ENVIRONMENTAL ACCOUNTING OF AGRICULTURAL SUSTAINABILITY USING EMERGY ANALYSIS

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Keywords: Embodied energy, agricultural sustainability, environmental accounting, emergy, alternative fuels, food production, aquaculture, international trade models, forestry, biofuels, energy analysis.

Contents

Summary

This chapter describes the application of emergy analysis to evaluate the sustainability of agricultural systems. An advantage of emergy analysis is the ability to quantify environmental and economic inputs and outputs on a common basis. This chapter explains the theory behind emergy analysis, defines related terms, and offers examples of applications related to 1) food production, 2) biofuels, 3) aquaculture, and 4) forestry. Numerical simulation of emergy is also illustrated as a method to analyze non-steady state systems. The emergy analysis method compares the sustainability of systems based on the amount of total input energy needed to produce outputs, such as food or timber. Greater sustainability is achieved when a system (1) requires a lesser amount of energy to produce a product or (2) uses a greater amount of renewable resources and a lesser amount of nonrenewable resources for production. Emergy analyses that compare the sustainability of different food production systems and changes in the sustainability of agricultural systems over time have been applied across scales ranging from single farms to national economies. These studies demonstrated how emergy was applied to compare agricultural inputs on a common basis and draw conclusions about resource use and sustainability. Production of biofuels required three to five times as much total emergy as fossil fuels, signifying that biofuels cannot contribute to increased sustainability. Studies of aquaculture systems quantified the relative importance of the work of nature and the human economy in producing fish and shrimp. The empower (emergy per unit time) density of renewable inputs from the environment was highest for a fishery in Panama and lowest for the mangroves of Ecuador. Across six forest systems managed for timber production renewable inflows, purchased inputs, and timber production were highest for the rainforest of Papua New Guinea and lowest in the ecologically managed Southern Appalachian forests of North Carolina. In a comparison to agroforestry systems, slash and burn was found to be more sustainable than slash and mulch in a Brazilian forest.

1. Introduction

The sustainability of agricultural systems must be quantified to select those that can best meet the challenge of supplying food and materials to a growing population in a world with finite environmental and energy resources. Such evaluations should identify the agricultural systems with greater yields relative to their resource use and the fraction of resource use that is supplied from renewable resources. This will allow the reversal of a trend through the last century that saw greater yields in industrialized nations become more dependent on the use of non-renewable resources (Pimentel and Pimentel 1996, Ko et al. 1998). Because agricultural systems depend on inputs from both nature and the human economy, it is problematic to determine their sustainability. Typically, high quality, non-renewable energies from the human economy are utilized to capture and concentrate lower quality, more abundant renewable energies provided by nature. Intensive agricultural methods rely more on resources purchased from the economy, while less intensive and indigenous methods typically rely more on natural inputs. Because most types of agriculture depend on a combination of natural and economic inputs, it is necessary to account for both in equivalent terms when comparing the resource use of agricultural systems (Campbell 1998). While the value of economic contributions are routinely quantified in economic analyses, such approaches often underestimate or miss environmental contributions to production systems because little or no money is directly associated with environmental contributions. If environmental inputs are not properly accounted for relative to economic inputs, optimum use of resources may not be achieved, and decisions will be based on incomplete information (Ulgiati et al. 1994). This undesired result highlights the need for integrated approaches that quantify economic and environmental inputs and provide a holistic basis for selecting sustainable systems (Lefroy and Rydberg 2003). H.T. Odum published a pioneering, comprehensive look (Odum 1967) at how energy accounting could be applied to evaluate the multiple inputs used to produce the world’s food. Odum’s novel approach went beyond an analysis of the energy inputs traditionally included — direct solar irradiance and fuel consumption — to include the contributions from the environment (e.g., dry air, water, soil organic matter) and the economy (e.g., labor, services) as embodied solar energy (emergy in later nomenclature). In the introduction to *Energy and Agriculture*, Stanhill (1984) pointed out that the Nobel laureate chemist F. Soddy (1933) envisaged a concept similar to Odum’s emergy analysis, having written the following:

"Although…energy seems quite a minor item in the production of wealth, if we concern ourselves with what is used up in the process of creating wealth it is the largest and most important item. Thus, in the cost of upkeep of a car the petrol is a minor item. …Yet if we pursue the tyres…their cost is due to the expenditures of energy. They call for the flow of solar energy…physical labour in rubber plantations, coal for the railways, and ships…[and] factories…These railways and ships…buildings and equipment necessary for their manufacture…iron, metals and coal…are the results of the expenditure of physical energy. The armies of peoples these industries maintain have to be supplied with food, cloths and houses, and energy under intelligent human direction is the first requisite for the supply of all such things."

