# Handbook of Emergy Evaluation

A Compendium of Data for Emergy Computation
Issued in a Series of Folios

## *Folio #3*
## *Emergy of Ecosystems*

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July 2001

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# PREFACE

Handbook of Emergy Evaluation

Emergy spelled with an “m” is a universal measure of real wealth of the work of nature and society made on a common basis. Calculations of emergy production and storage provide a basis for making choices about environment and economy following the general public policy to maximize real wealth, production and use (maximum empower). To aid evaluations, this series of folios provides data on emergy contents and the computations on which they were based. A series of Folios are to be issued. Folio #1 : Introduction and Global Budget, introduces the series and evaluates the empower of the geobiosphere. Folio # 2: Emergy of Global Processes presents calculations and transformities for global processes of atmospheric, geologic and oceanic systems.

There may be folios by many authors, who take the initiative to make new calculations or assemble results from the extensive but dispersed literature. Data on emergy content are in published papers, books, reports, theses, dissertations, and unpublished manuscripts. Tabulating unit emergy values and their basis is the main purpose of the folio series. Presentations document the sources of data and calculations. As received, Folios will go to reviewers, back to authors for revision and back for publication. Each will have an index to indicate the page where emergy is evaluated. Each Folio should be usable without reference to other folios.

**Policy on Literature Review and Consistency**

Folios are based on emergy evaluations assembled from various reports and published literature plus new tables prepared by folio authors. Our policy is to present previous calculations with due credit and without change except those requested by original authors. This means that unit emergy values in some tables may be different from those in other tables. Some tables may be more complete than others. No attempt is made to make all the tables consistent. Explanatory footnotes are retained. The diversity of efforts and authors enriches the information available to users, who can make changes and recalculate as they deem desirable to be more complete, update, or otherwise revise for their purposes.

The increase in global emergy base of reference to 15.83 E24 sej/yr (Folios #1 and #2) changes all the unit emergy values which directly and indirectly are derived from the value of global annual empower. All emergy values in this folio were calculated using the older empower base (9.44 E24 sej/yr). To convert emergy and transformities in this folio to the newer base, multiply values by 1.68.

— Howard T. Odum and Mark T. Brown

## INTRODUCTION TO FOLIO # 3

Folio #3 presents 21 emergy evaluations of ecosystems from Florida, Ecuador, Mexico, Sweden, Arizona and North Carolina. Many are forest systems. Some have significant inputs of human services and purchased fuels and goods. Two are "microcosms" (a sealed window-sill aquarium and the Biosphere II in Arizona). Empower densities are assembled in Table 1 and transformities in Table 2.

### General Comments Pertaining to Ecosystem Evaluations

The following ecosystem evaluations are from a wide variety of sources dating from the mid-1980's to 2001, and from a wide variety of spatial scales from the scale of an windowsill aquarium, to that of the Sea of Cortex, Mexico. The main inputs to each system are evaluated, but are not added to avoid double counting the global energies that are required to produce the renewable emergy inputs. For instance, if an area of ecosystem has inputs of sunlight, wind, rain, and tidal energies, the emergy of each of these sources is not added together to determine the total emergy driving the ecosystem, since all these source inputs to the ecosystem result from parallel processing of the global emergy driving the biosphere. Each of these inputs to the ecosystem contain the same global sources (since they are parallel processes) and if added together, would double count the global emergy required to produce them. When a system has non-renewable input, they are summed to calculate total emergy.

In practice, while each of the main renewable driving emergy inputs are evaluated, only the largest emergy input is used when evaluating total empower. However, if the inputs are from very different time scales, they can be added together. For instance, the sediment input to a floodplain forest results from eroded sediments that were produced with emergy in the past, while the inputs of sunlight, rain, and wind are the result of current global emergy inputs. Evaluating all driving energies provides information regarding the emergy signature of ecosystems, a way of classifying and comparing systems (Tilley 1999).

Here ecosystems are calculated on a yearly basis, and empower (emergy per unit time) is expressed as emergy used per year. Input emergy to an ecosystem that contributes to ecosystem process and products is the emergy that is used. The evaluations that follow, for the most part, consider inputs based on use. If an emergy input flows through a system and is only partially used, the entire input is not counted. Instead, only that portion of the input that is used contributes to the system. For instance, the emergy input of rain that contributes to an ecosystem's productivity is the rain that is transpired rather than the total rain falling on the ecosystem. Some rainfall runs off and some recharges groundwater beyond the chosen boundary.

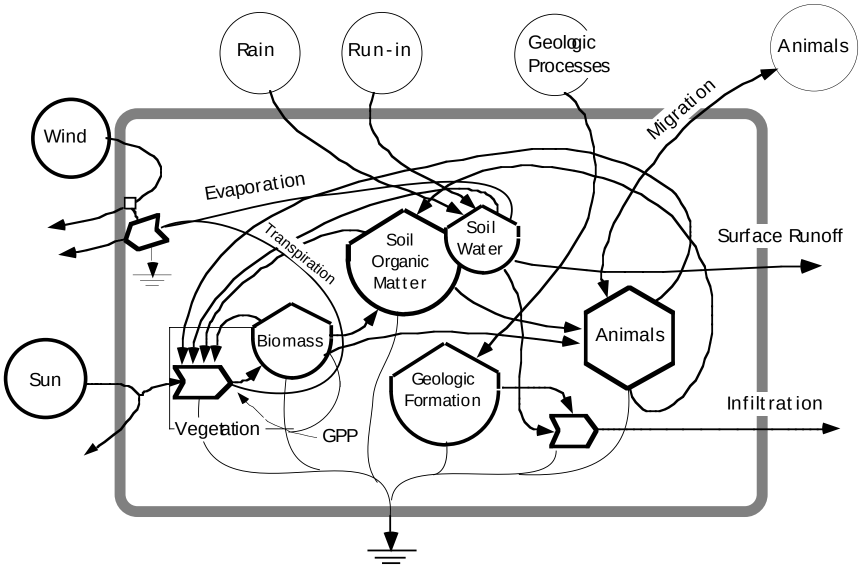

***Figure 1.** Generic ecosystem diagram showing the main inputs, outputs and compartments evaluated in the ecosystem evaluations that follow. Not all compartments are evalauted in each ecosystem*

In the evaluations that follow, most often the largest driving source is rainfall that is used by the ecosystem. For most ecosystems the portion of the rain transpired is evaluated as contributing to the ecosystem processes. In some cases, when rain is converged (lakes or estuaries) the entire input of rainwater is used. In these systems the rain is contributing to processes other than primary production. Figure 1 is a generic ecosystems diagram that shows the main driving energies, including rainfall and run-in as well the main components and processes.

Several of the ecosystems evaluated included calculation of transformities (emergy per available energy). The methods employed differ and the notes to the calculations should be consulted.

## SUMMARY OF ECOSYSTEM EVALUATIONS

Table 1 provides a summary of the empower of the ecosystems included in this folio arranged by system type and by their respective empower densities. Also included in the table is the area basis for the emergy evaluation of the ecosystem.

In most cases the evaluations were conducted for 1 hectare, although the larger watershed systems and the microcosms were evaluated using their respective areas. Empower is expressed as emergy per square meter per year (sej/m2 /yr). Renewable empower density and nonrenewable empower density for those ecosystems that had nonrenewable inputs are given in the table. Comparisons of empower density show the increasing convergence of landscape energies that result from landscape position and scale. Renewable empower density is lowest for the very small microcosm and the Biosphere II systems, and highest for the lake ecosystems reflecting the convergence of watershed emergy. Terrestrial ecosystems have renewable empower densities in the range of about 40-50 E9 sej/m2 yr-1. Wetlands have empower densities about one order of magnitude higher, while lake and estuarine ecosystems have one order of magnitude higher than wetlands.

Table 2 summarizes transformities and emergy per mass drawn from each of the tables.

### Emergy Evaluations of “Microcosms”

Two microcosms are included in this folio. Given in Tables 3 and 4 are emergy evaluations of a windowsill aquarium and the Biosphere II (Leigh, 1999). The purchased and non-renewable inputs dominate the total emergy requirements. Consider that these data represent the setup phase and so the implementation costs are not averaged over the life of the system. However, even if we assume a 50 year life of both systems, non-renewable inputs are still, by far, the greatest input — in essence dwarfing the renewable inputs.

### Forest Production Ecosystems

Three forest production ecosystems are given in Tables 5, 6, and 7 (Doherty 1995). The intensity of non-renewable inputs to the Melaleuca spp. plantation system is about 4 times that for slash pine (both are in Florida) and nearly 10 times the intensity of the Boreal Spruce Forest in Sweden. The obvious difference is in the silvicultural operation including site preparation and establishment.

### Landscape Scale Ecosystems Including Humans

Tables 8, 9 and 10 are evaluations of large scale systems, more appropriately considered landscape ecosystems. Included in the inputs to these system are both renewable basis for natural production and the non-renewable inputs supporting human developed areas. The evaluation of the Sea of Cortez (Brown, Tennenbaum, and Odum 1991) includes the areas within the coastal zone (within 1 kilometer of the coast), so there are many human settlements within this area. The inputs of non-renewables were evaluated by using per capita averages and then multiplying by population within the coastal zone. The temperate forest watershed in North Carolina (Tilley,1999) includes areas for tourism and scientific research. The non-renewables that support these activities were included in the evaluations. Finally the Florida estuary (Irvin, 2000) included urban areas and tourism and the nonrenewable inputs that support these activities.

**Aquaculture Systems**

The two aquaculture systems (Tables 11 and 12) have very different renewable inputs. The shrimp maricultural system in Ecuador (Odum and Arding, 1991)assumed shrimp larvae as a renewable input, while the Tilapia system in Mexico (Brown et. al, 1992) purchased fingerlings and therefore they were considered a purchased input. The Tilapia system was about two times as intensive as the shrimp systems. The majority of this difference resulted from the large differences in purchased inputs.

**Forest Ecosystems**

Forest ecosystems in Venezuela, a dry savannah with scrubby forest, (Prado-Jutar and Brown 1997) and Florida (mixed hardwood and pine flatwoods systems[Orrell, 1998] ) are given in Tables 13, 14, 15. Renewable emergy inputs are very similar in all three systems. Transformities were calculated for NPP and GPP for each of the systems.

**Wetland Ecosystem**s

Six wetland ecosystems were evaluated (Tables 16 – 21), including salt water mangroves in Ecuador (Odum and Arding, 1991)and forested wetlands in depressions in Florida (Weber, 1996 and Bardi and Brown, 2001). Emergy inputs to the wetland ecosystems include water used, sediments, and geologic emergy that form the wetland basin structure. On average, the wetland systems had about one order of magnitude higher renewable emergy than the emergy inputs to the forest systems in Tables 13-15.

**Lake Ecosystems**

The lake systems evaluated (Tables 22 and 23) were both in Florida. Lake Okeechobee (Odum, 2001) is in south Florida and has been the subject of much research over the past several decades because of its special significance in the Everglades system and public water supply. Newnans Lake (Brandt-Williams, 2000) is much smaller and is located in north central Florida. The evaluations of both lakes include emergy inputs from rain as well as runoff from their respective watersheds. By and large, the emergy inputs from their watersheds dominate and increase their total emergy so that inputs per unit area are about two orders of magnitude higher than those characteristic for terrestrial forested ecosystems.

**Table 1.** Summary of ecosystems empower density

| Ecosystem Type | Table # | Renewable Empower Density E 9 sej/m2*yr-1 | Nonrenewable Empower Density E 9 sej/m2*yr-1 |
|---|---|---|---|
| **Microcosms** | | | |
| Aquatic Microcosm (Florida) | 3 | 3 | 473098 |
| Biosphere II , Rainforest (Arizona) | 4 | 3 | 2145296 |
| **Foresty Production Ecosystems** | | | |
| Borreal Spruce Forest (Sweden) | 5 | 36 | 23 |
| Slash Pine Forestry Plantation (Florida) | 6 | 93 | 51 |
| Melaleuca spp. Fuelwood Plantation (Florida) | 7 | 93 | 240 |
| **Landscape scale ecosystems including humans** | | | |
| Sea of Cortez. (Mexico) | 8 | 31 | 16 |
| Montane Forest Watershed (North Carolina) | 9 | 176 | 246 |
| Estuary (Florida) | 10 | 305 | 226 |
| **Aquaculture systems** | | | |
| Tilapia (Mexico) | 11 | 246 | 8046 |
| Shrimp Mariculture (Ecuador) | 12 | 928 | 3188 |
| **Forest ecosystems** | | | |
| Dry Savannah (Venezuela) | 13 | 45 | NA |
| Mixed hardwood forest (Florida) | 14 | 47 | NA |
| Pine Flatwood (Florida) | 15 | 47 | NA |
| **Wetland ecosystems** | | | |
| Mangrove forest (Ecuador) | 16 | 149 | NA |
| Forested Wetland (Florida) | 17 | 224 | NA |
| Everglades Sawgrass Marsh (Florida) | 18 | 310 | NA |
| Depressional Herbaceous wetland (Florida) | 19 | 369 | NA |
| Depressional Shrub-scrub wetland (Florida) | 20 | 446 | NA |
| Depressional Forested Wetland (Florida) | 21 | 649 | NA |
| **Lake ecosystems** | | | |
| Lake Okeechobee (Florida) | 22 | 1114 | NA |
| Newnans Lake (Florida) | 23 | 3488 | NA |

NA = Not applicable

**Table 2**. Summary of transformities and Emergy per unit

| System & Item | Emergy per unit* sej/unit | Table # |
|---|---|---|
| Boreal silviculture (Spruce and pine) | | |
| Above ground production | 4, 930 sej/J | 5 |
| Harvested biomass | 10, 100 sej/J | 5 |
| Subtropical silviculture (Slashpine) | | |
| Above ground production | 5, 830 sej/J | 6 |
| Harvested biomass | 21,500 sej/J | 6 |
| Subtropical fuelwood plantation (*Eucalyptus* spp. & *Melaleuca* spp.) | | |
| Above ground production | 11,300 sej/J | 7 |
| Harvested biomass | 16, 100 sej/J | 7 |
| Temperate forest watershed (oak/ | | |
| NPP, total live biomass | 4, 700 sej/J | 9 |
| Wood accumulation | 16, 000 sej/J | 9 |
| Litterfall | 15, 000 sej/J | 9 |
| Rock weathering | 3.8 E9 sej/g | 9 |
| Tree diversity | 3.3 E 13 sej/species | 9 |
| Stream discharge (chem. pot.) | 32, 000 sej/J | 9 |
| Stream discharge (geo. pot.) | 18, 000 sej/J | 9 |
| Stream discharge (mass) | 160, 000 sej/g | 9 |
| Timber w/out service | 30, 000 sej/J | 9 |
| Timber with service | 70, 000 sej/J | 9 |
| Tropical brackish water tilapia aquaculture | | |
| Tilapia Yield | 561, 000 sej/J | 11 |
| Tropical shrimp mariculture | | |
| Shrimp yield | 4.0 E6 - 18.9 E6 sej/J | 12 |
| Tropical dry savanna | | |
| NPP of savanna vegetation | 9, 960 sej/J | 13 |
| GPP of savanna vegetation | 1, 880 sej/J | 13 |
| Savanna biomass | 10, 500 sej/J | 13 |
| Subtropical mixed hardwood forest (Oak/gum/magnolia/pine) | | |
| Biomass | 5, 500 sej/J | 14 |
| Soil moisture | 41, 000 sej/J | 14 |
| Soil organic matter | 11, 400 sej/J | 14 |
| Tree species richness | 1.1 E19 sej/spec. | 14 |

**Table 2** (continued)

| System & Item | Emergy per unit sej/unit | | Table # |
|---|---|---|---|
| Net production | 1, 540 | sej/J | 14 |
| Respiration | 1, 020 | sej/J | 14 |
| Gross production | 615 | sej/J | 14 |
| Subtropical pine flatwood ecosystem | | | |
| Biomass | 10, 700 | sej/J | 15 |
| Soil moisture | 41, 000 | sej/J | 15 |
| Soil organic matter | 13, 500 | sej/J | 15 |
| Tree species richness | 1.1 E19 | sej/spec. | 15 |
| Net production | 1, 690 | sej/J | 15 |
| Respiration | 1,130 | sej/J | 15 |
| Gross production | 676 | sej/J | 15 |
| Tropical mangrove ecosystem | | | |
| Biomass growth | 14,700 | sej/J | 16 |
| Litterfall | 13,300 | sej/J | 16 |
| Southern floodplain forest (Cypress dominated) | | | |
| Tree seeds | 4.7 E9 | sej/g | 17 |
| Gross primary production | 5,460 | sej/J | 17 |
| Subtropical herbaceous wetland | | | |
| Transpiration (water use ) | 26, 900 | sej/J | 19 |
| Gross primary production | 4, 320 | sej/J | 19 |
| Infiltration | 26, 900 | sej/J | 19 |
| Live Biomass | 73, 400 | sej/J | 19 |
| Peat | 184, 000 | sej/J | 19 |
| Water (avg. stored) | 26, 900 | sej/J | 19 |
| Basin Structure | 1.0 E12 | sej/J | 19 |
| Subtropical shrub-scrub wetland (titi and willow dominated) | | | |
| Transpiration (water use ) | 26, 900 | sej/J | 20 |
| Gross primary production | 4, 260 | sej/J | 20 |
| Infiltration | 26, 900 | sej/J | 20 |
| Live Biomass | 69, 100 | sej/J | 20 |
| Peat | 171, 000 | sej/J | 20 |
| Water (avg. stored) | 26, 900 | sej/J | 20 |
| Basin Structure | 7.9 E11 | sej/J | 20 |

**Table 2** (continued)

| System & Item | Emergy per unit sej/unit | | Table # |
|---|---|---|---|
| Subtropical depressional forested wetland (cypress dominated) | | | |
| Transpiration (water use) | 26, 100 | sej/J | 21 |
| Gross primary production | 4, 200 | sej/ | 21 |
| Infiltration | 26, 100 | sej/J | 21 |
| Live Biomass | 73, 200 | sej/J | 21 |
| Peat | 150, 00 | sej/J | 21 |
| Water (avg. stored) | 26, 100 | sej/J | 21 |
| Basin Structure | 4.7 E11 | sej/J | 21 |
| | | | |
| Subtropical freshwater lake (Lake Okeechobee) | | | |
| Net organic sediment | 32, 100 | sej/J | 22 |
| Consumer. production | 156, 000 | sej/J | 22 |
| Base fish production | 1.0 E7 | sej/J | 22 |
| Game fish production | 2.0 E8 | sej/J | 22 |
| | | | |
| Subtropical freshwater lake (Newnans Lake) | | | |
| Phytoplankton | 6.6 E12 | sej/g | 23 |
| TP in water column | 2.9 E13 | sej/g | 23 |
| Water | 6.2 E5 | sej/J | 23 |

* many of the original authors published results containing more than 3 significant figures. In this summary table we have rounded transformities and emergy per unit to 3 significant figures.

**Table 3.** Emergy requirements to build and maintain a windowsill aquatic microcosm for 1 year

| Note | Item Name | Data | Units | Emergy/ unit sej/unit | Emergy E9 sej |
|---|---|---|---|---|---|
| | Renewable Flux | | | | |
| 1 | Sunlight | 2.00E+09 | J/yr | 1 | 2.0 |
| | Other Environmental inputs | | | | |
| 2 | Water | 30750 | g | 72800 | 2.2 |
| 3 | Plants | 3662750 | J | 1.00E+04 | 36.6 |
| 4 | Sediment | 7500 | g | 1.00E+09 | 7500.0 |
| | Purchased goods | | | | |
| 5 | Glass | 3901 | g | 1.60E+09 | 6242.3 |
| 6 | Plastic | 952 | g | 3.20E+09 | 3046.4 |
| 7 | Human Service (purchased) | 13 | $ | 1.00E+12 | 13000.0 |
| 8 | Human Service (construction) | 8.37E+05 | J | 3.43E+08 | 287148.1 |

1 Sunlight

1.58E6 kcal/m2/yr. Assume 10% albedio, 50% incident light, and 0.67 $m^2$ surface area

energy = (1.58 E6 kcal/m2/yr) (1-10%) (0.67m2)(0.5) (4186 J/kcal)
= 2.0E+09J
Transformity= 1 sej/J (Odum 1996)

2 Water

Total volume= 1.45 ft3 = 4.1 E4 cm3 density of water 1 g/ cm3
aquarium 3/4 full
= (4.1 E4 cm3) (1 g/cm3) ( 0.75)
= 30750g
Transformity = 72800 (per gram rainwater… Odum, 1996)

3 Plants

included appoximately 250 gramsdry wt. of plant material (hydrilla)
energy = (250 g) ( 3.5 kcal/g) ( 418d J/kcal)
= 3662750J
Transformity= 1 E 4 sej/J (avg plant matter…Odum 1996)

4 Sediment

sediment harvested from stream bottom = 5000 cm3 and 1.5 g/cm3
= (5000 cm3) ( 1.5 g/cm3)
= 7500g
Transformity= 1.0 E 9 sej/J (Odum, 1996)

5 Glass

aqurium glass = 4800 cm2, 0.3175 cm thick and 2.56 g/cm3
= (4800cm2) ( 0.375 cm) (2.56 g/cm3)
= 3901.44g
Transformity= 1.6 E6 sej/g (w/out service…Buranakarn, 1998)

6 Plastic

aquarium contain 1700 cm3 plastic at 0.56g/cm3

= (1700 cm3) ( 0.56 g/cm3)

= 952g

Transformity = 3.2 E6 sej/g (w/out service…Buranakarn, 1998)

7 Service in purchased goods

service = $13.00

Transformity= 1 E12 sej/ $ (estimated from Odum, 1996)

8 Human service in construction

microcosum required 2 hours to collect materials and set up; assume 2400 kcal/day

energy = (2400 Kcal/day) ( 0.083 da) (4186 J/kcal)

= 837166.512J

Transformity= 3.43 E8 sej/J (Odum, 1996)

**Table 4**. Accumulated emergy inputs to Biosphere 2 rainforest for start-up of the system prior to material closure in 1991. (Leigh, 1999)

| Note | Item | Data & Units | Emergy/Unit sej/unit | Solar Emergy E13 sej |
|---|---|---|---|---|
| Environmental Sources | | | | |
| 1 | Sun | 5.66 E12J | 1 sej/J | 0.566 |
| 2 | Wind | 1.75 E14J | 1.5 E3 sej/J | 26,300 |
| Ecosystem Components | | | | |
| 3 | Plants at closure | 4.18 E10J | 1.63 E7 sej/J | 68,134 |
| 4 | Plant collection | 6.0 ES $ | 1.64 E12 sej/$ | 98,400 |
| 5 | Soil, mineral fraction | 4.78 E9 g | 1.0 E9 sej/g | 47,762 |
| 6 | Soil, organic fraction | 1.32 E12 J | 7.4 E4 sej/J | 9,768 |
| Design, construction and operations | | | | |
| 7 | Design and construction | 22.5 E6 $ | 1.64 E12 sej/$ | 3,690,000 |
| 8 | Electricity | 5.4 E13J | 2.0 E5 | 1,080,000 |

Notes.

Rainforest is approx. 15% (1900 $m^2$/12,766 $m^2$) of the total surface area and 17% (34,690 $m^3$/204,000 $m^3$) of the total volume of Biosphere 2. Transformity values from Odum (1996).

