“Quantus” Emergy

Mark T. Brown and Sherry Brandt-Williams

ABSTRACT

Several issues related to emergy accounting are raised. Accounting procedures that do not recognize the spatial and temporal domains of the input emergy to processes are questioned. The dynamic quality of systems and their use of their emergy signature are suggested as important attributes to be considered when computing the emergy value of outputs. A quantity termed Quantus Emergy is introduced and defined mathematically as the product of the input emergy flows of a process raised to a power that is a function of the total emergy input. The implications of these issues are discussed in relation to future integration of emergy within the LCA framework.

Quantus is Latin for "how much".

INTRODUCTION

Emergy is the available energy of one form used directly and indirectly to make something. When evaluating the emergy of a process the first rule of emergy algebra is to sum the inputs. However, if some of the inputs are from the same source and thus there is the possibility of double counting, it is customary to only sum original sources leaving out any portion of driving energies that come from the same source. This custom has resulted in using only the largest of the renewable inputs to geographic areas instead of summing all the inputs. For instance, in computing the total driving energy for geographic areas, all the renewable inputs (sunlight, wind, rain, tide, waves, etc.) are evaluated and then the largest is taken as the driving energy, under the assumption that each of the renewables is derived from the global web of emergy throughput driven by the renewable tripartite of sun, tide, and geothermal heat.

There have been several refinements on this algebra over the years. For instance, the recognition that sediments are from emergy of a different time domain lead to the practice of adding sediments to the other dominate renewable emergies driving estuaries. In the past, some researchers have added tide and geothermal heat to the largest of the following: sunlight, wind, and rain under the assumption that they were separate sources. However, since the transformities for deep heat and tide are calculated by including inputs from the other two tripartite energies (Odum, 2000), their transformities "contain" the emergy of the other two sources and are not independent.

The use of the eigenvalue method (Odum and Collins, 2001) or the linear optimization method (Bardi et.al, 2005) of computing transformities raises interesting issues related to the logic of static algebra used in emergy computations. In this paper we explore the rational for including or excluding inflowing emergy sources when conducting environmental accounting of spatial units. We propose a new logic for determining how to sum renewable inputs to regions and provide examples.

Emergy Driving the Geobiosphere

Beginning in the year 2000, the total emergy driving the geobiosphere was computed as 15.83 E24 seJ/yr. (Odum, 2000). While there are several “baselines” proposed by others, we will confine ourselves to discussions using this baseline. Figures 1 and 2 show the main components of the geobiosphere and the pathways of materials and energy that connect them. The renewable tripartite of sun, tide, and geothermal heat are shown as the main driving energy. The emergy accounting method
elucidated in Folios 1 and 2 is illustrated in Figure 1 where the pathways are evaluated using a static emergy accounting method. This method assumes that all pathways within a completely interconnected system share the same emergy; the sum of the input emergy. In Figure 2 the pathways are evaluated using an input-output matrix inversion technique (Leontief, 1986). In this technique, the emergy assigned to each pathway is based on estimates of energy flow between components but the

Figure 1. Renewable flows of emergy contributing to geobiosphere processes. Internal pathways were evaluated using the current practice of assigning the sum of the input energy to all pathways.

Figure 2. Renewable flows of emergy contributing to geobiosphere processes. Internal pathways were evaluated using an input-output matrix inversion technique based on energy assigned to each pathway.
recursive nature of the solution results in pathways “accumulating” more emergy than simply the assignment of the total energy driving the system. In essence, the input-output method is not a static method but one that takes into account time since the flow on each pathway has embedded in it this year’s inputs plus some portion of last year’s and a smaller portion of the previous year’s and so on back in history until the quantity is so small as not to be important.

This raises an interesting temporal perspective to the evaluation of emergy. While the static methodology has and will serve us well, the fact that it is static and does not account for cycling within networks means that it does not offer opportunities to think of emergy as a dynamic property. Evaluations of individual processes are easily visualized as static systems where inflows are summed over a specified time frame to achieve the total emergy required to make the product. While we see no problem with continuing to use static accounting methods for simple evaluations of processes, networks represent a very different perspective, one that is not static, but dynamic, and therefore offers the prospect of exploring temporal as well as spatial aspects of the theory more deeply.