Although the concept of accounting for indirect energy inputs may have been discussed by many prior to Odum's work, no others came close to providing his rigorous framework for conducting energy-based environmental accounting. After his 1967 world food article, Odum focused on perfecting emergy accounting by conducting evaluations of many systems of man and nature, including several key studies on agricultural systems. The vast majority of studies were published as reports by Odum and his associates through the University of Florida Center for Wetlands or, later, the UF Center for Environmental Policy (Odum 1996; UFCEP 2004).

Emergy analysis is a form of energy analysis that measures the value of natural and economic resource inputs on a common basis to derive the contribution of nature to the human economy (Odum, 1988). Solar emergy is used to determine the value of environmental and human work within a system on a common basis: the ultimate amount of solar energy required to produce each service or product. Due to the ability to quantify both environmental and economic resources needed for agricultural production, emergy analysis is a useful tool to assess the sustainability of agricultural systems. A fundamental assumption of emergy analysis is that the contribution a resource makes to economic activity is proportional to the total amount of energy of one kind that went into making it (Brown and Herendeen 1996). This assumption is based on the fact that "over time, selection among alternate pathways gradually changes the structure and function of systems so that the components retained do work at least equivalent to the work required to produce them" (Campbell 2001).

The solar emergy of products and services is calculated by multiplying units of energy (e.g., joules of oil) by emergy per energy ratios (transformities), units of mass by emergy per mass ratios (specific emergy), and dollars by emergy per dollar ratios (emergy per unit money) (Table 1). Using this technique, natural and economic contributions required to produce agricultural yields can be quantified and compared on a common basis as solar emjoules (sej). Emergy analysis has been used to evaluate the sustainability of farming methods in Australia (Lefroy and Rydberg 2003), Sweden (Rydberg and Jansen 2002), Italy (Ulgiati et al. 1993), Texas, USA (Odum and Odum 1987) and China (Hong-fang et al. 2003). Brown and Ulgiati (2004) traced the development of the emergy method from the 1960's to 2002 and offer more examples of applications. The objectives of this chapter are to (1) introduce the use of emergy analysis to assess the sustainability of agricultural systems and (2) review previous emergy evaluations of food production, biofuel alternatives, aquaculture and forestry.

Item	Unit/yr	Value (unit/yr)	Transformity (sej/unit)	Emergy (10^{14} sej/ha/yr)
Environment, Renewable,R				
Sunlight	J	3.65E+13	1.00E+00	0.37
Rain	J	2.12E+10	1.82E+04	3.86
Earth cycle	J	3.00E+10	3.44E+04	10.31
Renewable (R)				14.17
Non-renewable resources, N				
Loss of topsoil	J	1.26E+09	6.25E+04	0.79
Non-renewable				0.79
Economic Purchased, F				
Electricity	J	2.17E+08	2.00E+05	0.43
Lubricants	J	1.36E+08	6.60E+04	0.09
Diesel	J	1.53E+10	6.60E+04	10.10
Gasoline	J	4.60E+08	6.60E+04	0.30
Labor	J	2.87E+08	7.38E+06	21.18
Potash fertilizer	g	7.62E+04	2.96E+09	2.26
Nitrogen fertilizer	g	1.41E+05	4.62E+09	6.51
Phosphate fertilizer	g	3.33E+05	1.78E+10	59.27
Pesticides	J	3.61E+09	6.60E+04	2.38
Mechanical equipment	J	6.70E+08	6.60E+04	0.44
Seeds	J	4.19E+07	6.60E+04	0.03
Purchased, F				103.00
Exports, Y				
Sugar beets	J	1.39E+11	84,900	118

Table 1: Emergy analysis table of Italian sugar beet production per hectare (Ulgiati et al. 1994).