Environmental Sources

1 Sun

Average outside insolation for Tuxson is 5200 kcal/$m^2$/day (Romer 1985). Approximately 50% of the outside light enters the Biosphere and approximately 50% of the sun was intercepted by plant biomass. The rainforest biome is 1900 $m^2$. Planting began about 1.5 years before the 1991 closure.

(5200 kcal/$m^2$/day)(.5)(.5))(1900 $m^2$)(1.5 years)(365 days/yr)(4184 J/kcal)= **5.66 E12 J**

2 Wind

Wind contributed 3.37 E14 J/yr of kinetic energy for evaporative water cooling external to the Biosphere (SBV data cited in Engel 1994). Cooling began in Sept. 1989. Wind energy assumed to have been contributed in proportion to volume. Solar transformity for wind from Odum (1996).

(3.37 E14 J/yr)(2 yrs)(.26) = **1.75 E14 J**

Ecosystems Components

3 Rainforest plants

Biomass at closure was approximately 2500 kg dry weight (Bierner (1994) estimate for July, 1991).

(2500 kg*1000 g/kg)(4 kcal/gm)(4184 J/kcal) = **4.18 E10 J**

4 Plant collection

Emergy/money ratio for 1986-1991. The cost of collections, including labor, transportation, and permits, was approximately $600,000. Average $/sej ratio for the years 1987-1991 is 1.64 E12 sej/$ (Odum 1996).

5 Soil, organic fraction

Transformity of topsoil organic matter = 7.4 E4 sej/J (Odum 1996). Average organic matter content of topsoil is 3% (Scott 1999). Total amount of topsoil in rainforest is 1766 cubic meters. Avg. bulk density of topsoil = 1.1 g/cm$^3$.

(.03)(1766 E6 cm$^3$)(1,1 g/cm$^3$)(5.4 kcal/g)(4184 J/kcal) = **1.32 E12 J**

6 Soil, mineral fraction

Solar transformity for world sedimentary cycle is 1.0 E9 sej/g (Odum 1996). Bulk density for subsoil is 1.43 g/cm$^3$ and for topsoil = 1.1 g/cm$^3$ (Scott 1999). Volume of subsoil is 3340 cubic meters and for topsoil is 1766 cubic meters (Scarborough 1994). Mineral fraction of topsoil is 97%.

(3340 E6 cm$^3$)(1.43 g/cm$^3$) + (0.97)(1.1 g/cm$^3$)(1766 E6 cm$^3$) = **4.78 E9 g**

Design, construction and operations

7 Overall design, construction and operation prior to 1991 closure

Total cost for Biosphere 2 of design, construction and operation prior to 1991 closure was $150,000,000 (SBV, personal communication). The rainforest surface area is approx. 15% of the total Biosphere 2 area. Average $/sej ratio for the years 1987-1991 is 1.64 E12 sej/$ (Odum 1996).

($150 E6)(.15)(1.64 E12 sej/$) = **3.69 E19 sej**

8 Electricity

Electrical consumption for Biosphere 2 is approximately 5 E6 kWh/yr. The energy center was supporting the Biosphere for 3 years prior to closure in 1991.

(5 E6 kWh/yr)(3.6 E6 J/kWh)(3 yrs) = **5.4 E13 J**

**Table 5.** Emergy evaluation of boreal spruce (Picea aibes) and pine (Pinus silvestris) silvicultural production and timber extraction under 80 year rotation schedules in southern Sweden. (Doherty, 1995)

| Note | Item | Resource units/ha/yr (J,g,$) | Solar emergy per unit[b] | Solar emergy flow E+12 sej/ha*$yr^{-1}$ |
|---|---|---|---|---|
| I | Environmental sources: | | | |
| | 1. Sunlight | 2.57 E13 J | 1 | 25.7 |
| | 2. Wind, kinetic | 8.73 E10 J | 1500 | 130.9 |
| | 3. Evapo-transpired rain | 1.95 E10 J | 18200 | 355.1 |
| F1 | Silviculture: | | | |
| | 4. Motor fuel | 5.59 E7 J | 47900 | 2.7 |
| | 5. Tractors, trucks | 66 g | 6.70 E9 | 0.4 |
| | 6. Human services | 18.70 $ | 1.50 E12 | 28.1 |
| $Y_1$ | Above ground production (3.82 tons/ha/yr) | 7.84 E10 J | $ST_1$ | 386.3 |
| F2 | Harvesting: | | | |
| | 7. Motor fuel | 5.97 E8 J | 47900 | 28.6 |
| | 8. Feller, forwarder | 188 g | 6.70 E9 | 1.3 |
| | 9. Human services | 101.26 $ | 1.50 E12 | 151.9 |
| | 10. Capital investment | 14.44 $ | 1.50 E12 | 21.7 |
| Y2 | Harvested biomass (2.85 tons/ha/yr) | 5.85 E10 J | $ST_2$ | 589.7 |

Summary of measurements:

Solar Transformity:

| | | |
|---|---|---|
| ST1 | Above ground production | 4928 sej/J |
| ST2 | Harvested biomass | 10,083 sej/J |

Emergy yield ratio:

| | | |
|---|---|---|
| YR1 | Above ground production | 12.39 |
| Yr2 | Harvested biomass | 2.51 |

Emergy investment ratio:

| | | |
|---|---|---|
| IR1 | Above ground production | 0.09 |
| IR2 | Harvested biomass | 0.66 |

a. Analysis based on average spruce/pine forest production of 8.989 m3/ha/yr, harvesting 74.6% of production (6.704 m3/ha/yr) in southern Sweden (based on an 80 year, steady state rotation) (Doherty et al. 1993)

b.Inputs calculated as available energy are multiplied by solar transformities (sej/J) to obtain solar emergy; inputs reported as mass use sej/g: monetary inputs use sej/$ for regional economy and year of production (Table 2 in Doherty 1995 unless cited otherwise in footnotes).

I  Environmental inputs:
1.  Solar energy = (area)(avg insolation)(1-albedo) = (10,000 m2/ha)(85.4 kcal/cm2/yr)(10,000 cm2/m2)(4186 J/kcal)(1-0.28) = 2.57 E13 J/ha/yr

2.  Wind, kinetic energy = (Vertical gradient of wind)2 (hgt of atmospheric boundary)(density of air)(eddy diffusion coefficient)(1 ha)(sec/yr) = [(3.0 m/s)/(1000 m)(1.23 kg/m3)(25m2/sec)(10,000 m2/ha)(3.154E+7 sec/yr) = 8.73 E10 J/ha/yr

3.  Rain, chemical potential energy = (area)(rainfall)(% evapotrans)(Gibbs free energy) = (10,000 m2/ha)(0.8l m)(0.49)(1000 kg/m3)(4.94E+3 J/kg) = 1.95 E10 J/ha/yr

| F1 | Inputs to silvicultural management: | fuel (liters/ha/yr) | machines (g/ha/yr) |
|---|---|---|---|
| | scarification: | 0.28 | 19 |
| | planting: | 0.04 | 3.5 |
| | stand regulation: | 0.35 | 8.8 |
| | ditching: | 0.52 | 3.4 |
| | roads: | 0.38 | 31.7 |
| | Total: | 1.57l/ha/yr | 66.4 g/ha/yr |

4.  Motor fuel = (1.57 liters/ha/yr)(35.6 E6 J/l) = 5.59 E7 J/ha/yr

5.  Machinergy depreciation [given as%wgt (g)] = (0.1 operating hrs/ha/yr)/(15,000 hrs useful life)(10 ton trucks, tractors)(1 E6 g/ton) = 66.4 g/ha/yr

6.  Human services (total cost of production) = 13.52 SEK/m3)(9.989 m3/ha/yr)(6.50 SEK/$US, 1988)  = 18.70 $/ha/yr

Y1  Above ground production = (9.0 m3/ha/yr)(0.425 E+6 g/m3)(2.052 E4J/g) = 7.84E+10 J/ha/yr

F2 Harvesting:

7.  Motor fuels = (2.5 l/m3)(6.704 m3/ha/yr)(35.6 E6 J/liter) = 5.97 E8 J/ha/yr

8.  Feller and forwarder depreciation [given as %wgt (g)]: (0.07 operating hrs/m3) / 15,000 hrs useful life)(6 tons)(1 E6 g/ton)(6.704 m3/ha/yr)
= 187.71 g/ha/yr

9.  Human services = [(Direct costs 85.6 SEK/m3) - (silv. Prod. Costs 13.5 SEK/m3)] + indirect costs 12.1 SEK/m3) + (depreciation 14.0 SEK/m3) = (98.2 SEK/m3)(6.7 m3/ha/yr)/(6.5 SEK/$US, 1988)
= 101.26 $/ha/yr

10.  Capital cost of machines = (6.7 m3//ha/yr harvest)(0.07 hrs/m3)(0.47 hrs/ha/yr)(200.0 SEK/hr capital costs) = (93.9 SEK/ha/yr)/(6.50 SEK/$US, 1988)
= 14.44 $/ha/yr

Y2 Harvested biomass: (harvested stemwood, 5.6 m3/ha/yr + 1/2 of logging residues, 1.12 m3/ha/yr) =6.7 m3/ha/yr (0.425 E+6 g/m3)(2.052 E4 J/g)
= 5.85 E10 J/ha/yr

Summary of measurements:

I Item 1 = 355.14 E12 sej/ha/yr
F1 Items 4+5+6 = 31.17 E12 sej/ha/yr
F2 Items 7+8+9+10 = 203.50 E12 sej/ha/yr
Y1 I+F1 = 386.30 E12 sej/ha/yr
Y2 I+F1+F2 = 589.70 E12 sej/ha/yr

Solar transformities = Y1 (sej/ha/yr) / Y1 (J/ha/yr)
ST1 Above ground production = (386.30 E12 sej/ha/yr) / (7/84 E10 J/ha/yr)= 4928 sej/J
ST2 Harvested biomass = (5.65 E14 sej/ha/yr) / (5.85 E10 J/ha/yr) = 10,083 sej/J

Emergy yield ratio = Y1 / (F1+ …F1):
YR1 Above ground prod. = (386.30 E12 sej/ha/yr) / (31.17 E12 sej/ha/yr) = 12.39
YR2 Harvested biomass = (589.70 E12 sej/ha/yr) / 210.24 E12 sej/ha/yr = 2.51

Emergy investment ratio = (F1 + …F1) / I
IR1 Above ground production = (31.17 E12 sej/hayr) / (355.1 E12 sej/ha/yr) = 0.09
IR2 Harvested biomass = (31.17 + 203.50) E12 sej/ha/yr / (355.1 E12 sej/ha/yr) = 0.66

**Table 6.** Emergy evaluation of slash pine (*Pinus elliotti*) silvicultural production and timber extraction under 25 year rotation schedules in north Florida. (Doherty, 1995)

| Note | Item | Resource units ha yr (J. g. S) | | Solar emergy per unit[a] | Solar emergy flow E12 sej/ha*yr$^{-1}$ |
|---|---|---|---|---|---|
| I | Environmental sources: | | | | |
| 1. | Sunlight | 8.09 E13 | J | 1 | 70.9 |
| 2. | Rain, transpired | 5.09 E10 | J | 18200 | 926.1 |
| 3. | Soil organic matter | 1.36 E8 | J | 74000 | 10.1 |
| $F_1$ | Silviculture: | | | | |
| 4. | Phosphorus | 1910 | g | 2.0 E10 | 38.2 |
| 5. | Human services | 50.53 | $ | 1.60 E12 | 80.9 |
| $Y_1$ | Above ground Production (9.6 tons/ha/yr) | 1.81 E11 | J | $ST_1$ | 1055.3 |
| $F_2$ | Harvesting: | | | | |
| 6. | Diesel fuel | 4.45 E9 | J | 47900 | 213.0 |
| 7. | Labor | 1.56 E7 | J | 1.09 E7 | 170.5 |
| 8. | Capital costs | 7.90 | $ | 1.60 E12 | 12.6 |
| $Y_2$ | Harvested biomass (3.6 tons/ha/yr) | 6.73 10 | J | $ST_2$ | 1451.4 |

Summary of measurements:

| | | | |
|---|---|---|---|
| Solar transformity: | | | |
| $ST_1$ | Above ground production | 5829 | sej/J |
| $ST_2$ | Harvested biomass | 21.543 | sej/J |
| Emergy yield ratio: | | | |
| $YR_1$ | Above ground production | 8.86 | |
| $YR_2$ | Harvested biomass | 2.82 | |
| Emergy investment ratio: | | | |
| $IR_1$ | Above ground production | 0.13 | |
| $IR_2$ | Harvested biomass | 0.55 | |

Notes.

a. Inputs calculated as avilable energy are multiplied by solar transformities (sej/J) to obtain solar emergy; inputs reported mass use use sej/g; monetary inputs use sej/$ for regional economy and year of production .

I Environmental sources:

1. Solar energy = 7092 MJ/m$^2$/yr (Ewel 1991) = 7.09 E13 J/ha/yr

2. Rain, chemical potential energy = 1320 mm/yr rainfall (NOAA 1982); 1030 mm/yr actual evapotranspiration (Cropper and Ewel 1983); (area) (ET) (Gibbs free

energy) = (1,000 m$^2$/ha) (1.030 m/yr) (1000 kg/m$^3$) (4.94E+3 J/kg) = 5.09E+10 J/ha/yr

3. Soil used: 20 g/m$^2$/yr (Dissmeyer 1981); (20 g/m$^2$/r) (1E+4 m$^2$/ha) (3% OM content) (5.4 kcal/g) (4186 J/kcal) = 1.36E J/ha/yr

$F_1$ Silviculture:

4. Phosphorus: 5.7 lbs/acre/yr absorbed - 4.0 lbs/acre/yr returned (Prichett 1981) = (1.7 lbs P/acre/yr) (acres/0.4047 ha) (454 g/lb) = 1910 g/ha/yr

5. Human services (Strata 1989):

| | cost ($/application) | no. appl. / plantation cycle | per hectare cost ($/ha/yr) |
|---|---|---|---|
| prescribed burn: | 16.10 | 25 | 16.10 |
| tree removal (undesirables) | 141.38 | 1 | 5.66 |
| timber cruise | 6..10 | 25 | 6.10 |
| tree marking | 21.19 | 1 | 0.85 |
| site prep. | 228.80 | 1 | 9.15 |
| planting | 91.11 | 1 | 3.64 |
| thinning | 137.23 | 1 | 5.49 |
| fertilization | 88.50 | 1 | 3.54 |
| total: | | | 50.53 |

$Y_1$ Above ground production = 461 g-C/m$^2$/yr (Gholtz et al. 1991); (461 g-C/m$^2$/yr) (1E+4 m$^2$/ha) (1/0.48; 48% C in OM) (4.5 kcal/g) (4186 J/kcal) = 1.81 E11 J/ha/yr

$F_2$ Harvesting:

6. Fuels used in harvest (Anonymous 1976): (stump to mill handling; 4 gal/ton. Oven dry wt.) + (road construction and maintenance; 0.2 gal/ton) + (supervision; 0.15 gal/ton) = 4.35 gal/ton (2.86E+8 J/gal. Heat content of fuel) (3.57 tons/ha/yr; harvest. $Y_2$ below) = 4.45 E9 J/ha/yr

7. Labor (Anonymous 1976): (harvest planning and layout; 0.06 labor-hrs/ton. Oven dry wt.) + (road construction and maintenance; 0.06 hrs/ton) + (stump to mill handling; 2.21 hrs/ton) (equipment maintenance; 0.55 hrs/ton) (supervision; 0.10 hrs/ton) = 2.98 labor-hrs/ton (3.57 tons/ha/yr; harvest, item $Y_2$) (350 kcal/labor hr energy expenditure; Sundberg and Silversides 1988) (4186 J/kcal) = 1.56 E7 J/ha/yr

   Solar transformity for U.S. labor estimated as: (8.61E+24 sej/yr; emergy-use in U.S., 1990; Odum 1995) / (2.5E+8 people; U.S. population; (WRI 1994) / (64.5% population between ages 15-60) / (365 d/yr) / (3200 kcal/day, metabolism) / (4186 J/kcal) = 1.09 E7 sej/J.

8. Capital depreciation (Ananymous 1976): (2.21 $/ton) (3.57 ton/ha/r; $Y_2$ below) = 7.90 #/ha/yr

$Y_2$ Harvested biomass: (73 $ft^3$/acre/yr; Sheffield 1981) (2.47 acres/ha) (0.028 $m^3/ft^3$) (0.70 ton/$m^3$, oven dry wt.) = 3.57 tons/ha/yr (1.88E+10 J/ton) = 6.73E+10 J/ha/yr

$Y_2$ (2nd estimate): (14.983 g/$m^2$, tree wood biomass of 27 yr. Old plantation; Gholz et al. 1986) / (27 yrs) (1E+6 g/ton) (1E+4 $m^2$/ha) = 5.55 tons/ha/yr (62% sawn timber, pulpwood, sawdust) = 3.45 tons/ha/yr, harvest (1.88E+10 J/ton) = 6.48E+10 J/ha/yr

Summary of measurements:

| | |
|---|---|
| I | Items 2+3 = 936.2E+12 sej/ha/yr |
| $F_1$ | Items 4+5 = 119.1E+12 sej/ha/yr |
| $F_2$ | Items 6+7+8 = 396.1E+12 sej/ha/yr |
| $Y_1$ | $I+F_1$ = 1055.1E+12 sej/ha/yr |
| $Y_2$ | $I+F_1+F_2$ = 1451.2E+12 sej/ha/yr |

Solar transformities = $Y_1$ (sej/ha/yr) / $Y_1$ (J/ha/yr):

$ST_1$ Above ground production = (1.055E+15 sej/ha/yr) / (1.81E+11 J/ha/yr) = 5829 sej/J

$ST_2$ Harvested biomass = (1.451E+15 sej/ha/yr) / (6.73E+10 J/ha/yr) = 21.563 sej/J

Emergy yield ratio = $Y_1$ / ($F_1$ +…$F_1$ ):

$YR_1$ Above ground production = (1055E+12 sej/ha/yr) / (119.1E+12 sej/ha/yr) = 8.86

$YR_2$ Harvested biomass = (1451E+12 sej/ha/yr) / (119.1 + 396.1)E+12 sej/ha/yr = 2.82

Emergy investment ratio = ($F_1$ +…$F_1$ ) / I:

$IR_1$ Above ground production = (119.1E+12 sej/ha/yr) / (936.2E+12 sej/ha/yr) = 0.13

$IR_2$ Harvested biomass = (119.1 + 396.1)E+12 sej/ha/yr / (936.2E+12 sej/ha/yr) = 0.55

**Table 7** Emergy evaluation fuelwood plantation production (*Eucalyptus* spp. And *Melaleuca* spp.) under 5 year rotation schedules in south Florida.[a] (Doherty, 1995)

| Note | Item | Resource units/ha/yr (J. g. $) | | Solar emergy per unit[b] | Solar Energy flow E12 sej/ha*yr$^{-1}$ |
|---|---|---|---|---|---|
| I | Environmental sources: | | | | |
| 1 | Evapotranspired rain | 5.09 E10 | J | 18200 | 926.3 |
| | | | | | |
| $F_1$ | Silviculture: | | | | |
| 2 | Site preparation, clearing | 2.64 E9 | J | 47900 | 126.3 |
| 3 | Seedling establishment | 150.00 | $ | 3.2 E12 | 480.0 |
| 4 | Fertilization | 1.0 E5 | g | 4.8 E9 | 480.0 |
| 5 | Irrigation | 1.24 E9 | J | 2.55 E5 | 314.9 |
| 6 | Labor | 1.35 E6 | J | 1.09 E7 | 14.7 |
| 7 | Human services | 35.00 | $ | 3.2 E12 | 112.0 |
| | | | | | |
| $Y_1$ | Above ground production (13.0 tons/ha/yr) | 2.18E+11 | J | $ST_1$ | 2454.2 |
| | | | | | |
| $F_2$ | Harvesting: | | | | |
| 8 | Diesel fuel | 5.29 E9 | J | 47900 | 253.5 |
| 9 | Human services | 197.47 | $ | 3.2 E12 | 631.9 |
| | | | | | |
| $Y_2$ | Harvested biomass (12.4 tons/ha/yr) | 2.07 E11 | J | $ST_2$ | 3339.6 |
| | | | | | |
| Summary of measurements: | | | | | |
| | Solar transformity: | | | | |
| | $ST_1$ Above ground production | | | 11.270 sej/J | |
| | $ST_2$ Harvested biomass | | | 16,143 sej/J | |
| | | | | | |
| | Emergy yield ratio: | | | | |
| | $YR_1$ Above ground production | | | 1.61 | |
| | $YR_2$ Harvested biomass | | | 1.38 | |
| | | | | | |
| | Emergy investment ratio: | | | | |
| | $IR_1$ Above ground production | | | 1.65 | |
| | $IR_2$ Harvested biomass | | | 2.61 | |

Notes.

a. Data compiled from Wang et al. (1981) unless cited otherwise in footnotes.

b Inputs calculated as available energy are multiplied by solar transformities (*sej*/J) to obtain solar emergy; inputs reported mass use use *seg*/g; monetary inputs use *sej*/$ for regional economy and year of production (Table 2 unless cited otherwise in footnotes).