Adding Anthropogenic Sources

Here we define anthropogenic sources and the non-renewable and slowly renewable reserves (or storages) that humans are using and thus “releasing” into the geobiosphere.

In the first emergy folio (Odum, et al. 2000), inputs to the geobiosphere that resulted from anthropogenic activities were recognized as important (based on a paper by Brown and Ulgiati [1999]), and were included as Table 3. Annual Emergy Contributions to Global Processes Including Use of Resource Reserves. While these anthropogenic releases (i.e., fossil fuels, mineral reserves, and slowly renewable reserves like soils and forests) were recognized as contributing to the global processes, they were not included in computations of the UEVs of the renewable fluxes of energy driving the geobiosphere. The assumption was, in order to determine the UEVs of renewable flows, the anthropogenic flows must be omitted thus reflecting only the influence of the renewable tripartite of sun, tide, and geothermal heat. A reasonable assumption since the goal was to derive purely renewable UEVs.

However, as the evidence of anthropogenic impact on global climate mounts, one wonders if these anthropogenic sources are not equally or more important when evaluating global processes? Table 1 lists an updated version of Table 3 from Folio 1 based on the 15.83 E24 baseline. It is obvious from this table that the anthropogenic emergy is a little more than double that of the renewable emergy driving the geobiosphere suggesting the impact that these sources might have on global processes. Figure 3 shows the global system with the addition of the anthropogenic sources and evaluated using the same matric inversion technique used to obtain the flows in Figure 2. Comparison with Figure 2 reveals the magnitude of the changes in flows that result from the anthropogenic sources. An open question is whether the UEVs of secondary and tertiary renewable flows should be recalculated in light of the increased input from anthropogenic sources.

Emergy and Spatial Systems

The accounting procedure used to evaluate spatial phenomena is essential static in perspective, summing the inputs to obtain the total emergy driving the phenomena and assigning that emergy to the output. However, only the largest of the renewable inputs is used under the assumption that the renewables are ultimately from the same sources and it would be double counting to sum all of them.

Variations on this theme have resulted over the years where sediments, for instance, that may inflow to a system are considered to be from a different time than the evaluation timeframe and therefore can be added. Some authors have suggested that tide and deep heat can be added to other sources like wind and rain and runin, since they are the result of different global inputs.

Figure 4 is a reproduction of a figure from Odum (1996) showing the current spatial accounting practice as stated by Odum...“Since the flows to a local area are co-products from the same source, their emergy contents are not independent. To avoid double counting, utilize only the largest one...”. The rationale for taking the largest stemmed from the fact that it was logically reasoned that sun
Table 1. Annual energy contributions to global processes including use of resource reserves (after Brown and Ulgiati, 1999).

<table>
<thead>
<tr>
<th>Note</th>
<th>Inputs &amp; Units</th>
<th>Inflow (J/yr)</th>
<th>Emergy/Unit* (sej/unit)</th>
<th>Empower (E24 sej/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Renewable inputs</td>
<td>--</td>
<td>--</td>
<td>15.8</td>
</tr>
<tr>
<td></td>
<td>Nonrenewable energies released by society:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Oil, J</td>
<td>1.38 E20</td>
<td>9.06 E4</td>
<td>12.5</td>
</tr>
<tr>
<td>3</td>
<td>Natural gas (oil eq.), J</td>
<td>7.89 E19</td>
<td>8.05 E4</td>
<td>6.4</td>
</tr>
<tr>
<td>4</td>
<td>Coal (oil eq.), J</td>
<td>1.09 E20</td>
<td>6.71 E4</td>
<td>7.3</td>
</tr>
<tr>
<td>5</td>
<td>Nuclear power, J</td>
<td>8.60 E18</td>
<td>3.35 E5</td>
<td>2.9</td>
</tr>
<tr>
<td>6</td>
<td>Wood, J</td>
<td>5.86 E19</td>
<td>1.84 E4</td>
<td>1.1</td>
</tr>
<tr>
<td>7</td>
<td>Soils, J</td>
<td>1.38 E19</td>
<td>1.24 E5</td>
<td>1.7</td>
</tr>
<tr>
<td>8</td>
<td>Phosphate, J</td>
<td>4.77 E16</td>
<td>1.29 E7</td>
<td>0.6</td>
</tr>
<tr>
<td>9</td>
<td>Limestone, J</td>
<td>7.33 E16</td>
<td>2.72 E6</td>
<td>0.2</td>
</tr>
<tr>
<td>10</td>
<td>Metal ores, g</td>
<td>9.93 E14</td>
<td>1.68 E9</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**Total non-renewable empower**
34.3