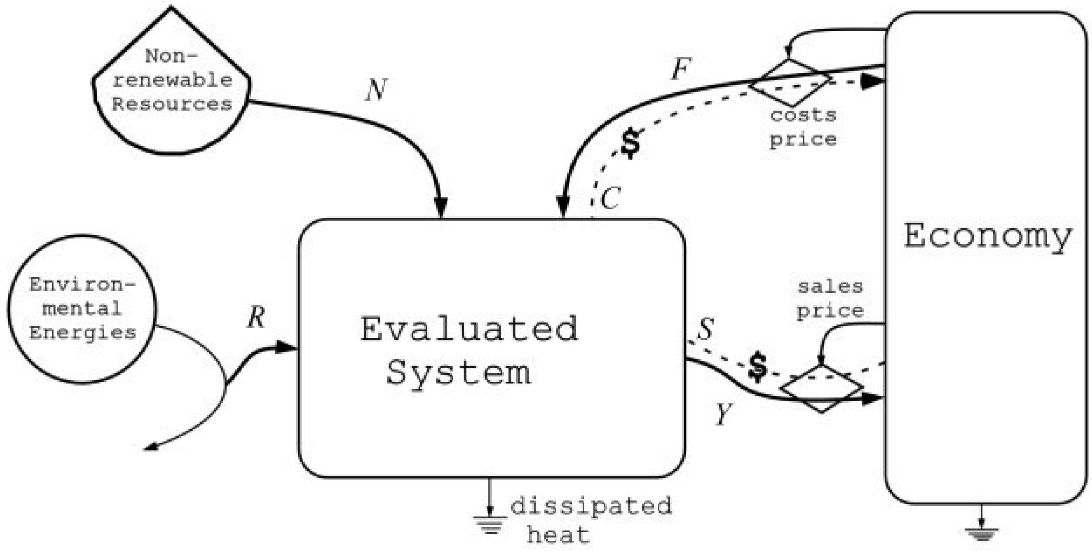

Figure 1: Energy systems diagram of the aggregated inputs (R, N, and F) to an evaluated system that produces a yield (Y) to the economy and generates sales revenue (S) which pays for purchased costs (C).

2. Environmental Decision-making with Emergy

The methodology for emergy analysis begins with the construction of a systems diagram to define the boundary, identify resource inputs, and conceptualize relationships among components, inputs, and outputs. More examples of systems diagrams can be found in Martin (2002) and Tilley and Swank (2003). Often the symbolic energy systems language developed by H.T. Odum is used to construct these diagrams (Brown 2004). The emergy analysis table (Table 1) is constructed directly from the systems diagram using inflows and outflows crossing the system boundary as row headings. The annual amount of flow of each input and output is first quantified in physical units (i.e., joules, grams, dollars). Then the annual solar emergy of each flow is estimated by multiplying each physical quantity by the appropriate emergy per unit factor, respectively, solar transformity, specific solar emergy, or the solar emergy-to-money ratio for the units listed above. The flows are aggregated into categories of renewable resources (i.e., replenished within a year or less), non-renewable resources (i.e., replenished after more than one year), non-indigenous purchased resources (i.e., paid for and brought from outside system), and exports (or yield) (Table 1).

Typically, renewable resources driving agricultural systems include sunlight, wind, and rain. Since the ultimate source of these energies is the same, care must be taken not to double count their contribution of solar emergy. This is accomplished by including only the largest one, which often is the chemical potential emergy of precipitation in agricultural systems (Odum 1996). Non-renewable resources often include soil, groundwater, forest biomass and any other environmental resource that is being consumed at a rate faster than what is formed during an annual cycle. Examples of purchased resources include fuel, electricity, fertilizer, irrigation water, chemicals, machinery, and labor. These aggregate categories serve as the basis for developing indices using an aggregated systems diagram like Figure 1. The aggregated systems diagram compares the amount of solar emergy contributed from each category used to produce the system's yield.

Emergy indices (Hong-fang et al. 2003, Brown and McClanahan, 1996, Figure 1) are calculated using data from the emergy analysis table and the aggregated systems diagram. These indices, which relate economic and environmental flows, are used to quantify investment intensity, net yield, environmental loading, and sustainability. The utility of a particular index depends on the specific goal or question of concern.

3. Food Production

Emergy analysis has been applied to compare the sustainability of different food production methods and used to assess changes in the sustainability of agricultural systems over time. Such studies have been applied across scales ranging from single farms to national economies. The following studies of food production systems demonstrate how emergy analysis was used to compare agricultural inputs on a common basis and draw conclusions about resource use and sustainability.

As part of an emergy analysis of Italy, Ulgiati et al. (1994) calculated emergy indices for many Italian crops and assessed the role of agriculture in Italy. They determined that the total emergy driving food production in Italy was 10.6 E22 (which means10.6×10^{22}) sej/yr . The two largest inputs driving Italian agriculture were purchased goods (24%, mostly chemicals and machinery) and labor (44%). The ELRs for crop production and livestock production in Italy were 2.5 and 3.3, respectively. Comparing these values to the Italian economy's mean ELR of 9.5, indicated that Italian agriculture relies more heavily upon natural environmental energy inputs than the economy as a whole. Table 2 compares the transformity and emergy indices for selected Italian crops. Almonds had the greatest transformity, indicating that more emergy was needed to produce one joule of almond than any other crop. The relatively low ELR for almonds, wheat, rice and forage indicated that these crops rely heavily on renewable emergy and less on purchased and non-renewable emergy. In contrast sunflowers, oranges and lemons required greater inputs of purchased and non-renewable emergy, and had greater ELR's. Greater EYR's for crops such as almonds, wheat, rice and forage indicated a greater yield from these crops relative to required economic investments. The ESI showed that the production of these same crops was more sustainable than sunflower, orange and lemon production. Table 2 is an example of how emergy analysis can be used to assess the sustainability of different farming alternatives in one geographical area.