I Environmental inputs:

1. Evapotranspired rain: (52 inches/yr; NOAA 1977) (25.4 mm/in) = (1321 mm/yr) / (1000 mm/m) (78% ET; est. using Cropper and Ewel 1983) (10,000 $m^2$/ha) (1000 kg/$m^3$) (4.94 E3 J/kg) = 5.09 E10 J/ha/yr

$F_1$ Silviculture inputs:

2. Site prepartion: (Disking, 20.00 gal/ha + bulldozing, 12.50 gal/ha + rotovating, 10.20 gal/ha + bedding, 3.41 gal.ha) = 46.11 gal/ha (2.86 E8 J/gal) = 1.32 E10 J/ha / (5 yr-rotation) = 2.64 E9 J/ha/yr
3. Seedling costs: (75 $/1000 individuals) (I $m^2$ spacing) (1E+4 $m^2$/ha) / (5 yrs.) = 150 $/ha/yr
4. Fertilization: N, 50 kg/ha/yr + P, 50 kg/ha/yr = (1000 kg/ha/yr) (1000 g/kg) = 1.0 E5 g/ha/yr
5. Irrigation: (0.025 m/yr) (1E+4 $m^2$/ha) (1000 kg/$m^3$) (4.94E+3 J/kg) = 1.24 E9 J/ha/yr
6. Labor: (disking, 2.43 hrs/ha + rotovating, 2.16 hrs/ha) = 4.59 hrs/ha (350 kcal/hr) (4186 J/kcal) = (6.73 E6 J/ha) / (5 yrs) = 1.35 E6 J/ha/yr
7. Human services: (50 $/ha, planting) / (5 yrs) = 10 $/ha/yr + 25 $/ha/yr, weeding = 35 $/ha/yr

$Y_1$ Harvested biomass: (5 tons/acre/yr) / (0.4047 ha/acre) = 12.35 ton/ha/yr (4 kcal/g) (4186 J/kcal) = 2.07 E11 J/ha/yr

Summary of measurements:

I Item 1 = 926.3 E12 sej/ha/yr
$F_1$ Items 2+…7 = 1527.9 E12 sej/ha/yr
$F_2$ Items 8+9 = 885.4 E12 sej/ha/yr
$Y_1$ I+$F_1$ = 2454.20 E12 sej/ha/yr
$Y_2$ I+$F_1$+$F_2$ = 3339.6 E12 sej/ha/yr

Solar transformities = $Y_1$ (sej/ha/yr) / $Y_1$ (J/ha/yr):

$ST_1$ Above ground production = (2.45 E15 sej/ha/yr) / (2.18 E11 J/ha/yr) = 11.270 sej/J
$ST_2$ Harvested biomass = (3.34 E15 sej/ha/yr) / (2.07 E11 J/ha/yr) = 16,143 sej/J

Emergy yeild ratio = $Y_1$ / ($F_1$+…$F_1$):

$YR_1$ Above ground production = (2454E+12 sej/ha/yr) / (1528E+12 sej/ha/yr) = 1.61

$YR_2$ Harvested biomass = (3340E+12 sej/ha/yr) / (1528 + 885)E+12 sej/ha/yr = 1.38

Emergy investment ratio = ($F_1$+…$F_1$) / I:

$IR_1$ Above ground production = (1528E+12 sej/ha/yr) / (926E+12 sej/ha/yr) = 1.65

$IR_2$ Harvested biomass = (152 = 885)E+12 SEJ/HA/YR / (926E+12 SEJ/HA/YR) = 2.61

**Table 8.** Annual emergy flows supporting productivity in the the Sea of Cortez , Mexico. (After Brown, Tennenbaum, and Odum, 1991)

| Note[a] | Name | Raw Units (units/yr) | Emergy/unit (sej/unit) | Emergy E18 sej/yr |
|---|---|---|---|---|
| 1 | SUN | 5.60 E20 J | 1.00 | 560.2 |
| 2 | RAIN | | | |
| 2 | Chemical Potential | 4.90 E16 J | 1.54 E4 | 756.5 |
| 2 | Kinetic Energy | 2.88 E14 J | 8.89 E3 | 2.6 |
| 12 | Organic Matter | 3.80 E14 J | 1.90 E4 | 7.2 |
| 12 | Phosphate | 5.95 E8 gm | 1.40 E10 | 8.3 |
| 12 | Nitrate | 2.08 E9 gm | 4.19 E9 | 8.7 |
| 3 | TIDE | 6.90 E16 J | 2.36 E4 | 1625.9 |
| 4 | WIND | 4.4 E17 J | 6.23 E2 | 295.4 |
| 5 | HURRICANES | 3.40 E13 J | 4.10 E4 | 1.4 |
| 6 | OCEAN CURRENT | | | |
| 6 | Geopotential | 2.22 E15 J | 2.36 E4 | 52.3 |
| 10 | Organic Matter | 6.58 E16 J | 1.90 E4 | 1250.2 |
| 10 | Phosphate | 4.25 E10 gm | 1.40 E10 | 595.0 |
| 10 | Nitrate | 2.77 E11 gm | 4.19 E9 | 1160.6 |
| 7 | RIVER | | | |
| 7 | Chemical Potential | 3.01 E16 J | 4.11 E4 | 1236.1 |
| 8 | Organic Matter | 1.67 E14 J | 1.90 E4 | 3.2 |
| 11 | Phosphate | 8.10 E8 gm | 1.40 E10 | 11.3 |
| 11 | Nitrate | 1.18 E10 gm | 4.19 E9 | 49.4 |
| 7 | OTHER RUNOFF | | | |
| 7 | Chemical Potential | 1.91 E16 J | 4.11 E4 | 784.4 |
| 8 | Organic Matter | 9.15 E15 J | 1.90 E4 | 173.9 |
| 11 | Phosphate | 5.07 E8 J | 1.40 E10 | 7.1 |
| 11 | Nitrate | 7.14 E9 J | 4.19 E9 | 29.9 |
| 13 | SEISMIC ACTIVITY | 4.24 E13 J | 4.70 E6 | 199.1 |
| 14 | FOSSIL FUELS (1983) | | | |
| | Coal | 2.02 E14 J | 3.98 E4 | 8.0 |
| | Oil | 5.33 E15 J | 5.30 E4 | 282.5 |

**Table 8** (continued)

| Note[a] | Name | Raw Units (units/yr) | Emergy/unit (sej/unit) | Emergy E18 sej/yr |
|---|---|---|---|---|
| | Gas | 1.99 E15 J | 4.80 E4 | 95.5 |
| | Wood | 1.53 E14 J | 3.50 E4 | 5.4 |
| 15 | ELECTRICITY (1983) | 4.58 E14 J | 1.59 E5 | 72.8 |
| 16 | GOODS & SERVICES (1983) | | | |
| | Direct | 2.10 E8 $ | 3.00 E12 | 630.0 |
| | Imports | 4.80 E7 $ | 3.80 E12 | 182.4 |
| | Taxes | 2.96 E16 | 3.00 E12 | 8.9 |
| 17 | TOTAL INPUT | | | 7539.5 |
| 18 | ENVIRONMENTAL INPUT | | | 2777.0 |
| 19 | GPP Transformity | 4.75 E17 J | 5846 | 2777.0 |

1. SUNLIGHT. Average sunlight over Gulf taken as 170 Kcal/m$^2$ . yr (Woldt and Jusatz, 1965). Area = 78700 km$^2$ (Roden 1958).

Sun energy = 170 Kcal/m$^2$ . yr * 4.187 E3 J/Kcal * 10 E9 cm$^2$/km$^2$
* 78700 km$^2$ = 560.14 E18 J/yr.

2. RAINFALL. Average rainfall over northern Gulf taken as 126 mm/yr (Roden, 1958).

Velocity = 762 cm/sec (Odum et al. 1983)
Chemical potential energy: 126 mm/yr * .1 cm/mm * .5 * 1 gm/cm$^3$
* (762 cm/sec)$^2$ * 2.38 E-11 Cal/erg = 87.062 E-6 Kcal/cm$^2$
* 4.1867 E3 J/kCal * 78700 km$^2$ * 1 E9 cm$^2$km$^2$ = 4.9 E16 J/yr.

3. TIDE. Average tidal height taken as 109 cm over 200 m deth limit (Alvarez-Borrago, 1983).
Assumed 3/8 of energy absorbed over area of 200 m depth (43700 km$^2$).

Tidal energy: 3/8 * 43700 km$^2$ * .5 x 706 tides/yr * (109 cm)$^2$
* (0.01 m/cm)$^2$ * 1.0253 E3 kg/m$^3$ * 9.8 m/sec$^2$
* (1000 m/km)$^2$ = 6.9 E16 J/yr.

4. WIND. Eddy diffusion coefficient = 8.4 $m^2$/sec.

Vertical wind velocity gradient: 4.29 E-3 (m/sec)/m (Odum et al., 1983)
Wind energy = 1000 m * 1.23 kg.$m^3$ * 8.4 $m^2$/sec * 3.154 E7 sec/yr
* [4.29 E-3 (m/sec)/m]$^2$ * 78700 $km^2$
* (1000 m/km)$^2$ = 4.72 E17 J/yr.

5. HURRICANES. Average energy per storm 5 E5 Kcal/$m^2$ • day (Odum et al., 1983); 3% kinetic energy; 10% dispersed to surface (Odum et al., 1986); residence time/day, 1 in 10 yrs reached 20 N lat. (Roden 1964); average area of a hurricane = 20,000 $km^2$ (Odum et al., 1983). Assumed area affected in Sea of Cortez is that of one hurricane diameter.

Hurricane energy = .1/yr * 1 yr/365 days * 5 E5 Kcal/$m^2$ • day * .003
* 20,000 $km^2$ * 1 E6 $m^2$/$km^2$ * 4186.7 J/Kcal = 3.44 E14 J/yr.

6. OCEAN CURRENT. Net current inflow assumed equal to difference between inflows and volume of wate evaporated (2500 mm/yr) (Alvarez-Borrego, 1983).

Colorado River inflow:
(1980-1984) 6.229 E9 $m^3$/yr (McCleary, 1986).

Runoff excluding colorado River: 3.9 E9 $m^3$ yr (Byrne and Emery, 1960);
Rainfall: 9.92 E9 $m^3$/yr (Roden, 1958);
Evaporation: 2500 mm/yr * 7.87 E10 $km^2$ * 1 E-3 m/mm
= 196.75 E9 $m^3$/yr.

Net ocean current inflow:
(1980-1984): 196.75 E9 $m^3$ - 6.23 E9 $m^3$ - 3.9 E9 $m^3$ - 9.9 E9 $m^3$ = 176 E9 $m^3$

Geopotential energy integrated over one year:
(1980-1984): 176 E9 $m^3$ * 2500 mm * 1 E-3 m/mm * 1/2 * 1027 kg/$m^3$
* 9.8 m/$s^2$ = 2.22 E15 J.

7. RIVER (Chemical Potential). Salinity in 1920s taken as approximately 400 mg/L (Applegate, 1986); in 1960s approximately 1000 mg/L (USGS, 1976); in 1980s approximately 800 mg/L (Applegate 1986).

Other runoff: 3.9 E9 $m^3$ - assume salinity of 400 mg/L (Byrne and Emery, 1960);

8. RIVER (Organic Matter). Sediments are 27% silt and 5% of that is organic (Byrne and Emery, 1960).

Sediment Load (Byrne and Emery, 1960; Fortier, 1928; McCleary, 1986):
1980s: .55 E6 T/yr;

Using data from McCleary (1986) for sediment load during 1970-1979, the following relationship between sediments and discharge was regressed.
Sediments (T/y) = 1.778 E-9 * discharge ($m^3$/yr) $^{1.54}$.
Sediments from other runoff sources approximately 30 E6 T/yr (Byrne and Emery 1960).

Colorado River Organic Matter:
1980s: .55 E6 T/y * .27 * .05 * 1 E6 gm/T * 5.4 Kcal/gm * 4186.7 J/Kcal = 1.67 E14 J/yr.

Other Runoff Organic Matter:
30 E6 T/y * .27 * .05 * 1 6 gm/T * 5.4 Kcal/gm * 4186.7 j/Kcal = 9.15 E15 J/yr.

9. PRIMARY PRODUCTIVITY (1968).

North Gulf (average December) .572 gm C/$m^2$ • d ($C^{14}$ method by Zeitzschel, 1969).
South Gulf (average December) .737 gm C/$m^2$ • d ($C^{14}$ method by Zeitzchel, 1969).
For southern Gulf, spring productivity is 42% of winter. If same drop is assumed for the northern Gulf, then May productivity is approximately

.42 * .572 gm C/$m^2$ • d = .24 gm C/$m^2$ • d.

Average for year= (.572 + .24) /2 gm C/$m^2$ • d = .41 gm C/$m^2$ • d.

$C^{14}$ method underestimates gross production (Mann, 1982; Valiela, 1984). Estimates range from 1/5 to 1/15 actual productivity, however, we will be conservative and assume 3 times this productivity:

3 x .41 gm C/$m^2$ • d = 1.23 gm C/$m^2$ • d.

(7.87E 10 $m^2$) (1.23 gc/$m^2$/d) (365 d) = 3.53 E13g C/yr.

10. NUTRIENTS CARRIED BY CURRENT.

Phosphate:
Pacific equitorial current: 2.6 µM $PO_4$ (Warsh et al., 1972).
Average Gulf concentration: 1.8 µM $PO_4$ (see Footnotes to Figs. 7-8, No. 3).

2.6 uM * 1 E3 L/$m^3$ * 1 E-6 mole/umole * 95 gm/mole = 0.25 gm/$m^3$.

1980s: 0.21 gm/$m^3$ * 172 E9 $m^3$/yr = 42.5 E9 gm/yr.

Nitrate: Regression for nitrate µM $NO_3$ = 16.2 µM $PO_4$ - 16.2 µM (Alvarez-Borrego, 1983).
Therefore, 2.6 µM $PO_4$ predicts have 25.9 µM $NO_3$.
Average Gulf concentration: 13 µM $NO_3$ (see Footnotes to Figs. 7-8, No. 4).

25.9 µM * 1 E3 L/$m^3$ * 1 E-6 mole/mole * 62 gm/mole = 1.61 gm/$m^3$.

1980s: 1.61 gm/$m^3$ * 172 E9 $m^3$/yr = 276.9 E9 gm/yr.

Organic Matter: Approximately 7.1 mg C/L assumed for incoming current. This number is from Mississippi coastal waters where $PO_4$ and $NO_3$ concentra-

tions were comparable to those above (Costanza 1983).
Average Gulf concentration: 1.5 mg C/L (see Footnotes to Figs. 7-8, No. 2).
7.1 gm C/$m^2$ * 1.72 gm OM/gm C * 6.5 Kcal/gm * 4816.7 J/Kcal = 3.8 E5 J/$m^3$.
1980s: 1.4 E5 J/$m^3$ * 172 E9 $m^3$/yr = 65.8 E15 J/yr.

11. NUTRIENTS IN COLORADO RIVER AND OTHER RUNOFF.
Colorado River: $PO_4$ is about .13 mg/L = .13 gm/$m^3$ (USGS, 1970).
$NO_3$ is about 1.9 mg/L = 1.9 gm/$m^3$ (USGS, 1970).

Other Runoff is assumed to be close to these values.

Phosphate:
1980s: .13 gm/$m^3$ * 6.23 E9 $m^3$/yr = 8.1 E8 gm/yr.

Other Runoff: .13 gm/$m^3$ * 3.9 E9 $M^3$/yr = 5.1 E8 gm/yr.

Nitrate:
1980s: 1.9 gm/$m^3$ * 6.23 E9 $m^3$/yr = 11.84 E9 gm/yr.

Other Runoff: 1.9 gm/$m^3$ * 3.9 E9 $m^3$/yr -= 7.41 E9 gm/yr.

12. NUTRIENTS IN RAIN.
$PO_4$ = .06 mg/L (Hendry and Brezonik, 1980; Graham, et al., 1979);
$NO_3$ = .21 mg/L (Hendry and Brezonik, 1980); Chapin and Uttormarsh, 1973);
Org C assumed to be 1 ppm (1 mg/L).

Phosphate: 06 gm/$m^3$ * 9.92 E9 $m^3$/yr = 5.95 E8 gm/yr.

Nitrate and Nitrite: .21 gm/$m^3$ * 9.92 E9 $m^3$/yr = 2.08 E9 gm/yr.

Organic Matter: 1 gm/$m^3$ Org C * 1.72 gm OM/gm C * 5.4 Kcal/gm * 4186.7 J/Kcal
* 9.92 E9 $m^3$/yr = 3.8 E14 J/yr.

13. SEISMIC ACTIVITY (Earthquakes).
Effective Peak Acceleration = .5 * X (force of gravity) (Odum et al., 1983).
Frequency 613.8/100 yrs (Odum et al., 1983).
Fault Length approximately 530 km (Alvarez-Borrego, 1983).
Fault Width approximately 3 m (Alexander, 1978).
Energy = $k_c A^2 \bullet f$ ($k_c$ = 4168) (Odum et al., 1983).

$E_s$ = 4168 * $(.5)^2$ * 6.138 * 4186.7 J/Kcal = 2.68 J/$m^2$ • yr.
2.68 E7 J/$m^2$ • yr * 3 m * 530 km * 1 E3 m/km = 4.26 E13 J/yr.

14. FUEL USE IN COASTAL REGION (based on percent of Mexico's population).

Total population (1983) 75,103,000 (UN, 195).

Coastal population: Guamos (1969) 60,981; Puerto Penasco (1970) 10,245; estimate for the rest of the northern gulf coastal area 29,000. Total approximately 100,000 (*Webster's Geographical Dictionary*, 1980).

Population increased at a rate of 2.6% per year (UN 1985). This yields an increase of 40% from 1970 to 1983.

100,000 + (.4 * 100,000) = 140,000.
(140,000/75,103,000) * 100% = 0.19% of total population.

Fossil Fuel Use (1983) (UN, 1985);
Coal: 3.346 E6 T coal eq/yr * 3.18 E10 J/T coal eq * 0.0019 = 2.02 E14 J/yr
Oil: 88.270 E6 T coal eq/yr * 3.18 E10 J/T coal eq * 0.0019 = 5.33 E15 J/yr
Gas: 32,914 E6 T coal eq/yr * 3.18 E10 J/T coal eq * 0.0019 = 1.99 E15 J/yr
Wood: 2.525 E6 T coal eq/yr * 3.18 E10 J/T coal eq * 0.0019 = 1.53 E14 J/yr

15. ELECTRICITY USE (based on percent of population).

66.954 E9 kWh/yr * 3.6 E6 J/kWh * 0.0019 = 4.58 E14 J/yr

16. GOODS AND SERVICES (assume fisheries are the major industries).

Mexico's GDP: 1.4274 E11 $US/yr (UN, 1985);
Mexico's fish production: 1.07 E6 T/yr (UN, 1985);
Emergy Dollar Ratio for Mexico: 2.86 E12 sej/$US (Odum 1984);
Transformity for fish: 8 E6 sej/J (Odum 1984);
Fish are .2 dry/wet weight and 5 Kcal/gm (dry) (Parsons et al., 1977; Kemp et al., 1975).

1.4274 E11 $US/yr * 3 E12 sej/$US = 4.28 E23 sej/yr.
1.07 E12 gm/yr * .2 dry/wet * 5 Kcal/gm (dry) * 4186.7 J/Kcal
* 8 E6 sej/J = 3.58 E22 sej/yr.

Fishing is #3.58 E22/4.14 E23) * 100% = 8.7% of Mexico's economy.
Assume 1/4 of this is from Sea of Cortez.

17. TOTAL EMERGY INPUT is of emergy of rain, tide, ocean currents, river inflow, other runoff: seismic activity, fossil fuels, and goods and services. Other emergies shown in the table are not added to minimize double counting.

18. ENVIRONMENTAL INPUTS. Sum of chemical potential emergy of rainfall, other runoff, and river inflow.

19. PRIMARY PRODUCTION. Average of spring and and winter productivity measured by the C14 method was 0.41 g C/$m^2$ $d^{-1}$. TheC14 method underestimates gross production so we assumed Gpp was 3x average measured values or 1.23 gC/$m^2$ $d^{-1}$.

GPP = (7.87 E10 m2)(1.23 gC/m2 d-1)(365 d) = 3.53 E13 g C/yr
= 4.75 E17 J

**Table 9.** Annual emergy flows supporting temperate forest watershed (Wine Spring Creek Watershed, North carolina). (Tilley, 1999)

| Note | Item | Physical Unit | Emergy per unit (sej/unit) | Solar Empower E12 sej | Emdollar Value 1992 Em$ |
|---|---|---|---|---|---|
| ENVIRONMENTAL ENERGY INPUTS: | | | | | |
| 1 | Sunlight | 5.0 E13 J | 1 | 50 | 46 |
| 2 | Vapor saturation deficit | 7.2 E11 J | 5.9 E2 | 423 | 384 |
| 3 | Wind, kinetic (annual) | 1.9 E11 J | 1.5 E3 | 281 | 256 |
| 4 | Precip., geopotential | 5.6 E10 J | 1.0 E4 | 577 | 525 |
| 5 | Hurricanes (long term) | 5.2 E10 J | 1.0 E4 | 522 | 474 |
| 6 | Precip., chemical | 9.7 E10 J | 1.8 E4 | 1763 | 1,603 |
| 7 | Transpiration | 2.7 E10 J | 1.8 E4 | 484 | 440 |
| 8 | Deep heat | 1.4 E10 J | 3.4 E4 | 468 | 425 |
| 9 | Atmospheric deposition | 3.0 E4 g | 1.0 E9 | 30 | 27 |
| IMPORTED ENERGY SOURCES: | | | | | |
| 10 | Auto-fuel, visitors within | 2.1 E8 J | 6.6 E4 | 14 | 12 |
| 11 | Auto-fuel, thru traffic | 2.1 E9 J | 6.6 E4 | 136 | 124 |
| 12 | Visitors, length of stay | 8.6 E7 J | 8.9 E6 | 768 | 699 |
| 13 | Timbering, services | 9 $ | 1.5 E12 | 13 | 12 |
| 14 | Timbering, fuels | 1.6 E07 J | 6.6 E4 | 1 | 1 |
| 15 | Road maintenance | 88 $ | 1.5 E12 | 133 | 121 |
| | Forest Service | 13 $ | 1.5 E12 | 20 | 18 |
| 16 | Researchers time | 4.0 E6 J | 3.4 E8 | 1377 | 1,252 |
| INTERNAL PROCESSES (transformities calculated): | | | | | |
| 17 | NPP, total live biomass | 2.1 E11 J | 4.7 E3 | 982 | 892 |
| 18 | Wood accumulation | 6.2 E10 J | 1.6 E4 | 982 | 892 |
| 19 | Litterfall | 6.4 E10 J | 1.5 E4 | 982 | 892 |
| 20 | Rock weathering | 6.0 E5 g | 3.8 E9 | 2261 | 2,055 |
| 21 | **Tree diversity | 30 species | 3.3 E13 | 982 | 892 |
| EXPORTS (transformities calculated): | | | | | |
| 22 | Stream discharge (chem) | ‘7.0 E10 J | 3.2 E4 | 2261 | 2,055 |
| | Stream discharge (geo) | 1.3 E11 J | 1.8 E4 | 2261 | 2,055 |
| | Stream discharge (mass) | 1.4 E10 g | 1.6 E5 | 2261 | 2,055 |
| 23 | Timber w/out service | 4.1 E9 J | 3.0 E4 | 124 | 113 |
| | Timber with service | 4.1 E9 J | 7.0 E4 | 291 | 264 |
| 24 | Recreated people | 8.6 E7 J | 2.4 E7 | 2065 | 1,877 |
| 26 | Total export (items 6, 8-16) | | | 4722 | 4,293 |

**Tree diversity varies with sampling area, 30 species observed in first ha sampled.

Footnotes to Table 9 (emergy evaluation of Wine Spring Creek watershed)

1 SOLAR ENERGY:

Land area of WSC, ha = 1128 Forest Service
Unit of analysis, m^2 = 10,000
Insolation @ ground = 5.02 E09 J/m^2/yr (taken from Coweeta, Swift et al., 1988)

Energy(J) = (___area)*(avg insolation @ ground) (___m^2)*(___J/m^2/y)
= 5.02 E13

2 VAPOR SATURATION DEFICIT

| | Mean conditions | With evapo-transp. | Difference |
|---|---|---|---|
| Atmos. pressure, mb | 1000 | 1,000 | |
| Mean annual temp. C | 12.6 | 12.6 | |
| sat. vap. press. ($e_s$), mb | 14.60 | 14.60 | |
| sat. mix. ratio ($q_s$). g/kg | 9.08 | 9.08 | |
| | | | |
| Evapotranspiration (ET), g/y | | 5.38 E9 | |
| Air exchange, m3/y | | 3.75 E11 | |
| Depression of mix. ratio, g/kg | | 0.0120 | |
| | | | |
| vapor press. (e), mb | 12.20 | 12.22 | 0.0192 |
| mix. ratio (q), g/kg | 7.59 | 7.60 | 0.0120 |
| sat. deficit ($q_s$-q), g/kg | 1.49 | 1.48 | -0.0120 |
| sat. deficit ($E_s$-e), mb | 2.39 | 2.37 | -0.02 |
| free energy, J/kg | 198.3 | 196.7 | -1.59 |
| free energy, J/$m^3$ | 238.0 | 236.1 | -1.91 |

