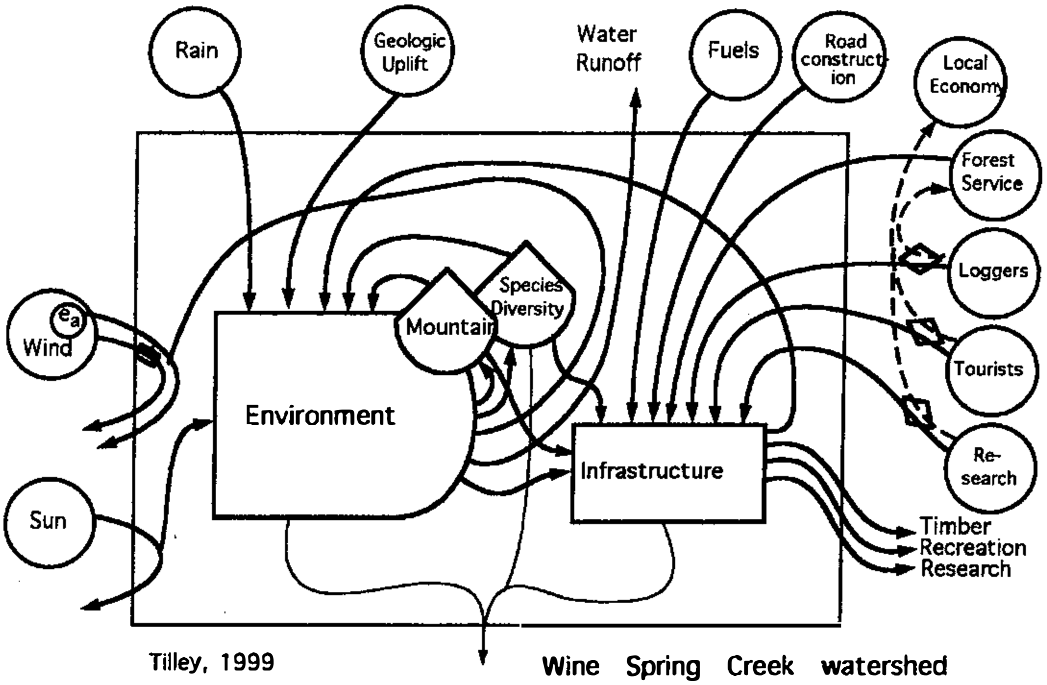

***Figure 5.** Systems diagram of the environmental—economic interface of Wine Spring Creek watershed.*

demonstrating the robustness of the log-log relationship of energy use versus energy quality, the graphs reveal the differences and similarities of the different sized systems. The largest system, North Carolina, had the highest curve over the entire range of solar transformities; use of all energy forms was greater than that for the county or watershed. As for similarities, the (log-log) slopes for each of the three power curves were between -0.97 and -0.79 (Figure 7).

A power density (energy use per area) spectra, which combined data from the three ecological-economic systems and standardized it by dividing energy use by the respective area of use, is shown in Figure 8 with a fitted curve and a 95% confidence interval. Regression equations are given for the mean, lower confidence interval, and upper confidence interval. The mean power density (J/ha/y) is a negative power function of solar transformity (sej/J); that is, for each order of magnitude increase in solar transformity, power density decreased one order of magnitude (Figure 8).

Comparison of Power Spectra of Environmental Driving Energies of three U.S. States

To further demonstrate the ubiquity and robustness of the hierarchial pattern of energy flow in complex systems, the "natural" power and empower spectra of two other U.S. states, Florida and Texas, were compared to North Carolina. The differences in the use of renewable, environmental energy inputs in the three states are demonstrated in power density spectra (Figure 9a) and empower density (sej/ha/y) spectra (Figure 9b). From the empower density spectra (Figure 9b) the greater role played by wind energy in Texas, as compared to North Carolina and Florida, is evident. In North Carolina and especially Florida, the greater significance of the chemical energy of rain is demonstrated. Table 1 lists the renewable energy sources used in North Carolina, Texas (Odum and Odum, 1987) and Florida (Odum et al. 1998) according to their solar transformity.