Crop	Solar transformity (1 E4 sej/J)	Environmental Loading Ratio (*ELR*)	Emergy Yield Ratio (*EYR*)	Emergy Sustainability Index (*ESI*)
Rice	7.78	2.86	1.38	0.48
Forage	8.00	1.45	1.76	1.21
Sugar beet	8.49	7.33	1.15	0.16
Corn	8.52	5.63	1.19	0.21

Wheat	15.90	3.38	1.32	0.39
Fruits	28.74	9.37	1.11	0.12
Vineyard	34.11	5.33	1.20	0.23
Oranges & Lemons	38.17	11.82	1.09	0.09
Olive	53.03	4.40	1.24	0.28
Sunflower	79.12	27.78	1.04	0.04
Almonds	84.28	3.10	1.35	0.44

Table 2: Emergy indices for selected crops in Italian agriculture (Ulgiati et al. 1994).

Lefroy and Rydberg (2003) used emergy analysis to compare an annual cropping system with two perennial plant-based subsystems. The three system designs analyzed were; 1) a lupin/wheat rotation, 2) an alley cropping system in which the lupin/wheat rotation is grown between rows of the fodder tree tagasaste (*Chamaecytisus proliferus* L.), and 3) plantation density tagasaste. Their goal was to identify which of these systems was best adapted and most sustainable for an area of southwestern Australia suffering from wind erosion and rising water tables. Their analysis revealed that the three largest solar emergy inputs to all three systems were soil loss through wind erosion, phosphate fertilizer, and evapotranspiration. It was differences in wind erosion that lead to substantial differences in sustainability between these systems. Wind erosion in the lupin/wheat system was three times greater than in the alley system, and 12 times greater than the plantation system. The amount of diesel fuel used was two times greater for the tagasaste plantation compared to the other systems. However, diesel fuel accounted for less than 3% of emergy inputs to the tagasaste plantation, making it relatively less important than soil erosion. This finding demonstrates how the ability of emergy analysis to directly compare soil loss and diesel inputs can quantify sustainability. The percentage of renewable emergy was greatest for the plantation system (53%), compared to the alley cropping system (30%) and lupin/wheat system (15%). The ELR decreased from 5.5 to 2.3 by adding spaced tree rows to the lupin/wheat system. The ELR for the plantation system (0.7) was substantially lower than either the lupin/wheat or alley cropping systems. The lower ELR and higher returns for the perennial tagasaste plantation suggested greater sustainability compared to the other two systems and a beneficial economic outcome for farmers converting from annual cropping systems.

Rydberg and Jansen (2002) evaluated 1927 horse traction with 1996 motorized traction for Swedish agriculture. They found that the change from horse to motor power represented a shift from a technology that was maintained and driven mainly by local renewable resources to a technology controlled and supported by non-local, non-renewable resources. This switch from horses to motors coincided with a 13-fold increase in external emergy supporting agriculture. While the total emergy needed per unit of traction was 64% greater for the horse, the energies supporting horse traction had lower transformities and were locally generated. Horse traction was supported by 60%

renewable emergy compared to only 9% for the motors. Their study found that horses had an advantage in settings where efficient utilization of limited renewable resources was important.

In another historical study the sustainability of US corn production was tracked from 1945 to 1994 by Ulgiati and Brown (1998) using emergy analysis. During this period corn solar transformities declined from 8.41 E4 to 5.11 E4 sej/J. This was thought to be due to more efficient use of nonrenewable resources and less use of renewable resources. The ESI declined from 1.12 in 1945 to 0.34 in 1994. This indicated that the gains in efficiency of industrialized corn production were overshadowed by increased non-renewable inputs. To increase sustainability of US corn production the authors suggested further increases in production per unit of emergy input and stressed increased reliance on local renewable resources and decreased use of purchased inputs such as fertilizers and pesticides. Ulgiati and Brown (1998) concluded that the optimum conversion efficiency and the optimum mix of input items are important components of sustainability.

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Biographical Sketches

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