Chapter 24. The Energy Basis Of A Subtropical Wetland Mesocosm

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ABSTRACT

A major challenge in Ecology is to design experimental units (microcosms, mesocosms, enclosures, exclosures, etc.) that adequately represent nature. One design approach is to match the energy signature, or set of outside forcing functions of a system, between the experimental system and the natural analog. To illustrate this approach, the energy basis of the Smithsonian Institution’s Florida Everglades mesocosm in Washington DC is described as a design analysis. The Everglades mesocosm was built in a greenhouse as a prototype for a portion of Biosphere 2 in 1987. It consists of a series of habitat tanks connected along a salinity gradient. The mesocosm maintained a biota characteristic of the Everglades for more than a decade and it served as an adequate model for the natural analog system. The energy signature of the mesocosm is compared with data from south Florida by using emergy analysis. Tide, waves, water circulation, precipitation, wind and temperature are maintained in the mesocosm through the use of human labor, natural gas and electricity along with natural sunlight. Natural gas and electricity dominate the mesocosm’s energy signature with inputs on the order of 10E16 solar emjoules/yr. The natural energy signature of south Florida is three orders of magnitude lower than that of the mesocosm and is dominated by wave energy at 10E14 solar emjoules/yr. These results are discussed in relation to the design, creation and restoration of ecosystems, with emphasis on mesocosm design.

INTRODUCTION

Modern ecological research is strongly dominated by the experimental method (Hairston 1989, Resetarits and Bernardo 1998). A first requirement of this method is that replicates exist so that manipulations can be conducted and compared with controls that were not manipulated. Although it is possible to employ a single system and replicate in time, most experiments involve multiple systems that are used as simultaneous replicates. There are special situations where nature provides replicate systems such as in phytotelemata, rock outcrop vegetation, tide pools or oceanic islands (Beyers and Odum 1993). However, in the absence of natural replicates, the human experimenter must devise them. Often artificial structures are used to isolate natural ecosystems into replicates or to create model ecosystems that serve as replicates. Design of these structures requires an ecological engineering approach to varying degrees.

Because the replicates must represent the natural ecosystem, the influences of the artificial structures must be minimized. Many design issues must be considered in this regard depending on the type of ecosystem (ie., forest, stream, mudflat, etc.). These include choice of materials, the size, shape and configuration of the experimental units and the role of possible edge effects caused by the structures. In some cases it is possible to divide the natural ecosystem into replicate units, as in the case of construction of enclosures or enclosures. These units utilize different kinds of materials in the form of cages or curtains to create replicates. This approach has the advantage that the replicates can be good models of the natural system since they are simply partitioned up pieces of the natural system itself. In other cases whole new ecosystems must be created, usually microcosms or mesocosms, either because the experiments involve manipulations that are not appropriate to be conducted in the natural ecosystem (ie., release of toxins) or...
because the experiment requires control over the environment that is not possible when done in nature. The creation of new experimental systems is a significant design challenge because of the complexity of ecosystems. In this paper the use of energy signatures as an aid to design of created experimental systems is described and illustrated for a case study of a mesocosm model of the Florida Everglades.

The energy signature of an ecosystem is the set of energy sources that affect it. Another term used for this concept is forcing functions, or those outside causal forces that influence system behavior and performance. H. T. Odum (1971) suggested the use of the energy signature as a way of classifying ecosystems based on a physical theory of energy as a source of causation in a general systems sense. A fundamental aspect of the energy signature approach is the recognition that a number of different energy sources affect ecosystems. Kangas (1990) reviewed the history of this idea in ecology. Sunlight was recognized early in the history of ecology as the primary energy source of ecosystems because of its role in photosynthesis at the level of the organism and by extrapolation in primary production at the level of the ecosystem. Organic inputs were formally recognized as energy sources to ecosystems in the 1960s with the development of the detritus paradigm, primarily in stream ecology (Cummins 1974) and in estuaries (Odum 1980, Sibert and Naiman 1980). The terms autochthonous (sunlight driven primary production from within the system) vs. allochthonous (detrital inputs from outside the system) were coined in the 1960s to distinguish between the main energy sources in ecosystems. Finally, in the late 1960s H. T. Odum introduced the concept of auxiliary energies to account for influences on ecosystems from sources other than sunlight and organic matter (Odum 1967). E. P. Odum (1971) provided a simple definition of auxiliary energies as follows:

“Any energy source that reduces the cost of internal self-maintenance of the ecosystem, and thereby increases the amount of other energy that can be converted to production, is called an auxiliary energy flow or an energy subsidy.”