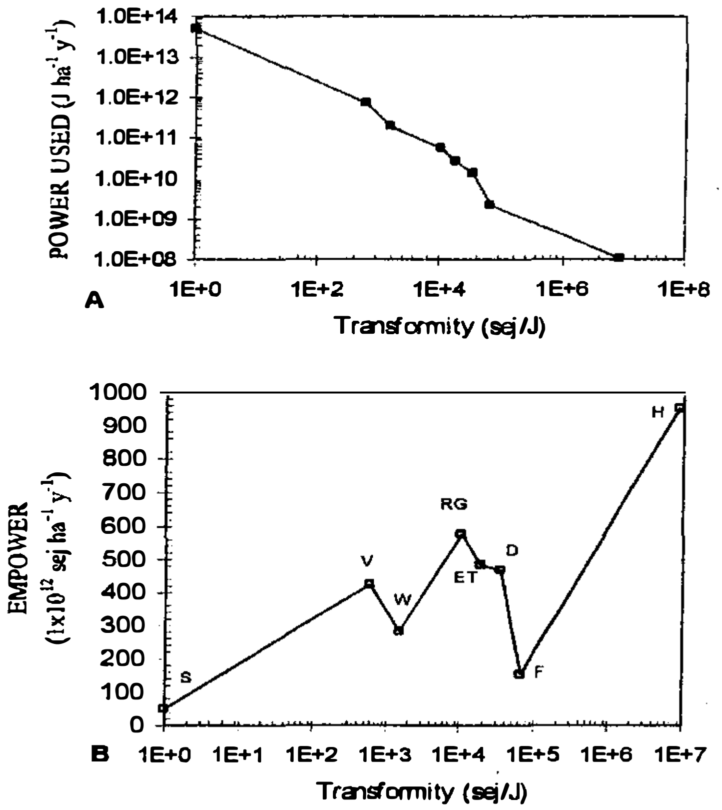

Figure 6. *Power (a) and empower (b) spectra of environmental energy inputs to Wine Spring Creek watershed. S-sunlight, V-vapor saturation deficit, W-wind,RG-geopotential precipitation, ET-evapotranspiration, D-deepheat, F-fuels, H-human service.*

Table 1. Average annual use of renewable energy sources in North Carolina, Texas and Florida.

		North Carolina[a]	Texas[b]	Florida[c]
Energy Source	Solar Transformity (sej/J)	Power (J/y)		
Sunlight	1	8.65E+20	3.48E+21	1.70E+21
Saturation deficit	590	1.61E+19	n.a. n.a.	
Wind, kinetic	1500	5.41E+18	1.95E+20	3.60E+18
Rain, geopotential	10500	1.69E+17	2.29E+18	3.60E+15
Tide	16800	1.12E+16	4.45E+16	1.12E+17
Rain, chemical	18200	9.74E+17	2.23E+18	2.20E+18
Waves	30600	1.80E+16	2.30E+17	1.23E+17
Earth Cycle	34400	2.16E+17	7.00E+17	1.40E+17

[a] Tilley (1999)
[b] Odum and Odum (1987)
[c] Odum, Odum and Brown (1998)