**Total global empower**
50.1

Abbreviations: sej = solar emjoules; yr = year; E3 means multiplied by 10^3; t = metric ton; oil eq. = oil equivalents
*Values of solar emergy/unit from Odum (1996); modified to reflect a global resource base of 15.83 E24 sej/yr

Footnotes for Table 3
1 Renewable Inputs: Total of solar, tidal, and deep heat empower inputs from Odum (1996).
2 Total oil production = 3.3 E9 Mt oil equivalent (British Petroleum, 1997)
   Energy flux = (3.3 E9 t oil eq.)(4.186 E10 J/t oil eq.) = 1.38 E20 J/yr oil equivalent
3 Total natural gas production = 2.093 E12 m^3 (British Petroleum, 1997)
   Energy flux = (2.093 E12 m^3)(3.77 E7 J m^-3) = 7.89 E19 J/yr
4 Total soft coal production = 1.224 E9 t/yr (British Petroleum, 1997)
   Total hard coal production = 3.297 E9 t/yr (British Petroleum, 1997)
   Energy flux = (1.224 E9 t/yr)(13.9 E9 J/t) + (3.297 E9 t/yr)(27.9 E9 J/t) = 1.09 E20 J/yr
5 Total nuclear power production = 2.39 E12 kwh/yr (British Petroleum, 1997). Energy flux = (2.39 E12 kwh/yr)(3.6 E6 J/kwh) = 8.6 E18 J/yr electrical equivalent
6 Annual net loss of forest area = 11.27 E6 ha/yr (Brown et al., 1997)
   Biomass = 40 kg m^-2; 30% moisture (Lieth and Whitaker, 1975)
   Energy flux = (11.27 E6 ha/yr)(1 E4 m^2/ha)(40 kg m^-2)(1.3 E7 J/kg)(0.7) = 5.86 E19 J/yr
7 Total soil erosion = 6.1 E10 t/yr (Oldeman, 1994; Mannion, 1995)
   Assume soil loss 10 t/ha/yr and 6.1 E9 ha agricultural land = 6.1 E16/g/yr
   (assume 1.0% organic matter), 5.4 kcal/g
   Energy flux = (6.1 E16 g)(0.1)(5.4 kcal/g)(4186 J/kcal) = 1.38 E19 J/yr
8 Total global phosphate production = 137 E6 t/yr (USDI, 1996)
   Gibbs free energy of phosphate rock = 3.48 E2 J/g
   Energy flux = (137 E12 g)(3.48 E2 J/g) = 4.77 E16 J/yr
9 Total limestone production = 120 E6 t/yr (USDI, 1996)
   Gibbs free energy phosphate rock = 611 J/g
   Energy flux = (120 E12 g)(611 J/g) = 7.33 E16 J/yr
10 Total global production of metals 1994: Al, Cu, Pb, Fe, Zn (World Resources Institute, 1996): 992.9 E6 t/yr = 992.9 E12 g/yr

illuminating an area contributed to the wind that blows across and the rain that falls on the area, as does the geothermal heat (land cycle in Figure 4). It was reasoned that all the renewable inputs were so tightly interconnected that their sum represents serious double counting issues. The question remains, are they really from the same source?

Consider for instance, that the rain that falls or the wind that blows may be the result of frontal activity whose main driving flows are so removed from the area under consideration as to make the local area’s contribution insignificant. Consider also that the accounting procedure explicitly requires that only energy that is used within a local area should be accounted for. Rain that runs off is not accounted for as being used by the local area. All the wind that blows across an area is not used, only
that portion that is absorbed. The sunlight used already takes into account the fact that albedo (the portion reflected) is subtracted. We think it is time to consider both the space and time domains of the input emergy to all systems.

**Figure 3.** Flows of emergy contributing to geobiosphere processes including anthropogenic sources. Internal pathways were evaluated using an input-output matrix inversion technique based on energy assigned to each pathway.