Tidal and wave energy are probably the most widely recognized auxiliary energies (Steever et al. 1976, Leigh et al. 1987) but Nixon (1988) covers a variety of energies for aquatic ecosystems. Furthermore, humans have developed technologies to harness some of these auxiliary energies (i.e., wind, geothermal, etc.) as alternatives to fossil fuels for input to the economy (see Isaacs and Schmitt 1980 for a marine example).

The concept can be used to design microcosms by matching, as closely as possible, the energy signature of the natural analog system with the microcosm under controlled conditions of the laboratory or field setting. The most straightforward approach to this matching of energies is to develop the microcosm in the field where it is at least physically exposed to the same energy signature as natural ecosystems. Examples are the pond ecosystem commonly used in ecotoxicology and in situ plastic bags floated in pelagic systems such as limnocorals. The challenge of matching energies is greater in the lab. Significant effort is usually taken to match sunlight with artificial lighting whose intensity, spectral distribution and timing can be controlled fairly easily. Simulating other kinds of auxiliary energy sources in microcosms requires more ingenuity and often detailed engineering, as can be seen for example in the efforts to create realistic turbulence in pelagic microcosms (Sanford 1997).

Adley and Loveland (1998) have developed a systematic method for creating experimental aquatic systems that includes a focus on simulating energy signatures. The purpose of this paper is to analyze the energy signature of a mesocosm that has been shown to be a successful model of a real ecosystem (Lange et al. 1994, Adley et al. 1996). H. T. Odum’s (1996) emergy analysis method is used to compare energy signatures for the mesocosm and the real ecosystem in both actual energy and emergy units for full perspective.

SITE DESCRIPTION
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The Everglades mesocosm was built in 1987 as a prototype for one of the biomes that was contained in Biosphere 2 in Arizona. The system was closed in Fall 2000. It was located in a 30.5m (100’) x 12.2m (40’) greenhouse on the grounds of the Smithsonian Institution’s horticultural complex in Northeast Washington DC. The systems consisted of seven interlocking tanks, characterized by a gradient of habitats ranging from freshwater to saltwater (Figure 1). Detailed descriptions of the mesocosm are given by Adey and Loveland (1998), Lange et al. (1994) and Adey et al. (1996). Engineering was used to provide tides, waves, currents (with pumps), wind (with fans), temperature regimes (with water chillers in summer and heaters in winter), freshwater (with a sprinkler system and a reverse osmosis unit) and water quality management (with algal turf scrubbers). Biota was imported from southwest Florida to seed the system and partial census found 369 species in the system in 1994-1995 (Adey et al. 1996). Construction costs of the mesocosm were approximately 300,000$.

METHODS

H. T. Odum’s emergy analysis method was used to construct energy signatures for the Everglades mesocosm in Washington DC and for a comparable area of the real Everglades in southwest Florida. The energy signatures are shown in Figure 2. The emergy analysis method requires separate calculations for each energy source. Actual energies are either evaluated directly (ie., sunlight) or calculated based on formulas for physical energy flow (ie., tide, waves, etc.). Although actual energy units for different kinds of energy are the same, the energies differ in their ability to do work within ecosystems. Thus, a joule of sunlight can not do the same amount of work as compared to a joule of electricity. Both can generate the same amount of heat but they can not do the same amount of work, as in operating a pump to move water or a fan to generate wind. The emergy analysis method is an accounting system that was developed to convert actual energy units into work equivalent values that can be directly compared. This is done by multiplying actual energies by scaling factors, called transformities, that account for abilities of different kinds of energy to do work, rather than to generate heat. The calculated work equivalent values are in units of energy, or emjoules, which is the amount of one kind of energy required to make another kind of energy. A base energy type is used for relating the different kinds of energies and solar is most often used

![Figure 1: Plan view of the Everglades mesocosm in Washington, D.C.](image-url)
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as a convention. In this case the transformities have units of solar emjoules per joule of actual energy and, therefore, different energies are compared in terms of their equivalent solar emjoules. In this study the transformity values given by Odum (1996) were used to calculate emergy values for energy signatures.