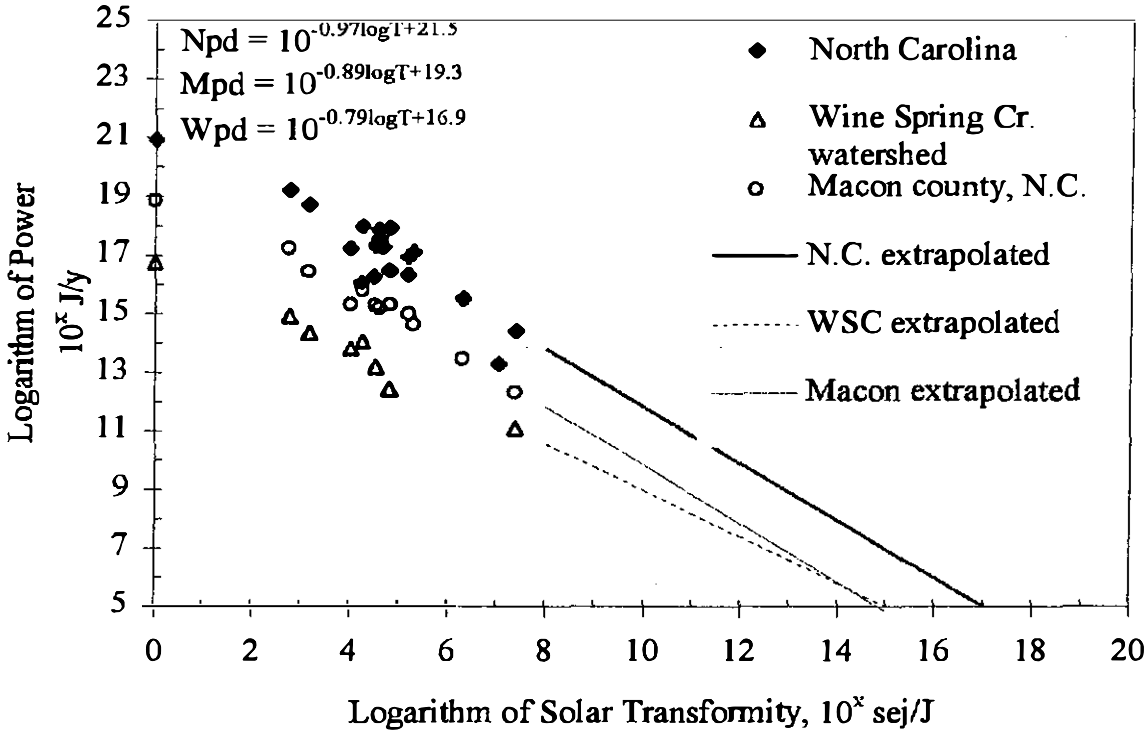

Figure 7. *Comparison of power spectra for three ecological-economic systems.*

DISCUSSION

Four types of energy spectra (power, power density, empower, and empower density) were demonstrated as tools for assessing ecological-economic systems in holistic overview. The energy spectra can show in one picture the relative importance of the different energy forcing functions, as well as the intensity at which a system is operating.

The empower spectra that were developed for the state of North Carolina (Figure 2b), the county of Macon (Figure 4b), and the forested watershed of Wine Spring Creek (Figure 6b) all clearly showed the importance of non-renewable, fossil fuel energies as driving forces in ecological-economic systems.

The power spectra shown in Figures 2a, 4a, 6a, and 9a demonstrated the robustness of the hierarchical pattern of energy flow in ecological-economic systems. This clearly demonstrated, when evaluating ecological-economic systems, why it is more informative to compare the different forms of energy on a common basis, such as emergy, rather than simply on a heat equivalent or exergy basis. Comparing the flow of different forms of energy on the basis of available energy will likely result in the analyst concluding that energy is not an appropriate metric for systems analysis. For example, in North Carolina, the exergy (available energy) of the petroleum consumed was orders of magnitude less than the exergy provided by sunlight, the vapor deficit, or wind, and approximately equivalent to the Gibb's free energy of rain, but obviously these free, environmental forms of energy were important to the overall functioning of the state economy. Transforming each energy form to solar emergy expresses all on a