Mean annual temperature at climate station CS301 in WSC basin.
Saturation vapor pressure ($e_s$), mb = 611*EXP ((17.27*T)/(237.3+T))/100
Where T is mean annual temperature, C
Saturation mixing ratio, g/kg = 622x($e_s$,mb)/(air pressure,mb)
Evapotranspiration, g/y = (0.91 m/y)x(10,000m^2/ha)x(1E6 g/m^3)
Air exchange, see Table cow-wind
Depression of mix. ration, g/kg = ET, g/y)/(Air exchange, m^3/y)/(1.2 kg/m^3)
mix. ratio, g/kg: assumed mean annual for WSC
Vapor pressure, mb = (mixing ratio, g/kg)x(air pressure,mb)/622
sat. deficit, g/kg = sat. mix. ratio - six. ratio
sat. deficit, mb = sat. vapor pressure - vapor pressure

free energy, J/kg = -8.33*(273+T)*LN((1000-$q_s$)/(1000-q))/18*100

Free energy of air mass = (8.33 J/mole/deg C)x(T deg C)x(Loge((1000-sat. mix. ratio, g/kg)/(1000-mix. ratio, g/kg)/(18 g/mole) x (1000 g/kg)

Energy of the saturation deficit used, Jy = (difference in free energy, J/m^3/y)

Energy of the saturation deficit used, J/y = (1.91 J/m^3)x(423 E12 m^3/y)
Energy of the saturation deficit used, J/y = 7.17 E11

3. WIND ENERGY:
Energy, Total (J) = 1.88 E11 J/yr

*Growing season only (April-September):*
Energy, grow season (J) = 4.81 E10 J/yr

*Non-growing season (October-March)*
Energy, winter (J) = 1.04 E11 J/yr

4. PRECIPITATION, GEOPOTENTIAL, ENERGY:

| | Hi-Wayah Bald | Lo-Nanta. Lake | Mean | |
|---|---|---|---|---|
| Area = | | | 10000 | m^2 |
| Rainfall = | 1839 | 1697 | 1961 | mm |
| Runoff = | | | 1423 | mm |
| Elevation = | 1625 | 920 | 1318 | m |

Mean elev. determined from GIS topo-coverage

Energy @ mean elev. (J) = (area)(runoff)(mean elev - min elev)(density)(gravity)
(___m^2)*(___mm/y)/(1000 mm/m)*(___m)*(1000 kg $m^{-3}$)*(9.8m/s^2)
Energy, geopotential (J) = 55.5 E9

5. HURRICANES
Energy, J/event = 5.22 E11 (assume 1 hurricane every 10 years
Energy, J/yr = 5.22 E10

6. PRECIPITATION, CHEMICAL POTENTIAL ENERGY:
Rain @ 925 m = 1,697 mm/yr Forest Service (long term)
Rain @ 1330 m = 1,961 mm/yr Forest Service (1995-1997)
Rain @ 1625 m = 1,839 mm/yr Forest Service (long term)
Mean E-T = 538 mm/yr Forest Service (1995-1997)
Total energy assuming rainfall @ 1330m (J )= (area)(rainfall)(Gibbs no.)
= (___m^2)*(___mm)(1000 mm/m)*(1000 kg/m^3)*(4940 J/kg)
= 9.69 E10
Total energy (J) = 9.69 E10

7. EVAPOTRANSPIRATION,
Mean E-T = 538 mm/y CS301t (pers. comm. L. Swift, Coweeta)
Total energy assuming rainfall @ 1330m (J)= (area)(evapotranspiration)(Gibbs no.)
Total energy (J) = 2.66 E10

8. DEEP HEAT (1)
Land Area (mΛ2) = 1.00 E4
Heat flow / Area = 1.36 E6 J/m^2/y, @ Bryson City, NC
Energy (J) = 1.36 E10 (Smith et al., 1981; in Pollack et al., 1991).
Transformity, 34,400 sej/J was the mean calculated for the continents by Odum, 1996.

If deep heat figured as a function of altitude.
Transformity, 75,000 sej/J based on height of geologic uplift (Appendix E)

9. ATMOSPHERIC DEPOSITION
Deposition rate, kg/ha/y = 30 estimate based on Coweeta watershed (Tilley, 1999)

**IMPORTED ENERGY SOURCES:**

10. Gasoline of visitors
Gas within WSC = 3,70 E01 (bbl/yr) (Tilley, 1999)
Energy (J) = (___bbl/yr)*(6.28 E9 J/bbl)

Energy (J/ha = 2.06 E8

11Gasoline of thru traffic
Gas wihin WSC = 3.70 E02 (bbl.r)
Energy (J) = (___bbl.yr)*(6.28e9 J/bbl)

Energy (J/ha) = 2.06 E9

12 Visitors, length of stay in WSC Cordell et al., 1996.
no. of groups/yr = 4,361
mean group size = 2.7 people
mean length of stay = 19.0 hours
Energy (J) = (___people-hrs/yr)*(104 Cal.hr)*(4186 J/Cal)
Energy *J/ha) = 8.63 E7
Transformity of 8,900,000 sej/J is the avg. for a U.S. citizen during avg. day.

13 TIMBERING
<u>Services</u>
Revenue from timber sales from 1973-1999 (26y) was $250,000 (Wayah Ranger District, B. Cullpepper).

Revenue, \$/ha/y = 8.5

Fuels

U.S. National average: 23 E15 J/y to harvest 648 E6 m^3 of wood (see Table wood-log)

U.S. National average J/m^3 = 3.55 E07

Fuel use in WSC timbering, J/ha/y = (harvest, m^3/ha/y)x(3.55E7 J/m^3)

Fuel use in WSC timbering, J/ha/y = 1.56 E07

14. ROAD MAINTENANCE

Length of unpaved roads = 24 km (GIS database)

Length of paved roads = 9 km (GIS database, FS 711)

Cost to maintain roads = 5,000 \$/mile/y (Bill Culpepper, FS Silviculturalist, Wayah Ranger District)

Cost of rd, \$/y = (length of rds, km)x(\$5,000 /mile/y)x(1 mile/1.609 km)

Cost of rd, \$/4 = 9.98 E04

Cost, \$/ha/y = 8.84 E1

15. FOREST SERVICE MANAGEMENT

Wayah Ranger District budget, \$/y = 750000

Area of Wayah R.D., ha = 56000

Expenditures, \$/ha/y = 13

16. RESEARCH EFFORT

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

Effort, hr/y = 1.04 E04

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

Energy (J/ha) = 4.01 E6

Transformity: post-college educated person (Odum 1996)

**INTERNAL PROCESSES**

17. NET PRODUCTION OF LIVE BIOMASS

Roots+wood+leaves = 14390 kg/ha/y; @ Coweeta Hydrologic Laboratory; Monk and Day, 1977

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

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

18. WOOD ACCUMULATION RATE

Net accumulation = 4.20 E3 kg/ha/y; @ Coweeta Hydrologic

Laboratory; Monk and Day, 1977
Energy (J) = (net accum.,kg/ha/y)x(area, ha)(1000 g/kg)(3.5 kcal/g-dry wt)
(4186 J/kcal)
= 6.15 E10

19. LITTERFALL
Net accumulation = 4.40 E3 kg ha Avg. 1984-89, US Forest Service, 1990
Energy (J) = (Litterfall, kg/ha/y)x(area, ha)(1000 g/kg)(3.5
kcal/g-dry wt)(4186 J/kcal)

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

20. ROCK WEATHERING
Erosion rate, g/mΛ2/y = 60 Velbel, 1988.
Sediment lost, g/ha/y = 6.00 E5
Empower-to-flux (sej/g) = (empower of rain+deep heat+atmos. dep.)/(weathering rate)

21. TREE DIVERSITY
Assume 30 species per ha based on species area curve (Tilley, 1999)

**EXPORTS**

22. STREAM DISCHARGE
Runoff = 1.42 m/y mean 1995-96. Source: Coweeta Hydro. Lab
Chemical Energy (J) = (___m^2)*(___m/y)*(1000 kg/m^3)*(4940 J/kg)
Chemical Energy (J) = .03 E10
Available geopotential energy (J) = (area)(runoff)(stream mouth elev above sea level)(density)(gravity)
= (___mΛ2)(___m/y)**(___m)*(1000 kg/m$^{-3}$)*(9.8m/sΛ2)
Geopotential Energy (J) = 1.26 E11 relative to sea level
Runoff (g) = 1.42 E10
All transformities: [empower of rain + deep heat]/energy (or mass)

23. TIMBER EXTRACTION
Since 1973 (26 y), timber harvest from WSC watershed was 8623 m^3 sawtimber and 4259 m^3 of roundwood, valued at $251,000 (Wayah Ranger District, courtesy of Bill Culpepper)
Timber harvest rate, m^3/ha/y = 0.44
Energy (J) = (___m^3)*(5 E5 g/m^3)*(4.5 Kcal/g)*(4186 J/Cal)
Energy (J) = 4.14 E9
Energy (J/ha) = 4.14 E9
Transformity of tember before harvest was based on simulation with EMERGYDYN for wood in Coweeta WS 18 (See Tilley, 1999)
Timber with services: services added were road maintenance, FS management, and timber fuels and services.
Transformity of timber after harvest was emergy/energy

24. RECREATED PEOPLE
Same energy as visitor's length of stay above (#24)
Transformity = [sum of empoer inputs/metabolism of visitors during length of stay]
Empower inputs were sum of environmental and economic
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 Forest Service management.

25. RESEARCH INFORMATION
From 1992 to 1998, 47 publications and 10 reports were produced (Swank 1999)
Publication rate over the six years was 57/6 = 9.5 pubs/yr
Publications average 10 pages in length
Page weighs 1 gram
Grams of research articles published, g/y = 9.5 articles/y x 10 pages x 1 g/page
Grams of research articles published, g/y = 9.5
Energy of articles, J/y = grams x 3/5 kcal/g x 4186 J/kcal
Energy of articles, J/y = 1.39 E6
Energy of articles, J/ha/y = 1,234
Tranformity = [sum of empower inputs (rain, deepheat, atmospheric deposition,
road maintenance, Forest Service management, and research effort)]/[energy of
publications, annual rate]

26. TOTAL EXPORT
Total export was rain + deep heat + atmos. deposition + all imported sources
(items 10-18)

**Table 10**. Annual Emergy Flows in a subtropical estuary and watershed*: the Guana Tolomato Matanzas National Estuarine Research Reserve (Irvin, 2000)

| Note | Items, units | Data | Emergy/unit (sej/unit) | Solar Emergy E17 sej/yr |
|---|---|---|---|---|
| 1 | Sunlight used, J | 1.82 E18 | 1 | 18 |
| 2 | Wind absorbed, J | 2.54 E15 | 1,496 | 38 |
| 3 | Rainfall, geopotential, J | 1.27 E12 | 27,874 | 0.35 |
| 4 | Rainfall, chemical potential, J | 1.88 E15 | 18,199 | 342 |
| 5 | Streams, chemical potential, J | 1.85 E15 | 48,460 | 897 |
| 6 | Streams, geopotential, J | 2.73 E12 | 27,806 | 0.76 |
| 7 | Stream organics, g | 9.35 E7 | 1.53E9 | 1.4 |
| 8 | Stream phosph., g | 1.31 E8 | 6.85 E9 | 8.97 |
| 9 | Stream nitrogen, g | 1.91 E8 | 2.00 E8 | 0.38 |
| 10 | Stream sediment, g | 3.74 E10 | 1.00 E9 | 374 |
| 11 | Unreplaced soil, g | 9.76 E7 | 1.71 E9 | 1.67 |
| 12 | Grnd and surface water withdrawl, J | 3.14 E11 | 41,000 | 0.13 |
| 13 | Geologic support, g | 3.04 E9 | 1 E9 | 30 |
| 14 | Wave energy, J | 3.65 E15 | 30,550 | 1115 |
| 15 | Tidal energy, J | | | |
| | Estuary | 2.31 E14 | 44,000 | 102 |
| | Shelf | 1.35 E15 | 44,000 | 594 |
| | Subtotal tidal energy | | | 696 |
| 16 | Plankton seeding, # species | 200 | 5.2E16 | 104 |
| 17 | Nekton, # species | 4.98 E3 | 7.3 E19 | 3636565 |
| 18 | Birds, seeding, # species | 20 | 2.00 E12 | 0.0004 |
| 19 | Fuel use | | | |
| | Gasoline, J | 6.13 E13 | 66,000 | 40.5 |
| | Petroleum, J | 2.76 E12 | 54,000 | 1.49 |
| | Natural Gas, J | 9.07 E11 | 48,000 | 0.44 |
| 20 | Electric Power, J | 4.28 E12 | 170,000 | 7.28 |
| 21 | Income into area, $ | 697,237.20 | 1.00 E12 | 6.97 |
| 22 | Services into area, $ | 1.46 E6 | 1.00 E12 | 14.6 |
| 23 | Visitors, J1.83 E13 | 4.90 E7 | 8967 | |
| 24 | Environmental Inputs | | | 58402 |
| 25 | Economic & human Inputs | | | 9038 |

*Area used for evaluation is 1.22 E08 $m^2$ land area (excluding the continental shelf (1.83 E08 $m^2$)) unless otherwise stated. Area of estuary (3.13 E07 $m^2$) includes bays, estuaries and salt marshes unless otherwise stated (Department of Environmental Protection, 1998).

1 Solar Energy is the sun's energy absorbed in the study area (sunlight received minus 10% reflected). (Odum & Hornbeck, 1997). (3.05 E08$m^2$)(1.58 E02 Kcal/$cm^2$/yr)(1-0.10)(1 E04 $cm^2/m^2$)(4186 J/kcal) = 1.82 E18 J/yr

2 Wind kinetic Energy Absorbed. D = r*C*V3; air density r = 1.3 kg/$m^3$; drag coefficient C=1.0E-3 (Regier 1969); velocity, V = 7.9 miles/hr (US Statistical Abstract, 1999) = 3.53 m/sec; (geostrophic wind = 10/6)* 3.53 m/sec = 5.88451 m/sec.
c$^2$)(3.14 E7 sec/yr)(3.05 E08 $m^2$) = 2.54 E15 J/yr

3 Geopotential energy in rain water reaching the ground relative to sea level. It is evaluated as the mass per year times the height times gravity. (1.22 E08 $m^2$)(0.18669 m/yr)(1.2446 m/yr)(1.00 E03 kg/$m^3$)(4.572 m)(9.8 m/sec) = 1.27 E12 J/yr (Odum, 1996)

4 Chemical potential energy in rain is the energy in rainfall on the land plus the energy in rainfall of the continental shelf. The energy in rain on land is the land area times the rainfall times Gibbs free energy in J/kg. (2.23 E08 $m^2$)(1.2446 m/yr)(1000 kg/$m^3$)(4.94 E03 J/kg) = 1.37 E15 J/yr. The energy in rain on the continental shelf is the area of the shelf times the rainfall times Gibbs free energy in J/kg. (1.83 E08 $m^2$)(0.56007 m/yr)(1000 kg/$m^3$)(4.94 E03 J/kg) = 5.05 E14 J/yr.
(1.37 E15 J/yr) + (5.05 E14 J/yr) = 1.88 E15 J/yr. (Odum, 1996)

5. Chemical potential in streams is the flow volume times the density of water times Gibbs free energy. (3.74 E08$m^3$/yr)(1.00 E06 g/$m^3$)(4.94 J/g) = 1.85 E15 J/yr. (Odum, 1996)

6 Geopotential in streams is the volume of flow times the density of water times the change in elevation from the river entry to egress times gravity. (3.74 E08 $m^3$/yr)(1.00 E03 kg/$m^3$)(7.46E-01 m) (9.8 m/$sec^2$) = 2.73 E12 J/yr. (Odum, 1996)

7 Stream organics is the volume of flow times the organics concentration. (3.74 E08 $m^3$/yr)(25 g/$m^3$) = 9.35 E9 g/yr;

Transformity 7.3 E4 sej/j multiplied by kcal/g)(4186 j/kcal) = 1.53 E9 sej/g

8 Stream phosphorus is the stream flow times the phosphorus concentration. The phosphorus concentration was averaged based on data from Fernald, 1974 and Mortin, 2000. (3.74 E08 $m^3$/yr) (1.35 g/$m^3$) = 1.31 E8 g/yr.

9 Stream nitrogen is the stream flow times the nitrogen concentration. (3.74 E08 $m^3$/yr) (0.51 g/$m^3$) = 1.91 E8 g/yr.

10 Stream sediment is the flow volume times the sediment concentration. (3.74E09 $m^3$/yr) (100?? G/$m^3$) = 3.74 E10 g/yr

11 Unreplaced soil is the erosion outflow minus the formation rate times the land area. (32 g/yr) – (31.2 g/$m^2$/r) (1.22 E08 $m^2$) = 9.76 E7 g/yr. This is assuming no net erosion. (Odum, 1996)

12 Ground and survace water withdraw energy is the withdrawl volume times the density of water times Gibbs number. (1.69 E10 gallons/yr)(1.0E03 kg/$m^3$)(3.79E-03 $m^3$/gallon)(4.9 J/g) = 3.14 E11 J/yr. (FL Statistical Abstract, 1998 and Odum, 1996)

13 Geologic support is the amount of solid materials (ie. Limestone) washed away in percolating water through the soil times the area of land. Rainfall percolating through = 10% of rainfall = 0.12446 m/yr; dissolved solids = 200 g/$m^3$; area of land = 1.22 E08 $m^2$.
(0.12446 m/yr)(200 g/$m^3$) = 24.9 g/$m^2$/ yr
(1.22 E8 $m^2$)(24.9 g/$m^2$/yr) = 3.04 E9 g/yr

14 Wave energy was estimated at the shore length times 1/8 the product of water density, gravity, wave height squared, and wave velocity calculated from the square root of the gauge depth (3m) times gravity and seconds per year. (7.56 E3 m)(1/8)(1.03 E3 kg/$m^3$)(9.8 m/$sec^2$)(5.4m/sec)$(1.5 m)^2$ (3.15 E7 sec/yr) = 3.65 E15 J/yr (Odum, 1996; NOAA)

15 Tidal energy absorbed within the estuary was estimated as geopotential energy of water brought in and dissipated in friction. Energy was estimated as the energy in the mass of water elevated equal to the weight of tidal water added in each tide times the elevation of the center of gravity times gravity times the number of tides per year. (3.13 E7 $m^2$)(1.44 m)(1.03 E3 kg/$m^3$)(0.5*1.44 m)(9.8 m/$sec^2$)(706 tides/yr) = 2.31 E14 J/yr. (Odum, 1996; Raisz, 1964) Tidal energy absorbed on the shelf was estimated as geopotential energy of water brought in and dissipated in friction. Energy was estimated as the energy in the mass of

water elevated equal to the weight of tidal water added in each tide times the elevation of the center of gravity times gravity times the number of tides per year. (1.83 E8 $m^2$)(1.44 m)(1.03 E03 kg/$m^3$)(0.5*1.44 m) (9.8m/$sec^2$)(706 tides/yr) = 1.35 E15 J/yr.

16 Tidal seeding of species of marine plankton in a year estimated as the number of species (200?) in the continental shelf area. The emergy per species was calculated as the emergy to produce the plankton in the water brought in by tides, which is equal to the tidal range (1.44m) times the area of the estuary (3.13 E7 $m^2$) = 4.50 E07 $m^3$.
Area of shelf to produce the plankton
(4.50 E7 $m^3$added per tide)(706 tides/yr)(10m depth) = 3.18 E11 $m^2$
Emergy per area is the sum of the solar emergy absorbed: (0.9)(1.60 E6 Kcal/$m^2$yr)(4186 J/kcal) = 6.00 E09 J/$m^2$/yr. With a transformity of 1, solar emergy from sunlight is 6.00 E09 sej/$m^2$/yr plus the tidal emergy absorbed over the shelf as in footnote 15:
(1.44 m)(1.03 E3 lg,$^3$)(0.5*1.44 m) (9.8 m/$sec^2$)(706 tides/yr) = 7.40 E6 J/yr.
Multiply by transformity 4.40 E4 sej/J = 3.25 E11 sej/$m^2$/yr. Sum: (6.00 E9 sej/$m^2$/yr) + (3.25 E11 sej/$m^2$yr) = 3.31 E11 sej/$m^2$/yr. Emergy to produce the plankton added to the estuary: (3.31 E11 sej/$m^2$/yr)(3.13 E07 $m^2$) = 1.04 E19 sej/200 species. (5.2 E16 sej/species)

17 Nekton species introduced from the sea estimated from the estuarine stock of nekton divided by the population turnover time. Assume that all populations (shrimp, crabs, fish) turnover once a year as part of their life cycle migrations. Assume an estuarine nekton stock of 5.3 g per $m^2$ (Odum and Hornbeck, 1997). Rate of biomass seeding:
(3.13 E07 $m^2$ area of estuary)(5.3 g/$m^2$)(1 turnover/yr) = 1.66 E08 g/$m^2$/yr
Assume a species variety of 30? Species per million g of estuarine adapted fish.
(30? Species per million g fish)(1.66 E2 g fish/$m^2$/yr) = 4.98 E3 species added per yr.

Assume that half of the population is fish inside the area and half come from outside. (3.13 E7 $m^2$ area of estuary)(5.3 g/$m^2$)(0.5) = 8.3 E07 g/yr from outside migration. Multiply by the emergy per gram of outside fish to raise the immigrants half of the year on the shelf. (5.3 g/$m^2$ shelf stock)(8.3 E07 g/year from outside)(1 $m^2$ of outside area/g)(1.66 E11 shelf emergy support in sej/$m^2$/half year) = 7.3 E19 sej/species seeded.

18 Annual introduction of outside birds is the species per $km^2$ which enter and leave in cycles and migration in a year. Annual emergy perspecies obtained using large area and a species area curve: (1.58 E16 sej per $km^2$of land per

year)/(0.0001259 number of species per km$^2$ (Rosenzweig, 1995)) = 2.00 E12 sej/species. Emergy of land is global emergy divided by global total land area. (9.44 E24sej)/(5.96 E8 km$^2$) = 1.58 E16 sej/km$^2$.

19 Fuel use has been divided up into the categories of gasoline, petroleum and natural gas due to the differing transformities of each.

Gasoline energy is the per capita usage of gasoline (FL Statistical Abstract, 1998) times the population times conversion factors. (1.70 E4 gallons/yr) (23.76) (3.62 E4 Kcal/gal) (4184 J/Kcal) = 6.13 E13 J/yr.

Petroleum energy is the per capita consumption of petroleum (FL Statistical Abstract, 1998) times the population times a conversion factor. (1.10 E02 million BTU's/yr) (23.76) (1.05 E09 J/MBTU) = 2.76 E12 J/yr.

Natural Gas energy is the per capita consumption of natural gas (FL Statistical Abstract, 1998) times the population times a conversion factor. (3.62 E01 million BTU's/yr) (23.76) (1.05 E9 J/MBTU) = 9.07 E11 J/yr. (FL Statistical Abstract, 1998)

20 Electricity energy is the per capita consumption times the population times a conversion factor. (5.00 E4 Kwh/yr) (23.76) (3.60 E6 J/kwh) = 4.28 E12 J/yr. (FL Statistical Abstract, 1998)

21 Income into area is the per capita income (FL Statistical Abstract, 1998) of the residents in the reserve times the population. (29,345 $/yr) (23.76) = 697,237.20 $/yr.