**Figure 4.** Diagram illustrating the current accounting procedure where only the largest renewable input emergy is used. (figure from Odum, 1996).
**Emergy Interaction**

Maybe more important is the fact that taking the largest renewable inflow fails to recognize the dynamic interaction that actually happens within a local area. If there were no sunlight, only rain falling, would there be the level of productivity exhibited by a system that has both? Is not the productivity of a system the result of the interaction of the emergy, not just the largest? This reasoning applies equally to all the inputs of a system including nonrenewable resources, and information. Is not the product and the processes that produces a product the interaction of the inputs and not just the sum of the inputs? The static accounting procedure has resulted in thinking of productive processes as summation rather than multiplication.

The word production is from product and the result of multiplying is the product of two or more numbers. Production processes in simulation models are most frequently considered multiplicative interactions of the inputs. These production functions take many forms, but the commonality is that the output of the process is some multiplicative function of the inputs. Economics is rife with production functions, but one of the more widely used is the Cobb-Douglas production function. In its most standard form the production of an output is the product of the inputs, where each input is raised to an exponent whose sum is equal to 1 as follows:

\[ Y = A L^\alpha K^\beta \]  

(1)

Where:

- \( Y \) = total production
- \( L \) = labor input
- \( K \) = capital input
- \( A \) = total production factor, a variable that accounts for other unaccounted for factors
- \( \alpha, \beta \) are elasticity coefficients whose sum is 1.0 if the production function exhibits constant returns to scale.

There a numerous criticisms of the Cobb-Douglas production function and it is not our interest here to defend or critique its validity within an economic framework, only to explore its functional form in relation to macro-scale production output from regional systems. One of the attractions of this functional form is the ability to achieve constant returns to scale, which insures that the multiplicative interactions of the input variables do not exceed the largest input. A second attraction is the responsiveness of output to changes in the levels of inputs used in production such that a percent increase in any one input represents a like change in output multiplied by its elasticity coefficient. Finally the production function formulation exhibits diminishing marginal returns to each factor of production; thus dominance by any single input as it is increased relative to others has an increasing smaller impact on the output.

Of course we are not suggesting that the pure form of the Cobb-Douglas production function be used in evaluating the emergy contributions to production of ecosystems, since obviously labor and capital are relatively meaningless in relation to production of ecosystem services, for instance. Instead, we are suggesting the use of the conceptual framework of Cobb-Douglas...the postulates that system production is the result of multiplicative interaction of the factors of production and that production of systems exhibits constant returns to scale. It seems logical, as we’ve stated above, that the output from productive processes is a function of all the inputs, not just the largest, and further that the output is not just a summation of the inputs, but a dynamic interaction of the inputs.

**Quantus Emergy**

Given in Figure 5 is a production function for an estuary. The aggregate output of the estuary can be considered ecosystem services. Since each service is a co-product of the entire ecosystem the output measures the emergy value of the estuary which is assigned to individual ecosystem services. It should be cautioned that computation of ecosystem services in this manner (i.e. treated as co-products
precludes adding the values of individual services together to obtain a grand total, as this would violate the emergy algebra which states that co-products are not to be added.

The sum of the inputs equals 29.0 E23 seJ/yr while the largest is sediments 17.0 E23 seJ/yr. If we assume that sediments are separate from the other inputs, we can add sediment input to the largest of the other inputs (Runin = 4.7 E23 seJ/yr + Sediments = 17.0 E23) yielding a total of 21.7 E23 seJ/yr.

We have termed the emergy values of system production obtained from a Cobb-Douglass like production function, Quantus Emergy to differentiate it from the emergy of products derived from static accounting procedures. The quantus emergy of any system is the following:

\[
P = \prod_{i=1}^{n} \left( E_{m_i} \left( \frac{E_{m_i}}{\sum_{i}^{n} E_{m_i}} \right) \right)
\]  

Where:
- \( \prod_{i=1}^{n} \) = the product
- \( E_{m_i} \) = Emergy input (i)

For the estuary in Figure 5, the quantus emergy is equal to 8.4 E23 seJ/yr. Comparing to the various methods given above we find that the quantus emergy is about 1/3 of the values obtained by either summing the inputs or taking the largest and adding sediments. Additionally we decreased the sediment input stepwise to 0.01% of the initial value given in Figure 5 which resulted in the quantus emergy asymptotically diminishing to a value of 3.1 E23 seJ/yr. As the largest input to the estuary its effect on quantus emergy is significant.