An energy signature for the Everglades in southwest Florida was developed by review of the literature. This effort was aided by published energy signatures for nearby sites (DeBellevue et al. 1979, Odum 1974, Odum and Hornbeck 1997). Calculations were made for sunlight, tide, wind, rain and waves and these were scaled to the dimensions of the mesocosm so that direct comparisons could be made.

An energy signature for the Everglades mesocosm in Washington DC was developed based
on actual energies used to operate the system. Calculations were made for sunlight, labor, natural gas, electricity and tap water. Actual energy values for labor, natural gas and electricity were taken from the operating log of the mesocosm and water input was from Lange (1998).

RESULTS

Energy signature calculations for the Florida Everglades are shown in Table 1. Sunlight contributed nearly 100% of the total actual energy budget but less than 1% of the total emergy budget. Conversely, waves contributed less than 1% of the total actual energy budget but 87% of the total emergy budget. These results are not surprising since sunlight is a spatially extensive but dilute energy source that provides heating and triggers molecular reactions in photosynthesis. Wave energy on the other hand is spatially intensive and highly focused on the coastline that does work in shaping landforms. Another way to conceptualize this dichotomy is that sunlight acts as a general driving force for the ecosystem while wave energy and the other types act as auxiliary energies in providing specialized work functions. The second most significant emergy contribution came from chemical potential energy for rain. This energy plays a special role in maintaining salinity patterns which are important in organizing the estuarine ecosystems characteristic of the southwest Florida Everglades.

Energy signature calculations for the Everglades mesocosm in Washington DC are shown in Table 2. This is a very different energy signature which is dominated by high quality energies (i.e., high transformity) characteristic of human systems. These energy types are utilized through conventional engineering to reproduce the natural Everglades energy signature inside the mesocosm greenhouse. Natural gas is used in heating the greenhouse, electricity is used in a variety of ways, such as powering pumps and fans, to provide the internal tides, waves and wind, tap water from the municipal supply is used for maintaining water balances after treatment by reverse osmosis and human labor is used for overall system maintenance, like a top predator in ecosystem control. Sunlight provides about 50% of the total actual energy budget but its contribution to the total emergy budget approaches zero. Nearly equal contributions from natural gas and electricity dominate the emergy budget, which reflects their important roles in powering devices that create the temperature regimes along with water and air movements within the greenhouse.

DISCUSSION

Although mesocosms are commonly used for conducting ecological experiments (Odum 1984, Kangas and Adey 1996), there has been little formal analysis of principles for their design. The work presented here describes an energy signature design approach that can be applied to any experimental system. The principle states that to create an adequate experimental system, one must match the energy signature of the experimental system to the natural system being modelled. This is a challenge which requires various ecological engineering considerations (Adey and Loveland 1998).

For the case study of the Florida Everglades, the mesocosm utilized three orders of magnitude more emergy equivalents than the natural system being modelled (1.39 x 10E17 vs. 1.32 x 10E14). The additional emergy for the mesocosm is needed to operate the engineering components that simulate the natural energy signature. Less emergy would have been required if the mesocosm had been physically built in south Florida rather than Washington DC, so that heating costs could have been minimized, but this probably would not have changed the difference in emergy totals by an order of magnitude, due to the large amounts of electricity utilized for purposes other than heating.

No similar comparison of energy signatures between an experimental system and the natural system being modelled seems to have been made. Beyers and Odum (1993) constructed an energy signature for the MERL (Microcosm Estuarine Research Laboratory) tanks used to model the pelagic system of Narragansett Bay, Rhode Island. Their study considered sunlight, turbulence and nutrient fluxes with both actual energy and emergy calculations. These mesocosms are open to the atmosphere without artificial heating so additional energy input was not needed for this purpose. Labor inputs and electricity for pumps
were not evaluated. No comparison was made for the natural bay energy signature though Nixon et al. (1980) had made some actual energy comparisons. Nelson et al. (1993) also provided a partial actual energy signature for Biosphere 2 with data on solar input and electricity for external support, heating and cooling, but no comparisons were made with natural systems that were being modelled.