22 Services into area is the estimated amount of money spent within the reserve for outside services.

23 Energy of visitors is the product of the number of visits per year times the duration of visit times metabolism per visit times 4186 J/kcal. Metabolism per visit is equal to 2500 kcal/day divided by 6 (4 hours per day) = 417 kcal/visit.
(2,622,212 vis.) (4 hrs/visit) (417 kcal/day) (4186 J/kcal) = 1.83 E13 J/yr.

24 Environmental Inputs: sum of main independent inflows (lines 4 – 18).

25 Economic Inputs: sum of the inputs from the economy (lines 19 through 23).

**Table 11.** Emergy evaluation of brackish water Tilapia aquaculture in Nayarit, Mexico 1989. (After Brown et al., 1992)

| Note | Item | Raw Units | Emergy/unit (sej/unit) | Solar Emergy E12 sej/ha*yr$^{-1}$ |
|---|---|---|---|---|
| RENEWABLE RESOURCES (per ha/yr): | | | | |
| 1 | Sunlight | 4.54 E13 J | 1 | 45.42 |
| 2 | Wind | 7.14 E10 J | 623 | 44.50 |
| 3 | Rain | 5.27 E10 J | 15423 | 812.94 |
| 4 | Tidal energy | 1.02 E9 J | 23564 | 24.07 |
| 5 | Pump. B-Water | 1.05 E11 J | 15444 | 1623.47 |
| | Sum of free inputs (sun, wind omitted) | | | 1729.48 |
| PURCHASED INPUTS: | | | | |
| 6 | Fish Fingerlings | 3.35 E10 J | 5.6E5 | 18760.0 |
| CONSTRUCTION INPUTS (per ha/yr, 10 yr useful life of ponds) | | | | |
| 7 | Labor (man-hr.) | 2.57 E7 J | 1.24 E6 | 31.78 |
| 8 | Fuel (diesel) | 3.14 E9 J | 5.30 E4 | 166.16 |
| 9 | Concrete | 3.70 E5 g | 9.26 E7 | 34.27 |
| 10 | Steel | 1.15 E4 g | 1.80 E9 | 20.70 |
| 11 | Machinery | 4.00 E5 g | 6.70 E9 | 2680.00 |
| 12 | Services (USS) | 2.33 E3 $ | 3.09 E12 | 7186.04 |
| OPERATIONAL INPUTS (per ha/yr) | | | | |
| 13 | Labor (man-hr.) | 7.16 E8 J | 1.24 E6 | 884.53 |
| 14 | Fuel | 7.80 E10 J | 5.30 E4 | 4134.25 |
| 15 | Fertilizer | 4.20 E4 g | 2.00 E10 | 840.00 |
| 16 | Feed | 2.01 E11 J | 1.31 E5 | 26321.57 |
| 17 | Misc. Supplies | 8.00 E2 $ | 3.09 E12 | 2472.00 |
| 18 | Services (US$) | 5.48 E3 $ | 3.09 E12 | 16930.88 |
| | Sum of purchased inputs | | | 80462.18 |
| PRODUCTION (per ha/yr): | | | | |
| 19 | Tilapia Yield | 2.34 E11 J | 5.61 E5 | 131138.67 |

1 SOLAR ENERGY:

Pond Area = 1.00 E4 m$^2$ (standard 1 Ha pond)
Insolation = 1.55 E2 Kcal/cm$^2$/yr IAM, UdeG, Circa, 1988.

Albedo = 0.30 (% given as decimal) *estimate

Energy (J) = (pond Area)*(avg insolation)*(10000cm$^2$/m$^2$)
(1-albedo)(4186J/Kcal)
(J) = 4.54 E13
2 WIND:
Pond Area = 1.00 E4 m$^2$ (standard 1 Ha pond)
Wind Energy = 7.14 E6 J/m$^2$/yr @ (1.4 E19 J/yr)/(1.96 E12 m$^2$)

Energy (J) = (Pond Area)*(wind energy)
(J) = 7.14 E10
3 RAIN:
Pond Area = 1.00 E4 m$^2$
Rainfall = 1.07 E0 m/yr
E-t = not used for this particular case

Energy (J) = (pond area)*(Rainfall)*(E-t)*(1000Kg/m$^3$)*(4940J/Kg)
(J) = 5.27 E10
4 TIDAL ENERGY:
Cont. Shelf Area = 4.00 E2 m$^2$ (area of the pumping station)
Tidal range = 8.40 E-01 m
Water density = 1.01 E3 Kg/m$^3$
# tides/yr = 7.30 E2

Energy (J) = (shelf)*(0.5)*(tides/yr)*(tidal range)$^2$
(density)*(gravity)
(J) = 1.02 E9
5 PUMPED B-WATER:
Area = 1.00 E4 m$^2$ (standard 1 ha pond)
depth = 1.20 E0 m (avg. pond depth)
water exchge. = 1.00 E-01 (10% daily)
No. of days = 3.65 E2

Energy (J) = ((area)(depth)+(area)(depth)*(wat-exch)*(days)
(1000000 gr/m$^3$)*(.08 fresh)(3.0 J/gr))
(J) = 1.05 E11
6 FISH FINGERLINGS:
Fish stocked = 4.00 E4 fish stocked @ 1/m$^2$/crop (2 crop/yr)
wt. @ stock = 4.00 E1 gr/fingerling
Energy (J) = (# fish)*(wt.)*(5 kcal/gr)*(4186 J/kcal)
(J) = 3.35 E10

**CONSTRUCTIN INPUTS** (Data from SEPESCA/JAL., 1989)

7 LABOR (clearing, excavation, leveling, etc.):
Man-hr = 5.90 E2 hr/Ha/yr

Energy (J) = ((man-hr)*((2500Kcal consumed/day)/24 hr)
*(4186 J/Kcal))/10
(J) = 2.57 E7

8 FUEL (diesel):
Vol. used = 2.20 E2 gal

Energy (J) = ((vol)*(34030 Kcal/gal)*(4186 J/Kcal))/10
(J) = 3.14 E9

9 CONCRETE:
Vol. used = 3.70 E3 kg

(g) = ((vol)*(1000 g/kg))/10
(g) = 3.70 E5

10 STEEL:
Vol. used = 1.15 E2 kg

(g) = ((vol)*(1000 g/kg))/10
(g) = 1.15 E4

11MACHINERY:
2 pumps = 4.00 E3 kg @ 2 tons/pump

(g) = ((vol)*(1000g/kg))/10
(g) = 4.00 E5

12 SERVICES:
total cost = 5.29 E7 $pesos/ha (1989)
exch. rate = 2.28 E3 $pesos/$US (1989)

($US) = ((pesos)*(exch. rate))/(deprec. time)
($US) = 2.33 E3

**OPERATIONAL INPUTS** (per ha/yr):

13 LABOR:
Man-hr = 1.64 E3 hr/ha/yr

Energy (J) = (man-hr)*((2500kcal consumed/day)/24 hr)
*(4186 J/Kcal)
(J) = 7.16 E8

14 FUEL:

| | US gal/yr | Kcal/USgal | Kcal/yr |
|---|---|---|---|
| Diesel = | 4.76 E2 | 3.40 E4 | 1.62 E7 |
| Gasoline = | 6.66 E1 | 3.62 E4 | 2.41 E6 |
| Oil = | 1.06 E0 | 3.74 E4 | 3.96 E4 |
| | | Total = | 1.86 E7 |

Total Kcal = 1.86 E7

Energy (J) = (fuel)*(Kcal/gal)*(4186 J/Kcal)
(J) = 7.80 E10
15 FERTILIZER:
Urea = 2.40 E1 kg
Superphosph. = 1.80 E1 kg
total = 4.20 E1 kg

(g) = (fertilizer)*(1000 g/kg)
(g) = 4.20 E4
16 FEED:
Pelleted feed = 8.00 E3 kg

Energy (J) = (feed)*(1000 g/kg)*(6kcal/g)*(4186 J/kcal)
(J) = 2.01 E11
17 MISCELLANEOUS SUPPLIES (5 yr. depreciation time):
total cost = 9.10 E6 $pesos/ha (1989)
exch. rate = 2.28 E3 $pesos/$US (1989)

($USD) = ((pesos)*(exch. rate))/deprec. time)
($USD) = 8.00 E2
18 SERVICES:
total cost = 1.25 E7 $pesos/ha (1989)
exch. rate = 2.28 E3 $pesos/$US (1989)

($US) = ((pesos)*(exch. rate))/(deprec. time)
($US) = 5.48 E3

**PRODUCTION** (per ha/yr):

19 TILAPIA YIELD:
Total yield = 1.14 E4 kg @ 95% survival and 300 gr/tilapia

Energy (J) = (yield)*(1000 g/kg)*(4.9 kcal/gr)
*(4186 J/kcal)
(J) = 2.34 E11

**Table 12**. Annual emergy flows of Shrimp Pond Mariculture in Ecuador, 1986; 53,000 Hectares; 1.5m deep. (Odum and Arding, 1991)

| Note | Item | Raw Units J,g,$ | Trans-formity Sej/unit | Solar Emergy E20 | Macroeconomic US $E6 |
|---|---|---|---|---|---|
| 1 | Sunlight | 1.97 E18 J | 1 | 0.0197 | 0.99 |
| 2 | Rain | 2.65 E15 J | 15444 | 0.41 | 20.5 |
| 3 | Pumped sea waters | 7.33 E15 J | 15444 | 1.1 | 55. |
| 4 | Post larvae | 3.2 E9 ind | 1.04 E11 | 3.4 | 170. |
|  | Sum of Free inputs, direct sun omitted |  |  |  |  |
| 5 | Labor | 1.32 E14 J | 2.62 E6 | 3.79 | 189. |
| 6 | Fuel | 2.34 E15 J | 5.3 E4 | 1.24 | 62. |
| 7 | Nitrogen fertilizer | 1.14 E9 g | 4.19 E9 | 0.048 | 2.4 |
| 8 | Phosphorus fertiliz. | 2.62 E8 g | 2.0 E10 | 0.053 | 2.6 |
| 9 | Feed protein | 3.29 E15 J | 1.31 E5 | 4.3 | 215. |
| 10 | Other services | 3.56 E7 $ US | 8.5 E12 | 3.0 | 151. |
| 11 | Costs of post-larvae | 3.56 E7 $ US | 8.7 E12 | 3.0 | 151. |
| 12 | Capital costs | 1.93 E6 $ US | 8.5 E12 | 0.164 | 8.2 |
| 13 | Interest paid back in sucres or sucre-converted-to $ | 11.2 E6 $ US | 8.5 E12 | .95 | 47.6 |
|  | Sum of Purchased Inputs |  |  | 16.9 | 845 |
|  | Sum without organic feed |  |  | 12.7635 |  |
|  | Sum of all Inputs |  |  | 21.82 | 1092 |
|  | Sum without organic Feed |  |  | 17.6 | 880 |
| 14 | Shrimp yield using organic feed |  |  |  |  |
|  | Efficient value | 1.68 E14 J | 4.0 E6 | 6.72 | 336 |
|  | Resource used | 1.68 E14 J | 13.0 E6 | 21.80 | 1092 |
| 15 | Shrimp yield without organic feed |  |  |  |  |
|  | Efficient value | 0.93 E14 J | 4.0 E6 | 3.72 | 186 |
|  | Resource used | 0.93 E14 J | 18.9 E6 | 17.58 | 879 |

Footnotes for Table 11

1. Direct solar energy:
   (127 E4 kcal/m$^2$/yr)(4186 J/kcal)(0.7 absorbed)(530 E6 m$^2$) = 1.97 E18 J/yr
2. Rain into ponds: (1 m/yr)(530 E6 m$^2$)(1 E6 g/m$^3$)(5 J/g) = 2.65 E15 J/yr
3. Pumped sea water to maintain water levels and salinity; evaluated freshwater content:
   (0.1 vol/d)(365 d)(1.5m)(5.38 E5 m$^2$)(.0 fresh)(1E6 g/m$^3$)(3J/g)=7.4 E15 J/yr
4. Input of post-larvae estimated from pond yield 3.0 E4 tonne (Aquacultura de Ecuador, 1988):

(30 E6 kg)(2.2 lbs/kg)(.70 tails)(35 tails/lb)/(.5 mortality) = .2 E9 ind./y

Larvae can be thought about as information packages with little energy. When a shrimp releases many larvae, this represents a split of the EMERGY. Each tiny new individual carries an information copy. If the population is at steady state the larvae grow and are depleted in number by mortality eventually replacing two adults. This is a closed life cycle dependent on all the inputs necessary for the whole sequence. The EMERGY per individual is a transformity that grows reaching a maximum with the reproducing individuals. For a mortality commensurate with growth of the surviving, post-larvae with 50% further mortality represents 2 individuals that will finally restore 1 adult. Thus a transformity for the post-larvae is half that of the reproducing adult before harvest (.5 * 4 E6 sej/J). On an individual basis the solar transformity is:

(0.5)(4 E6 sej/J)(10 g/ind)(.2 dry)(6.2 kcal/g)(4186 J/kcal) = 1.04 E11 sej/ind

5. Transformity of Labor in Ecuador estimated as national EMERGY/person/yr
   Energy/person = (2500 kcal/d)(365 d/yr)(4186 J/kcal)(4186 J/kcal) = 3.82 E9 J/yr.
   Solar transformity = (10 E15 sej/ind/yr)/(3.82 E9 J/ind/yr) = 1.32 E14 J/yr
6. Fuel: estimated as a percent of operating cost of pumped pond; price (Aquacultura del Ecuador, 1988):
   ($.10/lb shrimp)(26.4 E6 kg/yr)(2.2 lbs/kg)/($.34/gal fuel) = 17 E6 gal/yr
   (17.1 E6 gal/yr)(137 E6 J/gallon) = 2.34 E15 J/yr
7. Nitrogen fertilizer for each 6 month start; 1.3 g/m$^3$ N;
   Volume: (1.5 m deep)(2.91 E8 m$^2$) = 4.365 E8 m$^3$
   (4.365 E8 m$^3$)(1.3 g/m$^3$)(2/yr) = 1.135 E9 g/yr
8. Phosphorus fertilizer for each 6 month start: 0.3 g/m$^3$;
   (4.365 E8 m$^3$)(0.3 g/m$^3$)(2/yr) = 2.62 E8 g/yr
9. Feed; Fish meal from offshore herring, sardines; See text figure.
   Total feed = sum of 23,600 Ha of semi-extensive ponds, fed for last 60 days.
   (45 kg/ha/d)(1 E3 g/kg)(2.36 E4 ha)(60 d)(5.7 kcal/g)(4186 J/kcal) = 1.52 E15 J/yr and 5500 Ha of semi-intensive ponds, fed for 300 days:
   (45 kg/ha/d)(1 E3 g/kg)(5500 ha)(300 d)(5.7 kcal/g)(4186 J/kcal) = 1.77 E15 J/yr
   Total feed supplement: (1.52 + 1.77 = 3.29 E15) J/yr
   Much of the fish meal came from herring, sardines, etc mostly beyond the continental shelf. A solar transformity was estimated using organic carbon per spare meter in herring sardines and anchovettas yield from the pelagic upwelling system published by Walsh (1981) divided by the solar EMERGY of the current. EMERGY of direct solar energy, and chemical energy of rain were also evaluated but were less than the physical energy of the Humboldt current. As lesser by products of the world weather system direct sun and oceanic rain were omitted to avoid double counting.
   Fish yield was 6.71 grams Carbon/ m$^2$/year with energy content:
   (6.71 g C/m$^2$/yr)(2.5 g org./g C)(5.7 kcal/g)(4186 J/kcal) = 4.00 E5 J/m$^2$/yr.
   Solar Emergy input per square meter of pelagic ecosystem generating this meal includes direct sun, rain, and the physical energy being used from the several

sources driving the Humboldt current, the waves, and upwelling. The circulation of the east Pacific gyral includes wind energy transferred from the large scale circulation of the atmosphere wind plus large scale pressure gradients maintained by density differences due to temperature and salinity differences. In this pelagic system unlike the inshore ones, the tidal absorption and river contributions are less. The physical energy was estimated by assuming a fraction of 1% of the kinetic energy used up per day in steady state with the sources. As the calculations below show, the EMERGY of the direct sun and direct rain are small by comparison.
EMERGY of direct solar Energy under offshore stratus:
(1 m$^2$)(1.00 E6 kcal/m$^2$/yr)(4186 J/kcal)(1 sej/J) = 4.19 E9 sej/m$^2$yr
Physical energy (tentative pending better sources);
(0.5)(.3 m/sec)(.3 m/sec)(100 m deep)(1 m$^2$)(1025 kg/m$^3$)(.01/day)(365 d/yr) = 1.68 E4 J/m$^2$/yr physical energy
EMERGY flux using solar transformity of river current at New Orleans: (4.67 E4 J/m$^2$/yr)(80 E5 sej/J) = 1.34 E11 sej/m$^2$/yr
Rainfall chemical energy on the open sea:
The solar transformity of rain falling over the ocean is different from that over land. Land is at a higher level in the geological hierarchy in which the solar energy falling on the seas is part of the basis for converging atmospheric processes to interact with continent building processes to generate rain on land. Solar transformity of rain over land was calculated as the quotient of the earchs annual EMERGY divided by the Gibbs free energy of the rain over land relative to sea water. Rain over the sea is a necessary by-product feedback lower in the hierarchy with larger volume for the same earth EMERGY budget. Rain over ocean was assumed 71/29 of 1.05 E14 m$^3$/yr rain over land in proportion to the ocean/land areas.

$$\text{Solar transformity of oceanic rain} \quad \frac{8.1\text{ E24 sej/yr/earch}}{(2.57\text{ E14 m}^3\text{/yr})(1\text{ E6 g/m}^3)(4.94\text{ J/g})} = 6380\text{ sej/J}$$

(1.0 m) (1 m$^2$)(1 E6 g/m$^3$)(4.94 J/g) = 4.9 E6 J/m$^2$/yr
Solar Emergy: (4.9 E6 J/m$^2$/yr)(630 sej/J) = 3.13 E10 sej/m$^2$/yr
Solar transformity of the fish meal based on 1 m$^2$ of pelagic offshore; see Figure. EMERGY sum (1.34 + .014 = 1.35) E11
(5.24 E10 sej/m$^2$/yr)/(4.00 E5 J/m$^2$) fish meal = 1.31 E5 sej/J
Costs (services) of feed supplement for 1986 from Camara de Productores de Camaron (1989)
EMERGY value added in fishmeal preparation:
(17% cost for supplementary feeding)(150 E6 \$) = 25.5 E6 \$
(8.7 E12 sej/\$)(\$25.5 E6) - 2.2 E20 sej/yr

10. Operating costs given as \$2.70 (1986 U.S. \$) per kilogram of shrimp yield.
(\$2.70 US/kg)(26.4 E6 kg/yr yield) = 71.2 E6 U.S.\$;
Half of this is for post larvae (note 11) and half for other services:
(0.5)(71.2 E6 US\$) = 35.6 E6 US \$.

For evaluating EMERGY, use 8.7 sej/$ within Ecuador calculated in Table XXXX.

11. Costs of post larvae: 50% of total operating cost (note 10): 35.6 E6 $US
12. Capital costs: (235 E3 sucre/ha)(2.91 E4 Ha)/(122 sucre/$) = 58 E6 $US
    Assume 30 year life of ponds; annual cost = 58 E6 $US/30 yr = 1.93 $US/yr
13. Interest on loans for capital investment at 20% of principal
    (.2)(58 E6 $US/30 yr) = 11.6 E6 $US. Whether aid to an investor within Ecuador or one in the U.S., the sucres when converted to international $ represent EMERGY according to the Ecuadorian EMERGY/$ ratio (8.5 sej/$).
14. Yield: 30,000 tonne/yr:
    (3.10 E10 g/yr)(0.2 dry)(67 kcal/g dry)(4186 J/kcal) = 1.68 E14 J/yr
15. Yield without organic feed: 598 lb/a (Camara de productores de Camaron, 1989)
    (5.3 E4 Ha)(598 lb/Ha)(454g/lb)(.2 dry)(6.7 Kcal/g dry)(4186 J/kcal)
    = 9.28 E13 J/yr

**Table 13**. Emergy evaluation of 1 hectare Venezualian tropical dry savanna (after Prado-Jutar and Brown, 1997)

| Note | Item | Raw Units | Emergy/unit (sej/unit) | Solar Emergy E12 sej/ha*yr$^{-1}$ |
|---|---|---|---|---|
| RENEWABLE RESOURCES: | | | | |
| 1 | Sunlight | 4.10 E13 J | 1 | 41.0 |
| 2 | Rain, chemical | 2.47 E10 J | 18199 | 450.4 |
| 3 | Rain, geopotential | 2.45 E7 J | 27874 | 0.7 |
| 4 | Wind, kinetic energy | 3.10 E10 J | 1496 | 46.4 |
| 5 | Earth Cycle | 1.00 E10 | 34377 | 343.8 |
| Transformity of NPP and GPP | | | | |
| 6 | NPP of Savanna | 4.52 E10 | 9963 | 450.4 |
| 7 | GPP of savanna veg. | 2.40 E11 | 1880 | 450.4 |
| Transformity of Standing Biomass | | | | |
| 8 | Savanna Biiomass | 1.28 E11 | 10549 | 1351.2 |

1 SOLAR ENERGY:
Area = 1.00 E4 $m^2$
Insolation = 1.40 E2 Kcal/$cm^2$/yr (Marrero, 1978)
Albedo = 0.30 (% given as decimal)
Energy(J) = (area incl shelf)*(avg insolation)*(1-albedo)
= (____$m^2$)(____Cal/$cm^2$/y)( E4$cm^2$/$m^2$)
(1-0.30)(4186J/kcal)
= 4.10 E13 J/yr

2 RAIN, CHEMICAL POTENTIAL ENERGY:
Area = 1.00 E4 $m^2$
Rain = 1.00 m/yr (Marrero, 1978)
Transporation rate = 50.00 % (as percent of rain)
Energy (J) = (area)(Trans)(rainfall)(Gibbs energy of rain)
= (____$m^2$)(____m)(___%)(1000kg/$m^3$)(4.94 E3J/kg)
= 2.47 E10 J/yr

3 RAIN, GEOPOTENTIAL ENERGY:
Area = 1.00 E4 $m^2$
Rainfall = 1.00 m
Avg. Elev = 1.00 m
Runoff rate = 0.25 (percent, given as a decimal )
Energy(J) = (area)(% runoff)(rainfall)(avg elevation)(gravity)
= (____$m^2$)(____m)(1000kg/$m^3$)(____m)(9.8m/$s^2$)
= 2.45 E7 J/yr

4 WIND ENERGY:
Area = 1.00 E4 $m^2$
Eddy diffusion coef. = 5.00 E0 $m^3/m^2$/sec (estimate)
Wind gradient = 4.00E-03 m/sec/m (estimate)
Energy(J) = (height)(density)(diffusion coeff)(wind gradient)$^2$(area)
= (1000m)(1.23 kg/$m^3$)(___$m^3$/m/sec)(3.154 E 07 sec/yr) (____m/sec/m)$^2$(___$m^2$)
= 3.10 E10 J/yr