We evaluated the biomes given in Brandt-Williams and Brown (2011) and compared their quantus emergy to the sum of input emergy and the largest of the input emergy. The results of that analysis are given in Table 2. In all cases the quantus emergy is lower than either the sum of inputs or the largest. Quantus emergy is between 15% and 70% smaller than the sum, and between 15% and 50% smaller than the largest input method of accounting.

**DISCUSSION**

In this paper we have raised several issues that have potentially large impact on the methods of emergy accounting. We are not suggesting that the methods proposed in this paper be adopted without further detailed evaluation and serious discussion of the implications. The spatial and temporal issues raised here have broad applicability within the emergy methodology; especially if/when emergy is applied within an LCA framework. Currently there is considerable discussion regarding the applicability of the emergy algebra within the LCA framework, with some researchers suggesting that strict adherence to the emergy algebra will preclude the use of emergy within the LCA framework since double counting would seem to be prevalent throughout an analysis as fuels and raw resources are found through each input of a supply chain. However, it would seem that a simple assumption of
**Table 2.** Comparison of three methods of calculating the driving emergy of biomes, units = sej/year.

<table>
<thead>
<tr>
<th>Biome</th>
<th>Sum of Emergy</th>
<th>Largest Emergy</th>
<th>Quanton Emergy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open ocean</td>
<td>1.6E+25</td>
<td>1.6E+25</td>
<td>1.3E+25</td>
</tr>
<tr>
<td>Tropical Forest</td>
<td>8.0E+24</td>
<td>7.6E+24</td>
<td>6.5E+24</td>
</tr>
<tr>
<td>Tidal marsh, mangroves</td>
<td>3.1E+24</td>
<td>1.7E+24</td>
<td>9.6E+23</td>
</tr>
<tr>
<td>Temperate/Boreal Forest</td>
<td>2.9E+24</td>
<td>2.4E+24</td>
<td>1.6E+24</td>
</tr>
<tr>
<td>Estuaries</td>
<td>2.9E+24</td>
<td>1.7E+24</td>
<td>8.4E+23</td>
</tr>
<tr>
<td>Grass/rangelands</td>
<td>2.6E+24</td>
<td>1.8E+24</td>
<td>1.2E+24</td>
</tr>
<tr>
<td>Ocean Shelf</td>
<td>2.4E+24</td>
<td>1.4E+24</td>
<td>7.2E+23</td>
</tr>
<tr>
<td>Ice/rock</td>
<td>1.6E+24</td>
<td>1.5E+24</td>
<td>1.3E+24</td>
</tr>
<tr>
<td>Swamps/floodplains</td>
<td>1.2E+24</td>
<td>7.4E+23</td>
<td>5.4E+23</td>
</tr>
<tr>
<td>Cropland, renewables only</td>
<td>7.6E+23</td>
<td>6.6E+23</td>
<td>4.7E+23</td>
</tr>
<tr>
<td>Tundra</td>
<td>6.1E+23</td>
<td>5.8E+23</td>
<td>4.9E+23</td>
</tr>
<tr>
<td>Coral reefs</td>
<td>4.3E+23</td>
<td>3.8E+23</td>
<td>2.8E+23</td>
</tr>
<tr>
<td>Lakes</td>
<td>3.8E+23</td>
<td>1.9E+23</td>
<td>1.4E+23</td>
</tr>
<tr>
<td>Urban, urban renewables only</td>
<td>2.0E+23</td>
<td>1.6E+23</td>
<td>1.0E+23</td>
</tr>
<tr>
<td>Desert</td>
<td>1.3E+23</td>
<td>9.8E+22</td>
<td>6.3E+22</td>
</tr>
</tbody>
</table>

different space and time domains of the supply chain would elevate this potential problem. This assumption is not overly presumptuous since the mix of resources within the global economy comes from many places and many different times.

Finally the question of dynamic emergy where inputs to processes are accounted for in a multiplicative manner would address concerns that simple summation does not capture the interactions that provide the real complexity of systems and that account in part for the emergent properties exhibited by systems of the same general structure but with different mixes of input emergy. If indeed systems maximize inputs to achieve their outputs, it would seem likely that the resulting emergy of the output should be a more complex function of the inputs than a simple summation.

**REFERENCES**