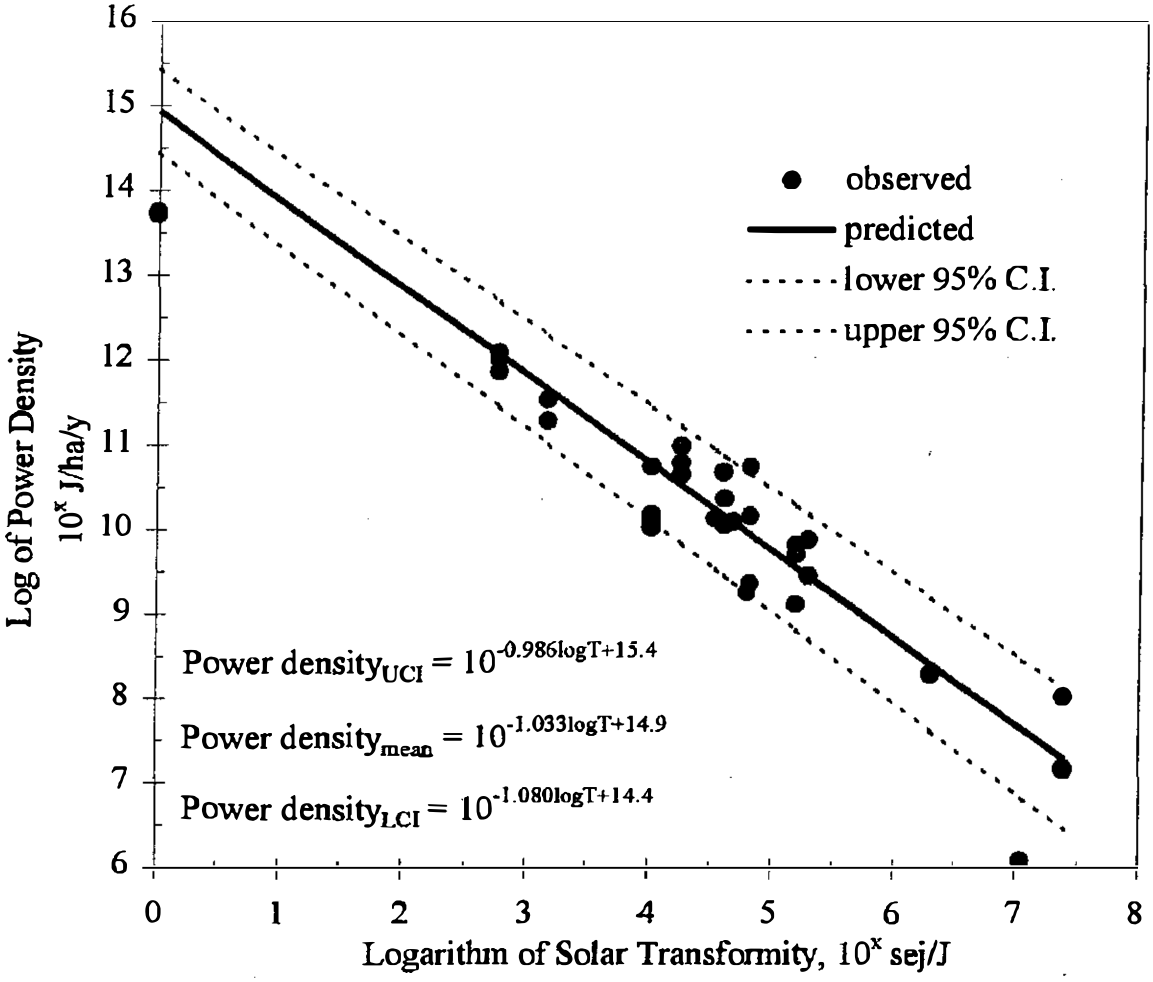

Figure 8. *Mean power density spectra with upper and lower confidence intervals (UCI & LCI) which combinesdata from the three ecological-economic systems studied (N.C., Macon, WSC).*

common basis, which allows direct numerical comparison as is evidenced from the empower spectra in Figures 2b, 4b, 6b, and 9b.

Emergy analysis of ecological-economic systems has been carried out for several decades, evaluating many countries around the world. To gain the extra holistic perspective which we seek by conducting emergy analyses, we propose that the power and empower spectra become a standard step in the evaluation process. We are just now beginning to evaluate countries and regional economies with the various energy spectra, so the potential for gaining a more thorough understanding of how these systems are organized is wide-open. Hopefully, knowledge gained will lead to better environmental policies and a more systems-minded populace.