5 EARTH CYCLE
Area = 1.00 E4 $m^2$
Heat flow = 1.00 E6 J/$m^2$ (Marrero, 1978)
Energy (J) = (5.11 E10)(1.00 E6)
= 1.00 E10

6 NPP of SAVANNA VEGETATION
Area = 1.00 E4 $m^2$
Production = 300 g/$m^2$/yr (Sarmiento, 1984)
Energy (J) = (area)(production)(3.6 Cal.g)(4186 J/Cal)
= 4.52 E10 J/yr

7 GPP of SAVANNA VEGETATION
Area = 1.00 E4 $m^2$
Production = 1590 kg/$m^2$/yr (dry wt) ( estimate = 5.3 times NPP)
Energy (J) = (area)(production)(3.6 Cal.g)(4186 J/Cal)
= 2.40 E11 J/yr

8 SAVANNA BIOMASS
Area = 1.00 E4 $m^2$
Standing biomass = 0.85 kg/$m^2$/yr (dry wt) (Prado-Jatar. 1997)
Turnover time = 3 yr
Energy (J) = (area)(biomass)(3.6 Cal.g)(4186 J/Cal)
= 1.28 E11 J/yr

**Table14**. Annual emergy supporting Southern Mixed Hardwood Forest Ecosystem (Florida) (Orrell, 1998)

| Note | Storage or Flow | Raw Units J/ha/yr | Emergy/unit sej/unit | Solar Emergy sej/ha*yr$^{-1}$ |
|---|---|---|---|---|
| | *Sources* | | | |
| 1 | Sun | 4.2 E13 | 1 | 4.2 E13 |
| 2 | Wind | 2.5 E9 | 1,496 | 3.8 E12 |
| 3 | Rain, physical | 2.2 E8 | 10,488 | 2.3 E12 |
| 4 | Rain, chemical potential | 6.4 E10 | 18,199 | 1.2 E15 |
| 5 | Run-in, chemical potential | 0 | 48,459 | 0 |
| 6 | Water use (Transpiration) | 2.6 E10 | 18,199 | 4.7 E14 |
| | *Storages (unit/ha)* | | | |
| 7 | Biomass | 2.2 E12 | 5,504 | 1.2 E16 |
| 8 | Soil moisture | 2.5 E8 | 41,000 | 1.0 E13 |
| 9 | Phosphorus | 3.2 E7 | 4.0 E7 | 1.3 E15 |
| 10 | Soil organic matter | 9.0 E12 | 11,360 | 1.0 E17 |
| 11 | Tree species richness | 20 species | 1.1 E19 sej/spec. | 2.2 E20 |
| | *Flows* | | | |
| 12 | Net production | 3.1 E11 | 1,543 | 4.7 E14 |
| 13 | Respiration | 4.7 E11 | 1021 | 4.7 E14 |
| 14 | Gross production | 7.8 E11 | 615 | 4.7 E14 |

Note:

1. *Sun*, North Central Florida mean net radiation 274 Langleys (Ly) per day; (Henning 1989); 10 kcal/m$^2$/Ly; 365 days;
   $(4.2 \times 10^9$ J/m$^2$/yr$)$ $(1 \times 10^4$ m$^2$/ha$) = 4.2 \times 10^{13}$ J/ha/yr
   Transformity: defined as 1.
2. *Wind*, North Central Florida mean daily wind 25 miles per day (NOAA, 1985);
   $P_m = (1000\text{ m})\ (1.23\text{ kg/m}^3)\ (2.24\text{ m}^2/\text{s})\ (.0017\text{ m/s/m})^2\ (7534)$
   $= 60\text{ cal/m}^2/\text{yr}\ (4186\text{ J/kcal})\ (1 \times 10^4\text{ m}^2/\text{ha}) = 2.51 \times 10^9\text{ J/ha/yr}$
   Transformity: 1,496 Sej/J (Odum 1996).
3. *Rain, physical*, 51 inches per year (NOAA, 1985);
   $(1.3\text{ m/yr})\ .5(1 \times 10^6\text{ g/m}^3)\ (5.79\text{ m/s})^2\ (2.38 \times 10^{-7})\ (4186\text{ J/kcal})$
   $(1 \times 10^4\text{ m}^2/\text{ha}) = 2.2 \times 10^8\text{ J/ha/yr}$
   Transformity: 10,488 (Odum 1996).
4. *Rain, chemical potential,* Rain has 10 ppm dissolved solids (Odum et al. 1987), 1.3 m/yr (NOAA 1985);
   $(1.3\text{ m/yr})\ (1 \times 10^4\text{ m}^2/\text{ha})\ (1/18\text{ g/mole})\ (1.99 \times 10^{-3}\text{ Cal/K*mole})$
   $(300\ ^0\text{K})\ (999{,}990)\ \ln\ (999{,}990/965{,}000)\ (4186\text{ J/kcal}) = 6.43 \times 10^{10}\text{ J/ha/yr}$
   Transformity; 18,199 (Odum 1996).
5. *Run-in, chemical potential,* Southern Mixed Hardwood Forest complex is not net sink for run-in.

6. *Water Use (transpiration),* Estimated .53 using information from Brown (1978) and Liu (1996);

   (.53 m/yr)(1 E4 m2/ha)(1/18 g/mole)(1.99E-3 Cal/
   K*mole)(300oK)(999,990)ln(999, 990/965,000)(4186 J/kcal) =
   =2.6 E10 J/ha/yr

Transformity: 18,199 (Odum 1996).

7. *Biomass,* green above ground biomass larger than 5 cm d.b.h. 216.6 tn/ha, estimated 40% water weight (Cost and McClure, 1982);

   (130 tn/ha)(1 E6 g/tn)(4 kcal/g)(4186 J/kcal) = 2.18 E12 J

Transformity: Emergy for transpiration 4.8 E14 sej/ha/yr, time to maturity estimated using simulation model 25 yrs.

   (4.8 E14 sej/ha/yr / 2.18 E12 J) * 25 yrs. = 5,504 sej/J

8. *Soil moisture,* 4.9 (g water/l soil) (Monk, 1968);

   (4.9 g/l)(1000 l/m3)(4.9 J/g)(1 E4 m2/ha) = 2.5 E8 J/m/ha

Transformity: 4.1 E4 sej/J (Odum 1996).

9. *Phosphorus,* 6.4 ppm total phosphorus (Monk 1968), bulk density 1.42 g/cm3 calculated using Soil Conservation Service maps and site location given (Monk 1968);

   (6.4 mg/phos./kg soil)(1 g/ 1000 mg)(1.42 g soil/cm3)(1 kg/1000 g)(1 E6
   cm3/m3)(1 E4 m3/ha)(348 J/g phos.) =
   =3.2 E7 J/ha

Transformity: Sun emergy per year + emergy of limestone uplift per year + emergy of rain + emergy of run-in per year /
Energy of phosphorus.

   3.5 E13 sej/ha/yr + 5.9 E13 sej/ha/yr + 1.2 E15 sej/ha/yr + 0 sej/ha/yr /
   3.2 E7 J/ha = 4.0 E7 sej/J

10. *Organic Matter,* .03976 g/cm3 calculated using Soil Conservation Service maps and site location given (Monk 1968);

    (.03976 g/cm3)(1 E6 cm3/m3)(1 E4 m2/ha)(5.4 kcal/g)(4186 J/kcal) =
    9.0 E12 J/ha

Transformity: Emergy for transpiration 4.8 E14 sej/ha/yr, time to develop soil storage of organic matter is estimated using simulation model 213 yrs.

   (4.8 E14 sej/ha/yr / 9.0+12 J) * 213 yrs. = 11,360 sej/J

11. *Species Richness,* Total north-central Florida area in which Monk's 156 ecosystem study plots were located (1966, 1967, 1968) 1904400 ha., average (weighted based on number of study plots for each ecosystem) emergy flow per unit area 1.5 E15 sej/ha/yr, total tree species counted for all ecosystem types 84.

    4.8 E14 sej/ha/yr * 1904400 ha = 9.1 E20 sej/yr

Transformity: (transpiration emergy * area) / total species found on study plots

   (9.1 E20 sej/yr) / 84 species = 1.1 E19 sej/species

12. *Net primary production,* 9.3 tn C /ha/yr estimated from available data;
    (9.3 tn/ha/yr)(1 E6 g/tn)(8 kcal/g)(4186 J/kcal) = 3.11 E11 J/yr

Transformity: Emergy for transpiration 4.8 E14 sej/ha/yr

   4.8 E14 sej/ha/yr / 3.11 E11 J/yr = 1,543 sej/J

13. *Plant respiration,* 14 tn C /ha/yr estimated from available data;
    (14 tn/ha/yr)(1 E6 g/tn)(8 kcal/g)(4186 J/kcal) = 4.7 E11 J/yr

Transformity: Emergy for transpiration 4.8 E14 sej/ha/yr
4.8 E14 sej/ha/yr / 4.7 E11 J/yr = 1,021 sej/J
14. *Gross production* = Net production + Respiration,
3.11 E11 J/ha/yr + 4.7 E11 J/ha/yr = 7.81 E11 J/ha/yr
Transformity: Emergy for transpiration 4.8 E14 sej/ha/yr
4.8 E14 sej/ha/yr / 7.81 E11 J/yr = 615 sej/J

**Table 15.** Annual emergy supporting Pine Flatwood Ecosystem (Florida). (Orrell, 1998)

| Note | Storage or Flow | Raw Units J/ha/yr | Emergy/unit sej/unit | Solar Emergy sej/ha*yr$^{-1}$ |
|---|---|---|---|---|
| | *Sources* | | | |
| 1 | Sun | 4.2 E13 | 1 | 4.2 E13 |
| 2 | Wind | 2.5 E9 | 1,496 | 3.8 E12 |
| 3 | Rain, physical | 2.2 E8 | 10,488 | 2.3 E12 |
| 4 | Rain, chemical potential | 6.4 E10 | 18,199 | 1.2 E15 |
| 5 | Run-in, chemical potential | 0 | 48,459 | 0 |
| 6 | Water use (Transpiration) | 2.7 E10 | 18,199 | 4.9 E14 |
| | *Storages (unit/ha)* | | | |
| 7 | Biomass | 1.8 E12 | 10,736 | 1.9 E16 |
| 8 | Soil moisture | 5.0 E8 | 41,000 | 2.1 E13 |
| 9 | Phosphorus | 6.3 E6 | 2.0 E8 | 1.3 E15 |
| 10 | Soil organic matter | 9.8 E12 | 13,450 | 1.3 E17 |
| 11 | Species richness | 10 species | 1.1 E19 sej/spec. | 1.1 E20 |
| | *Flows* | | | |
| 12 | Net production | 2.9 E11 | 1,690 | 4.9 E14 |
| 13 | Respiration | 4.4 E11 | 1126 | 4.9 E14 |
| 14 | Gross production | 7.3 E11 | 676 | 4.9 E14 |

1. *Sun*, North Central Florida mean net radiation 274 Langleys (Ly) per day; (Henning 1989); 10 kcal/m$^2$/Ly; 365 days;
   $(4.2 \text{ x } 10^9 \text{ J/m}^2\text{/yr}) (1 \text{ x } 10^4 \text{ m}^2\text{/ha}) = 4.2 \text{ x } 10^{13}$ J/ha/yr
   Transformity: defined as 1.
2. *Wind*, North Central Florida mean daily wind 25 miles per day (NOAA, 1985);
   $P_m = (1000 \text{ m}) (1.23 \text{ kg/m}^3) (2.24 \text{ m}^2\text{/s}) (.0017 \text{ m/s/m})^2 (7534)$
   $= 60 \text{ cal/m}^2\text{/yr} (4186 \text{ J/kcal}) (1 \text{ x } 10^4 \text{ m}^2\text{/ha}) = 2.51 \text{ x } 10^9$ J/ha/yr
   Transformity: 1,496 Sej/J (Odum 1996).
3. *Rain, physical*, 51 inches per year (NOAA, 1985);
   $(1.3 \text{ m/yr}) .5(1 \text{ x } 10^6 \text{ g/m}^3) (5.79 \text{ m/s})^2 (2.38 \text{ x } 10^{-7}) (4186 \text{ J/kcal})$
   $(1 \text{ x } 10^4 \text{ m}^2\text{/ha}) = 2.2 \text{ x } 10^8$ J/ha/yr
   Transformity: 10,488 (Odum 1996).
4. *Rain, chemical potential,* Rain has 10 ppm dissolved solids (Odum et al. 1987), 1.3 m/yr (NOAA 1985);
   $(1.3 \text{ m/yr}) (1 \text{ x } 10^4 \text{ m}^2\text{/ha}) (1/18 \text{ g/mole}) (1.99 \text{ x } 10^{-3} \text{ Cal/K*mole})$
   $(300\ ^0\text{K}) (999{,}990) \ln (999, 990/965{,}000) (4186 \text{ J/kcal}) = 6.43 \text{ x } 10^{10}$ J/ha/yr
   Transformity; 18,199 (Odum 1996).
5. *Run-in, chemical potential,* Pine Flatwood complex is not net sinks for run-in.
6. *Water Use (transpiration),* Estimated .554 using information from Brown (1978) and Liu (1996);

(.554 m/yr)(1 E4 m2/ha)(1/18 g/mole)(1.99E-3 Cal/K*mole)(300oK)(999,990)ln(999, 990/965,000)(4186 J/kcal) =
=2.7 E10 J/ha/yr

Transformity: 18,199 (Odum 1996).

7. *Biomass,* green above ground biomass larger than 5 cm d.b.h. 177 tn/ha, estimated 40% water weight (Cost and McClure, 1982);

   (106.2 tn/ha)(1 E6 g/tn)(4 kcal/g)(4186 J/kcal) = 1.78 E12 J

   Transformity: Emergy for transpiration 4.9 E14 sej/ha/yr, time to maturity estimated using simulation model 39 yrs.

   (4.9 E14 sej/ha/yr / 2.0 E12 J) * 39 yrs. = 10,736 sej/J

8. *Soil moisture,* 10 (g water/l soil) (Monk, 1968);

   (10 g/l)(1000 l/m3)(4.9 J/g)(1 E4 m2/ha) = 5 E8 J/m/ha

   Transformity: 4.1 E4 sej/J (Odum 1996).

9. *Phosphorus,* 1.3 ppm total phosphorus (Monk 1968), bulk density 1.4 g/cm3 calculated using Soil Conservation Service maps and site location given (Monk 1968);

   (1.3 mg/phos./kg soil)(1 g/ 1000 mg)(1.4 g soil/cm3)(1 kg/1000 g)(1 E6 cm3/m3)(1 E4 m3/ha)(348 J/g phos.) =
   =6.3 E6 J/ha

   Transformity: Sun emergy per year + emergy of limestone uplift per year + emergy of rain + emergy of run-in per year /
   Energy of phosphorus.

   3.5 E13 sej/ha/yr + 5.9 E13 sej/ha/yr + 1.2 E15 sej/ha/yr + 0 sej/ha/yr /
   1.8 E7 J/ha = 2.0 E8 sej/J

10. *Organic Matter,* .0434 g/cm3 calculated using Soil Conservation Service maps and site location given (Monk 1968);

    (.0434 g/cm3)(1 E6 cm3/m3)(1 E4 m2/ha)(5.4 kcal/g)(4186 J/kcal) =
    9.8 E12 J/ha

    Transformity: Emergy for transpiration 4.9 E14 sej/ha/yr, time to develop soil storage of organic matter is estimated using simulation model 269 yrs.

    (4.9 E14 sej/ha/yr / 9.8+12 J) * 269 yrs. = 13,450 sej/J

11. *Species Richness,* Total north-central Florida area in which Monk's 156 ecosystem study plots were located (1966, 1967, 1968) 1904400 ha., average (weighted based on number of study plots for each ecosystem) emergy flow per unit area
    1.5 E15 sej/ha/yr, total tree species counted for all ecosystem types 84.

    4.9 E14 sej/ha/yr * 1904400 ha = 9.3 E20 sej/yr

    Transformity: (transpiration emergy * area) / total species found on study plots

    (9.3 E20 sej/yr) / 84 species = 1.1 E19 sej/species

12. *Net primary production,* 8.6 tn C /ha/yr (Golkin and Ewel 1984);

    (8.6 tn/ha/yr)(1 E6 g/tn)(8 kcal/g)(4186 J/kcal) = 2.9 E11 J/yr

    Transformity: Emergy for transpiration 4.9 E14 sej/ha/yr

    4.9 E14 sej/ha/yr / 2.9 E11 J/yr = 1,690 sej/J

13. *Plant respiration,* 13 tn C /ha/yr (Golkin and Ewel 1984);

    (13 tn/ha/yr)(1 E6 g/tn)(8 kcal/g)(4186 J/kcal) = 4.35 E11 J/yr

    Transformity: Emergy for transpiration 4.9 E14 sej/ha/yr

    4.9 E14 sej/ha/yr / 4.35 E11 J/yr = 1,126 sej/J

14. *Gross production* = Net production + Respiration,
2.9 E11 J/ha/yr + 4.35 E11 J/ha/yr = 7.25 E11 J/ha/yr
Transformity: Emergy for transpiration 4.9 E14 sej/ha/yr
4.9 E14 sej/ha/yr / 7.25 E11 J/yr = 676 sej/J

**Table 16**. Annual Emergy supporting a Mangrove Nursery System of Ecuador. 119,500 Hectares. (Odum and Arding 1991)

| Note | Item | Raw Units J,g,$ | Emergy/unit Sej/unit | Solar EMERGY E18 sej/yr | EM$ 1989 US E6 em$/yr |
|---|---|---|---|---|---|
| 1 | Solar energy | 4.4 E18 J | 1 | 4.44 | 2.22 |
| 2 | Wind energy | 4.4 E14 J | 623 | 0.27 | 0.14 |
| 3 | Mangrove transpiration | 4.4 E15 J | 41068 | 179.06 | 89.53 |
| 4 | Rain chemical potential | 5.2 E15 J | 15444 | 80.31 | 40.15 |
| 5 | Tides | 4.2 E15 J | 23564 | 99.91 | 49.96 |
| 6 | Total solids from sewer | 5.8 E10 J | 62400 | 0.00 | 0.00 |
| 7 | Total N from sewers | 4.2 E8 g | 9.00 E8 | 0.38 | 0.19 |
| 8 | Total P from sewers | 5.15 E7 g | 8.10 E9 | 0.42 | 0.21 |
| 9 | Biomass growth | 1.9 E16 J | 14684 | 279.00 | 139.50 |
| 10 | Litterfall | 2.1 E16 J | 13285 | 279.00 | 139.49 |

1 Solar input: 1195E6 m2, 127 kcal/cm-yr average solar insolation.
(1195 E6 m2)(127E4 kcal/m2-yr)(.7 absorbed)(4186 J/kcal) = 4.44 E18 J/yr

2 Wind energy: 19% of total wind energy available to inshore system (areal ratio) = 4.4 E14 J (see Odum and Arding 1991. Table 12, note #2)

3 Mangrove transpiration:
(2.5 mm/d)(365 d/yr)(1000 g/mm/m2)(4.0 J/g)(1195 E6 m2) = 4.36 E15 J/yr

4 Rain chemical potential energy: Av. Precipitation in Guayaquil 885 mm/yr (Twilley, 1986):
(1195 E6 m2)(.885m)(1 E6 g/m3)(4.94 J/g) = 5.2 E15 J/yr

5 Tidal energy range absorbed in mangroves, 1.0 m:
(706 /yr)(9.8 m/s2)(1.025 E3 kg/m3)(11.195 E9 m2)(1.0 M)(1.0 m) = 4.23 E15 J/yr

6 Total suspended solids in sewer effluent: 6456 E6 g/yr. 0.2 of area;
(0.2)(6456 E6 g)(0.002 organic)(5.4 kcal/g)(4186 J/kcal) = 5.84 E10 J/yr

7 Nitrogen concentration in sewer effluent: 2.1 E9 g/yr; 0.2 of estuary area (Twilley, 1986).
(2.1 E9)(.2) = 4.2 E8 g/yr

8 Phosphate concentration in sewer effluent 2.58 E8 g/yr (Twilley, 1986); 0.2 area
(2.58 E8)(.2) = 5.15 E7 g/yr

9 Mangrove biomass growth: 2.8 g/m2-day (observation from Snedaker, 1986 and Sell, 1977).
(1195 E6 m2)(2.8 g/m2-d)(365 d)(3764 cal/g)(4.186 J/cal) = 1.9 E16 J/yr
Transformity: (279 E18 sej/yr -sum of transpiration and tide)/(1.9 E16 J/yr) = 14684 sej/J

10 Mangrove litter fall: 957 - 1032 g/m2-yr (Sell, 1977); av 995 /m2-yr.
(995 g/m2)(1195 E6 m2)(4139 cal/g)(4.186 J/cal) = 2.1 E16 J/yr
Transformity: (279 E18 sej/yr)/(2.1 E16 J/yr) = 13285 sej/J

**Table 17.** Emergy evaluation of environmental inputs to central Florida, Cypress dominated floodplain wetland, with solar transformity of tree seeds. (after Weber, 1996)

| Note | Item | Data, unit per m$^2$/day | Emergy/unit sej/unit | Solar Emergy E5sej/m$^2$*day$^-$ |
|---|---|---|---|---|
| Environmental inputs | | | | |
| a | Direct sun | 1.13 E7 J | 1.00 | 113 |
| b | Wind | 2.03 E2 J | 1.50 E3 | 3.04 |
| c | Water used | 4.29 E3 J | 1.82 E4 | 780 |
| d | Sediment deposition | 7.23 E3 J | 7.40 E4 | 5347 |
| e | total environmental inputs | | | 6127 |
| One of products yielded | | | | |
| f | Tree seeds | 0.13 g | 4.71 E9 sej/g | 6127 |
| g | Gross PrimaryPond | 1.1253 J | 5.46 E3 sej/J | 6127 |

Footnotes:

a Albedo = 0.30
Insolation = 3860 kcal/m$^2$/day
Sunlight used = (3860 kcal/m$^2$/day)(4186 J/kcal)(1-0.3) = 1.13 E7 J/m$^2$/day

b Kinetic energy of wind = (height)(density)(diffusion coefficient)(wind gradient)
Height = 1000 m
Density = 1.23 kg/m$^3$
Eddy diffusion coefficients (Tampa, FL) =
Winter: 2.8 m$^3$/m$^2$/sec
Summer: 1.7 m$^3$/m$^2$/sec
Wind velocity gradients (Tampa, FL) =
Winter: 2.3E-03 m/sec/m
Summer: 1.5E-03 m/sec/m
Winter wind energy = (1000 m)(1.23 kg/m$^3$)(2.8 m$^3$/m$^2$/sec)*
(1.577E7 sec/0.5 year)(2.3E-3 m/sec/m)$^2$ = 2.87 E5 J/m$^2$/0.5 year
Summer wind energy = (1000 m)(1.23 kg/m$^3$)(1.7 m$^3$/m$^2$/sec)*
(1577E7 sec/0.5 year)(1.5E-3 m/sec/m)$^2$ = 7.42 E4 J/m$^2$/0.5 year
Total wind energy = 3.62 E5 J/m/year
Transformity from Brown and Arding (1991)

c Water used (transpiration in Louisiana mixed hardwood forest) = 868 g/m$^2$/day
Water used = (868 g/m$^2$/day)(4.94 J/g) = 4.29 E3 J/m$^2$/day
Transformity from Brown and Arding (1991)

d Average deposition of organic matter in Apalachicola Basin = 150 g/m$^2$/year

Fraction of deposition absorbed by trees (Mitsch and Gosselink, 1993, for phosphorus in southern Illinois alluvial cypress swamp) = 0.78
Chemical potential in sediment deposition used by trees =
(150 g OM/m$^2$/year)(0.78)(1 year/365 days)(5.4 kcal/g)(4186 J/kcal) – 7225.15 J/m$^2$/day
Transformity from Brown and Arding (1991)

e Total environmental inputs = sum of a-d

f See Table G-1 for mass flux of tree seeds.
The emergy flux in primary production equals the emergy sum of environmental inputs, and is assigned to each byproduct, including tree seeds.
Solar transformity f tree seeds = solar emergy of tree seeds / grams of tree seeds

g Forest gross primary production = 7.05 g/m$^2$/day
Heat content of wood = 3.8 kcal/g
(note: heat content and transformity of leaves, harvested wood (bole & large branches), and unharvested wood (roots & small branches) are assumed to be similar enough for approximation)