The results of the energy signature comparison between the Everglades mesocosm and the real Everglades given in this report have implications for restoration ecology. The real Everglades has been dramatically altered by humans over the last century and large scale restoration is currently being attempted (Cohn 1994, Dahm et al. 1995, Gunderson et al. 1995). The cost to maintain the Everglades model in Washington DC was very large compared to the cost of maintaining the natural system in Florida. This magnitude of cost is a constraint on restoration and will limit efforts to artificially create habitat replacements. Lange et al. (1994) discussed this issue in terms of compensatory mitigation policies for wetlands, suggesting that the Everglades mesocosm represents a particularly high energy example of restoration. Thus, one indirect implication of this study is that calculations of the energy cost of replacement model systems can serve to illustrate the high value of intact, natural ecosystems. Cost effective approaches are needed to restore quality and quantity of water flows and many other aspects of the system.

### Table 1. Energy signature evaluation for the Everglades in Southwest Florida for an area equivalent to the Everglades Mesocosm.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Energy (E8 J/year)</th>
<th>Transformity (sej/J)</th>
<th>Emergy (E12 sej/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun (1)</td>
<td>26000</td>
<td>1</td>
<td>2.6</td>
</tr>
<tr>
<td>Wind (2)</td>
<td>3.6</td>
<td>1496</td>
<td>0.5</td>
</tr>
<tr>
<td>Tide (3)</td>
<td>2.1</td>
<td>16842</td>
<td>3.5</td>
</tr>
<tr>
<td>Rain (4)</td>
<td>6.1</td>
<td>18199</td>
<td>11.1</td>
</tr>
<tr>
<td>Waves (5)</td>
<td>37.5</td>
<td>30550</td>
<td>115</td>
</tr>
<tr>
<td>TOTAL</td>
<td>26049.3</td>
<td></td>
<td>132.7</td>
</tr>
</tbody>
</table>

1) Average solar insolation for south Florida is approximately 7.00 x 10E9 J/m2/yr. (E. P. Odum 1971). Total solar energy is (7.00 x 10E9 J/m2/yr)(372.1 m2).
2) Wind energy = (0.5)(density of air)(wind velocity^2)(eddy diffusion coefficient)(height of boundary layer). Density = 1.2 x 10E-3 g/cm3. Wind velocity = 378.3 cm/sec (Ruttenber 1979). Eddy diffusion coefficient = 1 x 10E4 cm2/sec (Kemp 1977). Height of boundary layer = 1 x 10E4 cm). Area affected = 130.5 m2.
5) Wave energy = (shore length)(1/8)(density of water)(gravitational acceleration)(wave height^2)(velocity) from Odum (1996). Shore length = 3.1 m. Density = 1000 kg/m3. Gravitational acceleration = 9.8 m/sec2. Wave height = 0.1 m (assumed). Velocity = (gravity x depth)^1/2, where depth = 1 m (assumed).
<table>
<thead>
<tr>
<th>Energy</th>
<th>Energy (E8 J/year)</th>
<th>Transformity (sej/J)</th>
<th>Emergy (E12 sej/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun (1)</td>
<td>20500</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>Tap Water (2)</td>
<td>2.5</td>
<td>18199</td>
<td>4.5</td>
</tr>
<tr>
<td>Labor (3)</td>
<td>——</td>
<td>——</td>
<td>4050</td>
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<td>Electricity (4)</td>
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<td>174000</td>
<td>58300</td>
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<tr>
<td>Gas (5)</td>
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<td>48000</td>
<td>76800</td>
</tr>
<tr>
<td>TOTAL</td>
<td>39852.5</td>
<td></td>
<td>139156.6</td>
</tr>
</tbody>
</table>

1) Average insolation for Washington, DC is approximately 5.50 x 10E9 J/m2/yr. (E. P. Odum 1971). Total solar energy is (5.50 x 10E9 J/m2/yr.)(372.1 m2).
3) Labor requirements for the mesocosm were 20 hours/week or 43.33 days/yr. multiplied by the Emergy use/person of 9.35 x 10E13 sej/day (Odum 1996).
4) Based on power consumption and operational times of of all pumps, heaters, fans, etc., the total electrical use was 3.35 x 10E11 Joules/yr. in the mesocosm.
5) Based on power consumption and operational time of gas heaters, the total gas use was 1.60 x 10E12 Joules/yr. in the mesocosm.

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