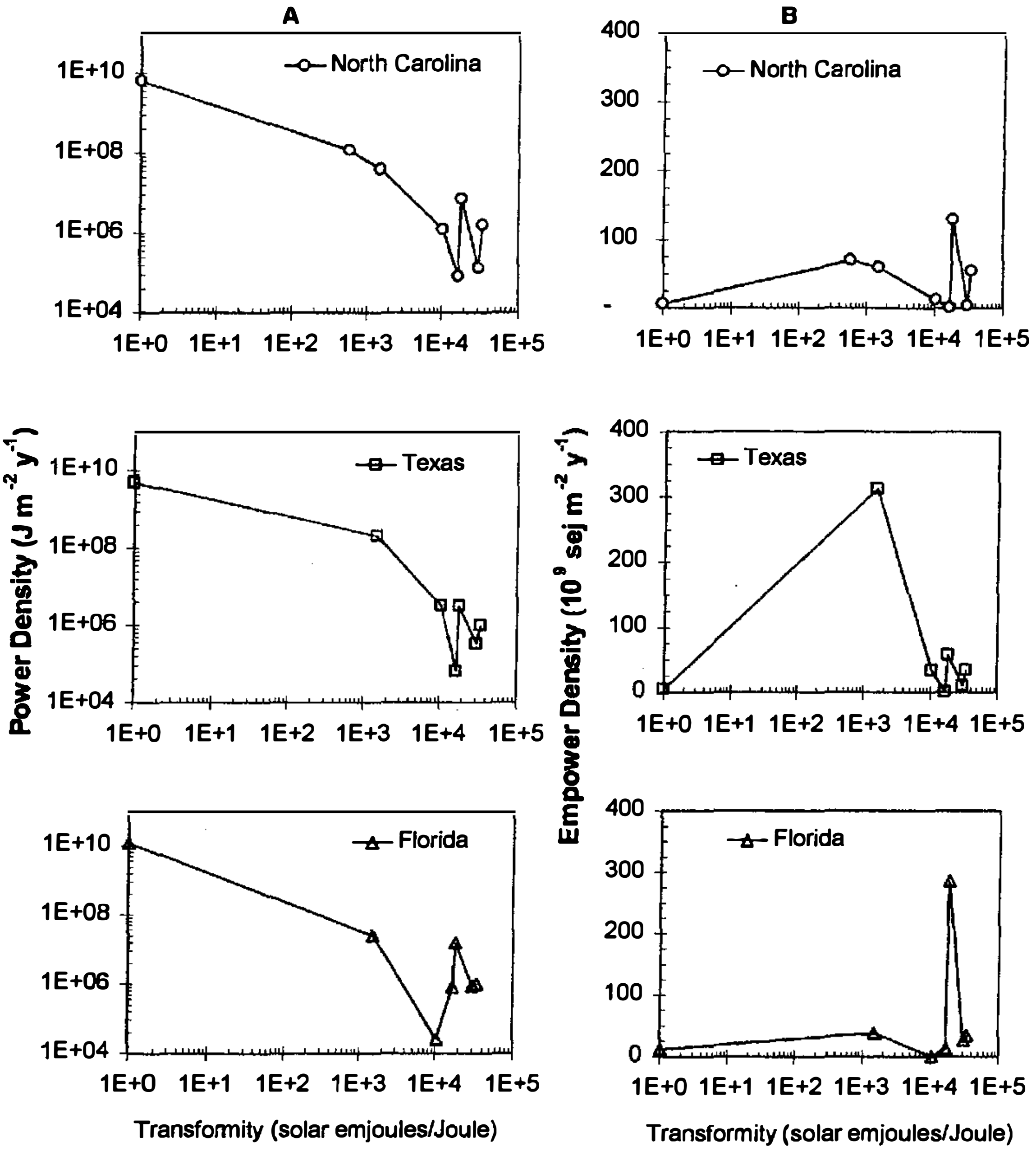

***Figure 9.** Power density spectra (a) and empower density spectra (b) of three U.S. states.*

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