Forest gross primary production = 7.05 g/m$^2$/day * 3.8 kcal/g * 4186 J/kcal = 1.12 E5 J/m$^2$/day
Emergy of forest gross primary production = total environmental inputs
Transformity of forest gross primary production = solar emergy of gross primary production / grams of gross primary production

**Table 18** Empower of Sawgrass Waters* (from Odum, 2000)

| Note | Item, units | Units/yr | Emergy/unit sej/unit | Empower E18 sej/yr | Emvalue# E6 Em$/yr |
|---|---|---|---|---|---|
| Sources | | | | | |
| 1 | Sun, J | 23.5 E18 | 1 | 24 | 24 |
| 2 | Rain, g | 5.2 E15 | 9 E4 | 468 | 468 |
| 3 | Flow from slough, g | 4.71 E14 | 6.8 E5 | 320 | 320 |
| 4 | Other inflow | 5.24 E14 | 5.6 E5 | 293 | 293 |
| 5 | Slough phos. flow, g | 2.35 E7 | 1 E11? | 2.3 | 2.3 |
| 6 | Other phos. inflow, g | 1.0 E8 | 1 E11? | 10 | 10 |
| 7 | Slough. nitrog., g | 4.7 E8 | 1 E10? | 4.7 | 4.7 |
| 8 | Other nitrog. inflow, g | 4 E8 | 1 E10? | 4 | 4 |
| 9 | ain phos., g | 2.93 E8 | 9 E4 | <0.1 | <0.1 |
| 10 | Rain nitrog., g | 4.2 E9 | 9 E4 | <0.1 | <0.1 |
| 11 | Land support, g | 7 E9 | 1 E9 | 7 | 7 |
| 12 | Maint. services | | | | |
| Sum (2 + 3 + 4) | | | | 1081 | 1081 |
| Emergy Production & Use within Conservation areas | | | | | |
| 13 | Evapotranspired | 4.2 E15 | 2.6 E5 | 1081 | 1081 |
| 14 | Net deposit peat, J | 9.2 E15 | 1.17 E5 | 1081 | 1081 |
| 15 | Water outflow | 2.0 E15 | 5.4 E5 | 1060 | 1060 |
| 16 | Phosphorus outflow | 4.0 E7 | 1 E11 | 4 | 4 |
| 17 | Nitrogen outflow | 1.55 E9 | 1 E10? | 16 | 16 |

* area: 862,800 acres = 3.49 E9 m$^2$ in Conservation areas (#1, 2, and 3)
1 acre-foot = 1233 m$^3$
#Empower divided by 1.0 E12 sej/(2000 $)

Footnotes for Table 18:

1 Solar energy from Miami, NOAA 441 langley/
(4410 kcal/m$^2$/day)(4186 J/kcal)(365 d/yr)(3.49 E9 m$^2$)
= 23.5 E18 J/yr

2 Rain, 60 inches (1930-1974, record US Corp of Army Engineers)
(60 in/yr)(0.0254 m/in)(1 E6 g/m$^3$)(3.49 E9 m$^2$) = 5.2 E15 g/yr

3 4.71 E14 g water/yr outflow from slough to the north. See Table Odum 2001).

4 Other water flow: restudy flow to conservation areas using Obeysekera diagram plus agricult. runoffs from 3/4 of present agriculture minus flow from slough:
(150 + 70 = 220 E3 acft/yr)(1233 m$^3$/acft)(1 E6 g/m$^3$) = 2.7 E14 g/yr
(9.75)(275 E3 acft/yr)(1233 m$^3$/acft)(1 E6 g/m$^3$) = 2.54 E14 g/yr from remaining ag areas
(2.7 E14 g/yr + 2.54 E14 g/yr) = 5.24 E14 g/yr

5 2.35 E7 g P/yr outflow from slough to the north, ( See Odum, 2001)

6 Other phos inflow:
(5.24 E14 g water/yr)(0.20 g P/m$^3$)/(1 E6 g water/m$^3$) = 1 E8 g/yr

7 Nitrogen from slough from Odum, (2001)

8 Other nitrog. inflow:
(0.8 E14 g water/yr)(5.0 g N/m$^3$)/(1 E6 g water/m$^3$) = 4 E8 g/yr

9 Rain phosphorus (Joyner, 1974 in Morris, 1975) 0.056 g P/m$^3$ in rain
(0.056 g Pm$^3$)(1.5 m rain)(3.49 E9 m$^2$) = 2.93 E8 g P/yr

10 Rain nitrogen (Morris, 1975)
(1.2 g N/m$^2$/yr)(2 E6 g/m$^3$ marl)(3.49 E9 m$^2$) = 7.0 E9 g/yr

11 Land cycle small, little solution or erosion
(1 E6 m$^3$/m$^2$/yr)(2 E6 g/m$^3$ marl)(3.49 E9 m$^2$) = 7.0 E9 g/yr

12 (___$/mile/yr)(50 miles levee) = $/yr

13 Evapotranspiration; Fla. Atlas has excess rain over pot. evaporation for that area as 9"; so evapotranspiration ma be 60" minus 9" = 49" or 81% of rain: (5.2 E15 g/yr)(0.81) = 4.2 E15 g/yr ET
Emergy/mass that of the water and its outflow in line 15

14 Peat deposit by sawgrass: Gleason et al., 1974) = 0.084 cm/yr
(0.084 cm/yr)(0.01 m/cm)(1 E6 g/m$^3$)(0.15 g dry) = 126 g dry/m$^2$/yr
(126 g/m$^2$/yr)(3.49 E9/m$^2$) = 4.4 E11 g dry/yr
(4.4 E11 g dry/yr)(5 kcal/g)(4186 J/kcal) = 9.2 E15 J/yr
Transformity using emergy of evapotranspiration:
2268 E18 sej/yr)/(9.2 E15 J/yr) = 2.5 E5 sej/J

15 Water outflow = inflow + rain – transpiration – percolation
(4.71 E14 + 5.24 E14 + 5.2 E15 – 4.2 E15 – 0?) = 2.0 E15 g/yr
Emergy/mass of water X from in-out transformation equation:
Emergy inflow in rain and inflow: 815 E18 sej/yr)
(1081 E18 sej/yr) = (X)(2 E15 g/yr) and therefore
X = 5.3 E5 sej/g

16 Phosphorus outflow
(2.0 E15 g water/yr)(0.02 g P/m$^3$ water)/(1 E6 g water/m$^3$) = 4 E7 g P/yr

17 Nitrogen outflow
(1.55 E15 g water/yr)(1 g/m$^3$ N)/1 E6 g water/m$^3$) = 1.55 E9 g N/yr

**Table19.** Emergy flows supporting subtropical herbaceous wetland, Florida. (Bardi and Brown, 2001)

| Note | Item | Data | Units | Emergy/unit (sej/unit) | Solar Emergy E15 sej/ha*yr$^{-1}$ |
|---|---|---|---|---|---|
| | *Energy Sources* | | | | |
| 1 | Sun | 4.19 E13 | J/ha/yr | 1 | 0.04 |
| 2 | Wind | 3.15 E9 | J/ha/yr | 1496 | 0.005 |
| 3 | Rain, chemical potential | 6.42 E10 | J/ha/yr | 18199 | 1.17 |
| 4 | Run-in, chemical potential | 2.25 E10 | J/ha/yr | 51867 | 1.17 |
| 5 | Geologic input | 2.97 E6 | g/ha/yr | 1.00 E9 | 2.97 |
| | *Functions (Env. Services)* | | | | |
| 6 | Transpiration (water use ) | 2.67 E10 | J/ha/yr | 26928 | 0.72 |
| 7 | GPP | 8.54 E11 | J/ha/yr | 4319 | 3.69 |
| 8 | Infiltration | 1.82 E10 | J/ha/yr | 26928 | 0.49 |
| | *Structure (Natural Capital)* | | | | |
| 9 | Live Biomass | 1.00 E11 | J/ha | 73426 | 7.38 |
| 10 | Peat | 3.77 E12 | J/ha | 183870 | 693.41 |
| 11 | Water | 3.94 E10 | J/ha | 26928 | 1.06 |
| 12 | Basin Structure | 6.10 E6 | J/ha | 1.0 E12 | 6209.30 |

Notes to **Table 19**.

1 SOLAR INSOLATION

Area of wetland = 1.00 E4 $m^2$
Mean Net Radiation = 274 Ly (Henning, 1989)
= (1.00 E4 $m^2$)(274 Ly)(10 Cal/$m^2$/Ly)(4186 J/Cal)(365 days)
= 4.19 E13 J/ha/yr
Transformity = defined as 1

2 WIND

Boundary Layer Height = 1000 m
Density = 1.23 Kg/$m^3$ (Odum 1996)
Eddy Diff. Coefficient = 2.25 $m^2$/s (Odum 1996)
Wind Gradient = 1.9 E-03 m/sec/m
Area = 1.00 E4 $m^2$/ha
= (boundary layer hgt)(den.)(eddy diff. Coeff.)

(3.15E7 sec/yr)(wind. gradient)$^2$(area)
= 3.1 E9 J/ha/yr
Transformity = 1,496 (Odum 1996)

3 RAIN, CHEMICAL POTENTIAL
Area = 1.00 E4 $m^2$/ha
Rainfall = 1.3 m/yr (NOAA 1985)
Gibbs Free Energy = 4.94 J/g2
= (1.00 E4 $m^2$/ha)(1.3 m)(4.94 J/g)(1.00 E6 g/$m^3$)
= 6.42 E10 J/ha/yr
Transformity = 18,199 (Odum 1996)

4 RUN IN, CHEMICAL POTENTIAL
Assume 1 to 1 watershed to wetland ratio and run-off coefficient of 0.35
Run-in = 0.455 m/yr
Area = 1.00 E4 $m^2$/ha
Gibbs Free Energy = 4.94 J/g
= (0.406 m/yr)(1.00 E4 $m^2$/ha)(1.00 E6 g/$m^3$)(4.94 J/g)
= 2.25 E10 J/ha/yr
Transformity = 51,867 (calculated as 2.85 * transformity of rain assuming total rainfall is required to generate 35% runo-off)

5 GEOLOGIC INPUT
Limestone Eroded = 0.01485 cm/yr (44% less than Cypress based on filtration)
Density of Limestone = 2 g/$cm^3$
= (0.01898 cm/yr)(1.00 E8 $cm^2$/ha)(2 g/$cm^3$)
= 2.97 E6 g/ha/yr
Transformity = 1.00 E9 Sej/g (Odum 1996)

6 WATER USE (TRANSPIRATION)
(estimate from Zolteck, 1979; Abtew, 1996; Rushton, 1996)
Transpiration = 0.54 m/yr
Gibbs Free Energy = 4.94J/g
= (0.64 m)(1.00 E4 $m^2$/ha)(1.00 E6 g/$m^3$)(4.94 J/g)
= 2.67 E10 J/ha/yr
Transformity = 26928 (Calculated as weighted average of water and run-in)

7 GROSS PRIMARY PRODUCTION
*Net Primary Production + Respiration*
Net Primary Production = 600 g/$m^2$/yr (estimate from Zolteck et al., 1979)

= (600 g/m$^2$/yr)(4 Cal/g) (4186 J/Cal)(1.00 E4 m$^2$/ha)
= 1.00 E11 J//ha/yr
Plant respiration = 3000 g/m$^2$/yr(based on 80% of GPP)
= (2800 g/m2/yr)(4 Cal/g) (4186 J/Cal)(1.00 E4 m2/ha)
= 5.02 E11 J/ha/yr
Gross Production = 8.54 E11 J/ha/yr (sum of NPP and 1.5 * Respiration)
Total annual emergy = Sum of transpiration and geologic input
= 3.69 E15 Sej/ha/yr
Transformity = (3.69 E15 Sej/ha/yr / 8.54 E11 J/ha/yr)
= 4319 sej/J

8 INFILTRATION

Estimate from Rushton, 1996; 31% of water loss in marsh due to seepage.

Infiltration Rate = 0.37m/yr
Gibbs free energy = 4.94J/g
= (0.48 m/yr)(4.94 J/g)(1.00 E6 g/m$^3$)(1.00 E4 m$^2$/ha)
= 1.82 E10 J/ha/yr
Transformity = 26928 (Calculated as weighted average of rain and run-in)

9 LIVE BIOMASS

Biomass = 600 g dry weight/m$^2$ (estimate from Zolteck et al., 1979)
= (600 g/m$^2$/yr) (4 Cal/g) (4186 J/kcal) (1.00 E4 m$^2$/ha)
= 1.00 E11 J/ha
Total ann. emergy = Sum of transpiration and geologic input
= 3.69 E15 Sej/ha/yr
Time = 2 yrs
Transformity = (3.69 E15 sej/ha/yr * 2 yrs)/ 1.00 E11 J/ha/yr
= 73426 sej/J

10 PEAT

Peat Storage = 7.50 E3 m$^3$/ha (Zolteck et al., 1979)
Heat Content = 5.20 Cal/g
Density of Peat = 0.11 g dry matter/cm$^3$ (estimate from Zolteck et al., 1979)
% organic matter = 0.21 (as decimal) (estimate from Zolteck et al., 1979)
Time to dev. peat = 188 yrs @ 4 mm/yr (estimate)
Peat = (7.50 E3 m$^3$/ha)(1.00 E6 cm$^3$/m$^3$)(5.2

kcal/g)(4186 J/kcal)(0.07 g/cm$^3$)
= 3.77 E12 J/ha/yr
Total ann. Emergy = Sum of transpiration and geologic input
= 3.69 E15 Sej/ha/yr
Transformity = (3.69 E15 Sej/ha/yr * 188) / 3.77 E13 J/ha/yr
= 183870

11 WATER

Volume of water taken as 89.6% moisture content of volume of peat plus avg. standing water

Peat water = 6.72 E3 m$^3$/ha
Avg. water depth = 1.25 E3 m$^3$/ha
Gibbs Free Enrgy = 4.94 J/g
= (7.97 E3 m$^3$/ha)(1.00 E6 g/m$^3$)(4.94 J/g)
= 3.94 E10 J/ha/yr
Transformity = 26,928 (Calculated as weighted average of rain and run-in)

12 BASIN STRUCTURE

Energy in Basin =(density)(mass displ.)(ht/2)(gravity)(2.38E-11 Cal/erg)(4186 J/Cal)

Density = 2 g/cm$^3$ (Odum 1984)
Mass displaced = 25 cm$^3$
height = 25 cm (assume 25 cm depth)
gravity = 980 cm/s$^2$
= 6.10 E6 J/ha
Time = 1684 yrs (25cm/.01485cm/yr)
To.l ann. emergy = Sum of transpiration and geologic input
= 3.69 E15 Sej/yr
Transformity = (3.69 E15 sej/yr * 1684yrs) / 6.1 E6 J/ha
= 1.02 E12 sej/J

**Table 20.** Emergy evaluation of annual driving energies supportinga shrub-scrub wetlands (titi and willow dominated). (Bardi and Brown, 2001)

| Note | Item | Data | Units | Emergy/unit (sej/unit) | Solar Emergy E15 sej/ha*$yr^{-1}$ |
|---|---|---|---|---|---|
| | *Energy Sources* | | | | |
| 1 | Sun | 4.19 E13 | J/ha/yr | 1 | 0.04 |
| 2 | Wind | 3.15 E9 | J/ha/yr | 1496 | 0.00 |
| 3 | Rain, chemical potential | 6.42 E10 | J/ha/yr | 18199 | 1.17 |
| 4 | Run-in, chemical potential | 2.25 E10 | J/ha/yr | 51867 | 1.17 |
| 5 | Geologic input | 3.41 E6 | g/ha/yr | 1.0 E9 | 3.41 |
| | *Functions (Env. Services)* | | | | |
| 6 | Transpiration (water use ) | 3.89 E10 | J/ha/yr | 26928 | 1.05 |
| 7 | GPP | 1.05 E12 | J/ha/yr | 4261 | 4.46 |
| 8 | Infiltration | 1.98 E10 | J/ha/yr | 26928 | 0.53 |
| | *Structure (Natural Capital)* | | | | |
| 9 | Live Biomass | 1.29 E12 | J/ha | 69129 | 89.13 |
| 10 | Peat | 6.53 E12 | J/ha | 170606 | 1114.08 |
| 11 | Water | 5.17 E10 | J/ha | 26928 | 1.39 |
| 12 | Basin Structure | 8.79 E6 | J/ha | 7.9 E11 | 6941.60 |

Notes to **Table 20**

1 SOLAR INSOLATION

Area of wetland = 1.00 E4 $m^2$

Mean Net Radiation = 274 Ly (Henning 1989)

= (1.00 E4 $m^2$)(274 Ly)(10 Cal/$m^2$/Ly)(4186 J/Cal)(365 days)

= 4.19 E13 J/ha/yr

Transformity = defined as 1 (Odum 1996)

2 WIND

Boundary Layer Height = 1000 m

Density = 1.23 Kg/$m^3$ (Odum 1996)

Eddy Diff. Coefficient = 2.25 $m^2$/s (Odum 1996)

Wind Gradient = 1.9 E-03 m/sec/m

Area = 1.00 E4 $m^2$/ha

= (boundary layer hgt)(den.)(eddy diff. Coeff.)(3.15E7 sec/yr)(wind. gradient)$^2$(area)

= 3.1 E9 J/ha/yr

Transformity = 1,496 sej/J (Odum 1996)

3 RAIN, CHEMICAL POTENTIAL

Area = 1.00 E4 $m^2$/ha

Rainfall = 1.3 m/yr (NOAA 1985)
Gibbs Free Energy = 4.94 J/g2
=(1.00 E4 m$^2$/ha)(1.3 m)(4.94 J/g)(1.00 E6 g/m$^3$)
= 6.42 E10 J/ha/yr
Transformity = 18,199 (Odum 1996)

4 RUN IN, CHEMICAL POTENTIAL
Based on watershed area of 1 hectare and runoff coeff of 0.35
Run-in = 0.455 m/yr (Schwartz, 1989)
Area = 1.00 E4 m$^2$/ha
Gibbs Free Energy = 4.94 J/g
=(0.91 m/yr)(1.00 E4 m$^2$/ha)(1.00 E6 g/m$^3$)(4.94 J/g)
= 2.25 E10 J/ha/yr
Transformity = 51,867 (calculated as 2.85 * transformity of rain assuming total rainfall is required to generate 35% runo-off)

5 GEOLOGIC INPUT
Limestone Eroded = 0.01705 cm/yr (38% less than Cypress based on filtration)
Density of Limestone = 2 g/cm$^3$
= (0.01705 cm/yr)(1.00 E8 cm$^2$/ha)(2 g/cm$^3$)
= 3.41 E6 g/ha/yr
Transformity = 1.00 E9 Sej/g (Odum 1996)

6 WATER USE (TRANSPIRATION)
Transpiration = 2155 g $H_2O$/m$^2$/day (estimate from Schwartz, 1989)
Gibbs Free Energy = 4.94 J/g
= (2155g $H_2O$/m$^2$/day)(365 days)(1.00 E4 m$^2$/ha)(4.94 J/g)
= 3.89 E10 J/ha/yr
Transformity = 26928 (Calculated as weighted average of rain and run-in)

7 GROSS PRIMARY PRODUCTION
Net Primary Production = 551 g C/m$^2$/yr (estimate from Flohrschutz, 1978)
= (551 g C/m$^2$/yr)(8 Cal/g) (4186 J/C)(1 E4 m2/ha)
= 1.85 E11 J//ha/yr
Plant respiration = 1286 g C/m$^2$/yr (estimate from Flohrschutz, 1978)
=(1286 g C/m$^2$/yr)(8 Cal/g) (4186 J/Cal)(1 E4 m2/ha)
= 4.31 E11 J/ha/yr
Gross Production = 1.05 E12 J/ha/yr (Sum of NPP and 2*respiration)
Total annual emergy = Sum of transpiration and geologic input
= 4.46 E15 Sej/ha/yr

Transformity = (4.46 E15 Sej/ha/yr / 1.05 E12 J/ha/yr )
= 4261 sej/J

8 INFILTRATION

Infiltration Rate = 0.0011 m/day (estimate based on water balance)
Gibbs free energy = 4.94 J/g
= (0.0016 m/d)(365d/yr)(4.94 J/g)(1.00 E6 g/m$^3$)(1.00 E4 m$^2$/ha)
= 1.98 E10 J/ha/yr
Transformity = 26928 (Calculated as weighted average of water and run-in)

9 LIVE BIOMASS

Biomass = 7700 g/m$^2$ (Schwartz, 1989)
= (8400 g/m$^2$/yr) (1.00 E4 m$^2$/ha) (4 Cal/g) (4186 J/kcal)
= 1.29 E12 J/ha
Total ann. emergy = Sum of transpiration and geologic input
= 4.46 E15 Sej/ha/yr
Time = 20 yrs (estimate)
Transformity = (4.66 E15 sej/ha/yr * 20 yrs) / 1.41 E12 J
= 69129 Sej/J

10 PEAT

Peat Storage = 1.00 E4 m$^3$/ha (Schwartz, 1989)
Heat Content = 5.20 kcal/g
Density of Peat = 0.50 g/cm$^3$ (Schwartz, 1989)
% organic matter = 0.06 as decimal (Schwartz, 1989)
Time to dev. peat = 250 yrs @ 4mm/yr (estimate)
Peat = (1.00 E4 m$^3$/ha)(1.00 E6 cm$^3$/m$^3$)(0.5g/cm$^3$)(0.06)(5.2 kcal/g)(4186J/kcal)
= 6.53 E12 J/ha/yr
Total ann. emergy = Sum of transpiration and geologic input
= 4.46 E15 Sej/ha/yr
Transformity = (4.66 E15 Sej/ha/yr * 250) / 6.53 E12 J/ha/yr
= 170606 Sej/J

11 WATER

Volume of water taken as 89.6% moisture content of volume of peat plus avg. standing water

Peat water = 8.96 E3 m$^3$
Avg. water depth= 1.50 E3
Gibbs Free Enrgy = 4.94 J/g
= (10.06 E3 m$^3$)(1.00 E6 g/m$^3$)(4.94 J/g)
= 5.17 E10 J/ha/yr
Transformity = 26,928 (Calculated as weighted average of rain and run-in)

12 BASIN STRUCTURE

Energy in Basin =(den.)(mass displ.)(ht/2)(gravity)(2.38E-11 Cal/erg)(4186 J/Cal)

Density = 2 g/cm$^3$ (Odum 1984)
Mass displaced = 30 cm$^3$
height = 30 cm (assume avg. dept of 30 cm)
gravity = 980 cm/s$^2$
= 8.79 E6 J/ha
Time = 1760 yrs (30cm/.01705cm/yr)
Total ann. emergy = Sum of transpiration and geologic input
= 3.94 E15 Sej/yr
Transformity = (3.94 E15 sej/yr * 1760) / 8.79 E6 J/ha
= 7.90 E11 sej/J

**Table 21.** Annual emergy supporting subtropical, cypress dominated, depressional forested wetland (Bardi and Brown, 2001).

| Note | Item | Data | Units | Emergy/unit (sej/unit) | Solar Emergy E15 sej/ha*yr$^{-1}$ |
|---|---|---|---|---|---|
| | *Energy Sources* | | | | |
| 1 | Sun | 4.19 E13 | J/ha/yr | 1 | 0.04 |
| 2 | Wind | 3.15 E9 | J/ha/yr | 1496 | 0.005 |
| 3 | Rain, chemical potential | 6.42 E10 | J/ha/yr | 18199 | 1.17 |
| 4 | Run-in, chemical potential | 2.52 E10 | J/ha/yr | 46225 | 1.16 |
| 5 | Geologic input | 5.50 E6 | g/ha/yr | 1.00 E9 | 5.50 |
| | *Functions (Env. Services)* | | | | |
| 6 | Transpiration (water use ) | 3.80 E10 | J/ha/yr | 26096 | 0.99 |
| 7 | GPP | 1.54 E12 | J/ha/yr | 4207 | 6.49 |
| 8 | Infiltration | 2.88 E10 | J/ha/yr | 26096 | 0.75 |
| | *Structure (Natural Capital)* | | | | |
| 9 | Live Biomass | 3.55 E12 | J/ha | 73162 | 259.71 |
| 10 | Peat | 8.16 E12 | J/ha | 149536 | 1220.62 |
| 11 | Water | 4.32 E10 | J/ha | 26096 | 1.13 |
| 12 | Basin Structure | 2.44 E7 | J/ha | 4.66 E11 | 11367.70 |

Notes to **Table 21**.

1 SOLAR INSOLATION

Area of wetland = 1.00 E4 $m^2$

Mean Net Radiation = 274 Ly (Henning 1989)

= (1.00 E4 $m^2$)(274 Ly)(10 Cal/$m^2$/Ly)(4186 J/Cal)(365 days)

= 4.19 E13 J/ha/yr

Transformity = defined as 1 (Odum, 1996)

2 WIND

Boundary Layer Height = 1000 m

Density = 1.23 Kg/$m^3$

Eddy Diff. Coefficient = 2.25 $m^2/s$ (Odum 1996)

Wind Gradient = 1.9 E -03 m/sec/m (Odum 1996)

Area = 1.00 E4 $m^2$/ha

= (boundary layer height)(density)(eddy dif.coef)(3.15E7 sec/yr)(wind. gradient)$^2$(area)

= 3.1 E9 J/ha/yr

Transformity = 1,496 sej/J (Odum 1996)

3 RAIN, CHEMICAL POTENTIAL

Area = 1.00 E4 $m^2$/ha

Rainfall = 1.3 m/yr (NOAA 1985)
Gibbs Free Energy = 4.94 J/g
= (1.00 E4 m$^2$/ha)(1.3 m)(4.94 J/g)
(1.00 E6 g/m$^3$)
= 6.42 E10 J/ha/yr
Transformity = 18,199 (Odum 1996)

4 RUN IN, CHEMICAL POTENTIAL
Run-in = 0.51 m/yr (Heimberg 1984)
Area = 1.00 E4 m$^2$/ha
Gibbs Free Energy = 4.94 J/g
= (1.04 m/yr)(1.00 E4 m$^2$/ha)(1.00 E6 g/
m$^3$)(4.94 J/g)
= 2.52 E10J/ha/yr
Transformity = 46,225 (calculated as 2.54 * transformity of rain assuming total rainfall is required to generate 39% avg. runoff)

5 GEOLOGIC INPUT
Limestone Eroded = 0.02750 cm/yr (Odum 1984)
Density of Limestone = 2 g/cm$^3$
= (0.0275 cm/yr)(1.00 E8 cm$^2$/ha)(2 g/cm$^3$)
= 5.50 E6 g/ha/yr
Transformity = 1.00 E9 Sej/g (Odum 1996)

6 WATER USE (TRANSPIRATION)
Transpiration = 0.77 m/yr (estimate from Heimberg, 1984)
Gibbs Free Energy = 4.94 J/g
= (0.77 m)(1.00 E4 m$^2$/ha)(1.00 E6 g/m$^3$)
(4.94 J/g)
= 3.80 E10 J/ha/yr
Transformity = 26,096 (Calculated as weighted average of rain and run-in)

7 GROSS PRIMARY PRODUCTION
Net Primary Production = 6.13 tn C/ha/yr (Brown, Cowles, and Odum 1984)
= (6.13 tn/ha/yr) (1,000,000 g/tn) (8 kcal/g)
(4186 J/kcal)
=2.05 E11 J//ha/yr
Plant respiration =39.96 tn C/ha/yr (Brown, Cowles, and Odum 1984)
= (39.96 tn/ha) (1,000,000 g/tn) (8 kcal/g)
(4186 J/kcal)
= 1.34 E12 J/ha/yr
Gross Production = 1.54 E12 J/ha/yr
Total annual emergy = Sum of transpiration and geologic input
= 6.49 E15 Sej/ha/yr
Transformity = (6.49 E15 Sej/ha/yr / 1.54 E12 J/ha/yr )
= 4,207 sej/J

8 INFILTRATION
Infiltration Rate = 0.0016 m/day (Heimberg 1984)
Gibbs free energy = 4.94 J/g
= (0.0016 m/d)(365 d/yr)(4.94 J/g)(1.00 E6 g/m$^3$)(1.00 E4 m$^2$/ha)
= 2.88 E10 J/ha/yr
Transformity = 26,096 (Calculated as weighted average of rainfall and run-in)

9 LIVE BIOMASS
Biomass = 212 tn/ha dry weight (Brown, 1978)
Energy = (212 tn/ha) (1,000,000 g/tn) (4 Cal/g) (4186 J/kcal)
= 3.55 E12 J/ha
Time to maturity = 40 yrs
Total annual emergy = sum transpiration, and geologic input
= 6.49 E15 Sej/ha/yr
Transformity = (6.55 E15 sej/ha/yr * 40 yrs) / 3.55 E12 J/ha
= 73,162 sej/J

10 PEAT
Peat Storage = 7.50 E3 m$^3$/ha (average, Spangler 1984)
Heat Content = 5.20 Cal/g
Bulk density = 0.50 g/m$^3$ (estimate from Nessel and Bayley, 1984)
% organic matter = 0.10 as decimal (estimate from Nessel and Bayley, 1984)
Time to dev. peat = 188 yrs @ 4mm/yr
Peat = (7.50 E3 m$^3$/ha)(1.00 E6 cm$^3$/m$^3$)(5.2 Cal/g)(4186 J/kcal) (0.10)(.5g/m$^3$)
= 8.16 E12 J/ha
Total annual emergy = Sum of transpiration and geologic input
= 6.49 E15 Sej/ha/yr
Transformity = (6.55 E15 Sej/ha/yr * 188 yrs) / 8.16 E12 J/ha
= 149,536 sej/J

11 WATER
Volume of water taken as 89.6% moisture content of the volume of peat plus avg. standing water
Peat water = 6.72 E3 m$^3$
Avg. water depth = 2.03 E3
Gibbs Free Energy = 4.94 J/g
= (8.75 E3 m$^3$)(1.00 E6 g/m$^3$)(4.94 J/g)
= 4.32 E10 J/ha
Transformity = 26,096 (Calculated as weighted average of rain and run-in)

12 BASIN STRUCTURE
Energy in Basin = (density)(mass displ.)(ht/2)(gravity)(2.38E-11 Cal/erg)(4186 J/Cal)
Density = 2 g/cm$^3$ (Odum 1984)

Mass displaced = 50 $cm^3$
height = 50 cm
gravity = 80 $cm/s^2$
= 2.44 E7 J/ha
Time = 1818 yrs (Odum 1984)
total annual emergy = Sum of transpiration and geologic input
= 6.25 E15 Sej/yr
Transformity = (6.25 E15 sej/yr * 1818) / 2.44 E7 J/ha
= 4.66 E11 sej/J

**Table 22.** Empower of Lake Okeechobee* (From Odum, 2000)

| Note | Item, units | Units/yr | Emergy/unit sej/unit | Empower E18 sej/yr | Emvalue# E6 Em$/yr |
|---|---|---|---|---|---|
| Sources | | | | | |
| 1 | Sun, J | 1.22 E19 | 1 | 12.2 | 12.2 |
| 2 | Rain, g | 2.29 E15 | 9 E4 | 206 | 206 |
| 3 | Tributary water, g | 2.61 E15 | 5.6 E5 | 1484 | 1484 |
| 4 | Tributary organ., J | 1.74 E15 | 7.13 E5 | 1242 | 1242 |
| 5 | Evaporation, g | 2.64 E15 | 6.57 E5 | 1734 | 1734 |
| 6 | Marsh product., J | 7.28 E16 | 4026 | 293 | 293 |
| 7 | Water circulation, J | 3.9 E10 | 1.84 E7 | 0.7 | 0.7 |
| 8 | Open water emergy, sej/yr | —— | 1412 | 1412 | |
| 9 | Lake net prod, J | 4.36 E16 | 3.21 E4 | 1412 | 1412 |
| 10 | Phos. in streams, g | 3.45 E8 | 7.2 E10 | 25 | 25 |
| 11 | Phos., marsh cycle, g | 3.29 E9 | 7.5 E10 | 247 | 247 |
| 12 | Phos. sedim. cycle, g | 9.67 E9 | 1.48 E11 | 1430 | 1430 |
| 13 | Phos. plankt. cycle, g | 6.06 E9 | 1.48 E11 | 900 | 900 |
| 14 | Total lake empower | — | — | 2027 | 2027 |
| 15 | Outflow, ag canals, g | 0.44 E15 | 6.57 E5 | 289 | 289 |
| 16 | Outflow reg. canals, g | 2.07 E15 | 6.57 E5 | 1360 | 1360 |
| 17 | Net org. sediment, J | 4.62 E16 | 3.21 E4 | 1485 | 1485 |
| 18 | Consumer. prod., J | 1.09 E16 | 1.56 E5 | 1709 | 1709 |
| 19 | Base fish prod, J | 1.71 E14 | 1.00 E7 | 1709 | 1709 |
| 20 | Game fish prod, J | 8.5 E12 | 2.0 E8 | 1709 | 1709 |

*area of 16 ft contour above sea level 450,000 acres = 1.82 E9 m$^2$
volume; 3.46 E6 acreft = 4.27 E9 m$^3$ = 4.27 E15 g
Marsh area within the lake: 7.59 E4 acres = 3.07 E8 m$^2$
Openwater area: 1.58 E9 m$^2$
1 acre-foot = 1233 m$^3$
# Empower divided by 1.0 E12 sej/(2000 $)

Data from Gayle, 1975; estimates based on 14 ft contour
1 Solar energy from Miami, NOAA 441 langley/day
(4410 kcal/m$^2$/day)(4186 j/kcal)(365 d/yr)(1.82 E9 m$^2$) = 4.6 E18 J/yr
2 Rain, USGS Hartwell, 2.29 E15 g/yr or
(1.75 E6 acreft/yr)(1233 m$^3$/acreft)(1 E6 g/m$^3$) = 2.16 E15 g/yr
3 Tributaries 2.61 E15 g/yr
Kissimmee, 1.58 E6 acreft; Others, 0.544 E6 acreft
4 Tributary organixs (Gayle, 1975-Joyner)
(20 g TOC/m$^3$)(2 g organic/g C)(2.61 E15 g/yr)/(1 E6 g/m$^3$) = 1.04 E11 g org/yr
(1.04 E11 g org/yr)(4 kcal/g)(4186 J/kcal) = 1.74 E15 J/yr
5 Evaporation, USGS Hartwell, 10 E15 g/yr?

(2.14 E6 acreft/yr)(1233 m$^3$/acreft)(1 E6 g/m$^3$) = 2.64 E15 g/yr
Emergy/mass from note 12

6 Marsh production, emergents: Gayle, 1975;
(17.4 E12 kcal/yr)(4186 J/kcal) = 7.28 E16 J/yr
Emergy from area-based share of evaporation
(3.07 E8 m$^2$/1.82 E9 m$^2$) = 0.169 (16.9%)
(0.169)(2.64 E15 g/yr) = 4.46 E14 g/yr
(4.46 E14 g water/yr)(6.57 E5 sej/g) = 293 E18 sej/yr
Marsh transformity: (293 E18 sej/yr)/(7.28 E16 J/yr) = 4026 sej/J

7 Water circulation energy from current velocities (Gayle's simulation)
(0.033 ft/sec)(0.3 m/ft) = 0.010 m/sec; Kinetic energy: 0.5 mv$^2$
(0.5)(0.010 m/sec)(0.010 m/sec)(4.27 E12 kilograms) = 2.13 E8 kg m$^2$/sec$^2$ = 2.13 E8 J; Transformity from Folio #1 for ocean current
If turnover time is 2 days: (2.13 E8 J) (365 days/yr)(2 days) = 3.9 E10 J/yr
Kinetic emergy in lake: (2.13 E8 J)(1.84 E7 sej/J) = 3.9 E15 sej
Rate of contribution = Kinetic energy multiplied by replacement time
assume 5 days: (3.9 E15 sej/2 days)(365 days/yr) = 7.1 E17 sej/yr
(get another source of velocity to check)

8 Emergy of water area is 83% of sum of inflows, rain, sun, wind
(0.83)(1484 + 206 + 12 + .7) E18 = 1418 E18 sej/yr

9 Phytoplankton and submerged gross prod., Gayle, 1975: 48 g C/m$^2$
2.1 g C/m$^2$day)(365 days/yr)(2 g org/g C)(1.51 E9 m$^2$)(4.5 kcal/g)
94,186 J/kcal) = 4.36 E16 J/yr
Transformity: 1412 E18 sej/yr/4.36 J/yr = 3.21 E4 sej/J

10 Phosphorus inflow in streams (Gayle, 1975)
Kissimmee River, 1.22 E7 g P/yr, Indian Prairie Creek, 0.529 E7 g P/yr; Sum, 3.446 E7 g P/yr

11 Phosphorus cycled through lake marsh (Gayle, 1975):
(0.035 g P/m$^2$/day)(365 days)(3.07 E8 m$^2$) = 3.92 E9 g P/yr

12 Phosphorus cycled through lake sediment (Gayle, 1975):
(6.4 g P/m$^2$/yr)(1.51 E9 m$^2$) = 9.67 E9 g P/yr

13 Phosphorus cycle through plankton (Gayle, 1975):
(0.011 g P/m$^2$/day)(365 days)(1.51 E9 m$^2$) = 6.06 E9 g P/yr

14 Total lake empower: evapotranspiration of lake and marsh (1734 + 294) = 2027 E18 sej/yr

15 Outflow in agricultural canals south, 3.55 E5 acre ft/yr
(3.55 E5 acreft/yr)(1233 m$^3$/acreft)(1 E6 g/m$^3$ = 4.37 E14 g/yr
Emergy/mass from emergy equation
Emergy in rain and streams = (X em/g)(discharge in all canals)
Emergy/mass = X = (1690 E18 sej/yr)/(2.57 E15 g/yr) = 6.57 E5 sej/g

16 Outflow regulation canals, 1.68 E6 acreft/yr
(1.68 E6 acreft/yr)(1233 m$^3$/acreft)(1 E6 g/m$^3$) = 2.07 E15 g/yr

17 Gayle 1975: net organic sediment formation
(1.78 g C/m$^2$/day)(2 g Org/g C)(365 days/yr)(4.5 kcal/g org)(4186 J/kcal)(1.89 E9) m$^2$ = 1.29 E18 J/yr

18 Gayle (1975) lumped consumers, assign full emergy
(0.38 g C/m$^2$/day)(2 g Org/g C)(365 days/yr)(5 kcal/g org)(4186 J/kcal)(1.89 E9) m$^2$ = 1.09 E16 J/yr

19 Fish production (Ager, 1968, 1969)
100 lb/acre)(454 g/lb)(0.20 dry)(2/yr replacement time)(5 kcal/g dry)(4186 J/kcal)(4.5 E5 acres) = 1.71 E14 J/yr

20 Game Fish Prod assumed 5% and 3 yr turnover
(5 lb/acre)(454 g/lb)(0.20 dry)(2/yr replacement time)(5 kcal/g dry)(4186 J/kcal)(4.5 E5 acres) = 8.5 E12 J/yr
Transformity 1709/8.5 E12 J/yr = 2.01 E8 sej/J

**Table 23.** Emergy evaluation of Newnans Lake watershed/lake interface, 1970. (Brandt-Williams, 2000)

| Note | Item | Unit | Data (units/yr) | Emergy/unit (sej/unit) | Solar Emergy E15 sej/yr | Solar 1970 EM$ E4 US$ |
|---|---|---|---|---|---|---|
| **Atmospheric inputs** | | | | | | |
| A | Insolation | J | 1.78 E17 | 1 | 178 | 2 |
| B | Wind Shear | J | 2.61 E14 | 1.50 E3 | 391 | 5 |
| C | Rain, chemical potential | J | 1.96 E14 | 1.82 E4 | 3574 | 45 |
| D | Transpiration emergents | J | 1.03 E12 | 1.54 E4 | 16 | <1 |
| E | TP in Rain | g | 7.14 E6 | 2.00 E6 | <1 | <1 |
| | | Total atmospheric (sun omitted) | | | 3981 | 50 |
| **Watershed inputs** | | | | | | |
| F | Stream, geopotential | J | 1.38 E13 | 1.85 E3 | 26 | <1 |
| G | Stream, chemical potential | J | 1.60 E3 | 1.82 E4 | <1 | <1 |
| H | Sediment | J | 3.16 E12 | 7.30 E4 | 231 | 3 |
| I | Runoff, non-point | J | 1.25 E15 | 6.31 E4 | 79077 | 99 |
| J | TP in streams | g | 3.70 E9 | 6.85 E9 | 25318 | 32 |
| K | TP in runoff | g | 4.28 E7 | 6.85 E9 | 293 | 4 |
| | | | | Total Wateshed | 104945 | 131 |
| | | Total emergy/lake/yr | | | 108927 | |
| | | Total emergy/ha/yr | | | 36 | |
| **Transformities** | | | | | | |
| 1 | Phytoplankton | | | 6.59 E12 | sej/g | |
| 2 | TP in water column | | | 2.90 E13 | sej/g | |
| 3 | Water | | | 6.16 E5 | sej/J | |

Notes:

TP = total phosphorus

A Annual energy = (Avg. Total Annual Insolation J/yr)(Area)(1-albedo)

Insolation: 6.90 E9 J/m2/yr (Vishner, 1954)
Area: 3.01 E7 m2
Albedo: 0.14 (Odum, 1987)
Annual energy: 1.78 E17 J/yr

B Wind mixing energy = (density, kg/m3)(drag coefficient)(geostrophic wind velocity3,m3/s3)(area)

u = wind velocity (m/s) = 3.58 m/s
geostrophic wind velocity = 5.97 m/s
Energy = 1.3 kg/m3 * 1E-3 * 212.77 m3/s3 * 3.14 E7 s/y * 3.01E7 m2

Energy/yr = 2.61 E14 J/yr

C Rain, chemical potential = (rain, m)(lake area, m2)(1E6 g/m3)*G
Rain, m 1.32 E0 m
Lake area, m2 3.01 E7 m2
G, free energy, J/g 4.94 E0 J/g
Energy/yr = 1.96 E14 J/yr

D Transpiration from emergent and floating macrophytes
14.2 ha cover (Huber et al., 1982)
7.30 E10 J/ha, estimated transpiration
(Odum, 1996)

E Phosphorus in rain = area * rainfall * concentration
Area = 3.01 E7 m2
Rainfall = 1.4224 m/yr (~52 in, NOAA, 1995)
Concentration = 0.167 g/m3 (Brezonik, 1969)
Annual amount = 7.14 E6 g/yr

F Stream, geopotential, J/yr = (flow volume)(density)(dh)(gravity)
Hatchett Creek
flow, cfs = 18 cfs (SJRWMD, 1997)
dh, m = 76 m (Brandt-Williams, 1999)
Energy/yr = 18 cfs * 0.028317 m3/f3 * 3.1536E7 sec/yr * 1E6 g/m3 * 7 = 1.20 E13
Little Hatchett Creek
flow, cfs = 4 cfs (SJRWMD, 1997)
dh, m = 53 m (Brandt-Williams, 1999)
Energy/yr = 1.86 E12 J

G Stream, chemical potential = (volume flow)(density)(G)
G = (8.33 J/mole/deg)(300K)/18 g/mole)(ln[(1E6 - S) / 965000] J/g
S, ppm= 5.9 (calculated from turbidity, SJRWMD, 1997)
flow, cfs = 18 cfs
Energy/yr = 1.60 E3 J/yr

H Sediment = (Sediment kg/yr)*(1E3 g/kg)*(avg.% organic)*(5.4 Cal/g OM)*(4186 J/Cal)
Energy = (2.8E7 kg/yr)*(1E3 g/kg)*(0.5 % organic)*(5.4 Cal/g)*(4186 J/Cal)
= 3.16 E12 J/yr

I Runoff, nonpoint = (volume/yr)(G) = (Volume, m3)(4.82 J/g)( 1E6 g/m3)
Volume = 2.60 E8 m3/yr
Energy/yr = 1.25 E15 J/yr
Tranformity = 6.31 E4 sej/J
Transformity calculated from spatial simulation of total emergy at lake perimeter divided by total volume of water converted to Joules

J Total phosphorus in streams
(volume, cfs)(P, mg/l)(0.02831 m3/f3)(3.1536E7 sec/yr)((1E-3 g/mg)(1E6 L/m3)
Volume, cfs = 1.80 E1 cfs (SJRWMD, 1997)
Average concentration, mg/l 0.23 mg/l (SJRWMD, 1997)
Average TP mass = 3.70 E9 g/yr
Transformity = 1.82 E4 sej/g (Appendix D)

K Phosphorus in runoff from spatial model
Annual amount = 4.18 E7 g/yr
Tranformity = 6.85 E9 sej/g
Transformity calculated from spatial simulation of total emergy at lake perimeter dividedby total mass of phosphorus

Transformities calculated from this analysis

1 Phytoplankton, g
= (avg. chlorophyll a concentration, g/m3)(lake volume, m3)(2g phytoplankton/g Chl a)
Avg. Chl a = 0.231 g/m3 (Huber et al., 1982)
1.65 E7 g

2 TP in water column, g = (avg. TP in water column, mg/L)(lake volume, m3)
Average concentration 0.105 mg/l (Huber et al., 1982)
Total g 3.76 E6

3 Water, J = (lake volume, m3)(1E6 g/m3)(4.94 J/g)
Volume 3.58 E7 m3 (SJRWMD, 1997)
Energy stored 1.77 E14 J

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