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Emergy evaluation of the performance and sustainability of three agricultural systems with different scales and management

Jay F. Martin[a,*], Stewart A.W. Diemont[a], Erick Powell[b], Michele Stanton[c], Samuel Levy-Tacher[d]

[a] *Ecological Engineering Group, Department of Food, Agricultural & Biological Engineering, Ohio State University, 590 Woody Hayes Dr., Columbus, OH 43210, USA*

[b] *Department of Food, Agricultural & Biological Engineering, Ohio State University, USA*

[c] *Department of Horticulture and Crop Science, Ohio State University, 2001 Fyffe Court, Columbus OH 43210, USA*

[d] *El Colegio De La Frontera Sur, Division of Conservation and Biodiversity, Department of Ecology and Terrestrial Systems, Carretera Panamericana y Periférico Sur, Barrio de María Auxiliadora, San Cristóbal de Las Casas, Chiapas, Mexico*

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Abstract

Emergy analysis was used to analyze three agricultural systems to compare and contrast resource use, productivity, environmental impact, and overall sustainability. Emergy analysis was appropriate for this task because of its ability to transform different types of inputs to a common form (solar energy equivalents) to allow meaningful comparisons across the three systems. The systems analyzed were conventional corn (*Zea mays* L.) production in Kansas, USA, blackberry (*Rubus rubus* Watson) production in Ohio, USA, and a Lacandon polycultural rotation system in Chiapas, Mexico. Despite these different systems and diverse inputs, emergy allowed the quantification and comparison of flows for each system on a common basis. This allowed system-level conclusions and demonstrated the utility of emergy analysis when evaluating agricultural systems. The greatest inputs of emergy across the three systems were for fertilization and irrigation of the corn system. These two inputs accounted for 95% of the purchased emergy input to the corn system. The indigenous system was most reliant on renewable resources, and therefore, had the lowest level of environmental loading. The sustainability index for the three systems ranged from 0.06 for the corn system, to 0.65 for the blackberry system, to 115.98 for the indigenous system. The respective energy and emergy yield for each system were 2.6E9 J ha^{-1} $year^{-1}$ and 3.57E15 sej ha^{-1} $year^{-1}$ for the indigenous system, 3.71E10 J ha^{-1} $year^{-1}$ and 8.59E15 sej ha^{-1} $year^{-1}$ for the blackberry system, and 1.40E11 J ha^{-1} $year^{-1}$ and 1.30E16 sej ha^{-1} $year^{-1}$ for the corn system. While the indigenous system has the highest level of sustainability, its energy yield was 14 times less than the blackberry system, and 53 times less than the corn system. The results confirm the need for food production systems with large yields that are more dependent on renewable energies.

Keywords: Resource use; Production; Environmental impact; Corn; Maize; Blackberry; Lacandon Maya

1. Introduction

An important challenge facing the world is how to feed an increasing population with decreasing energy supplies and finite environmental resources. To meet this challenge the sustainability of agricultural methods must be evaluated to determine those with greater yields relative to their resource use and environmental degradation. Processes using larger percentages of renewable energy need to be identified because they are likely to be more sustainable than those using a larger percentage of non-renewable energy (Lefroy and Rydberg, 2003; Martin, 2002). Therefore, to increase agricultural sustainability the trend of increasing production with greater non-renewable inputs, which characterized the Green Revolution (Ko et al., 1998), should be ended.

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[*] Corresponding author. Tel.: +1 614 247 6133; fax: +1 614 292 9448.
E-mail address: martin.1130@osu.edu (J.F. Martin).

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Additionally, adverse environmental consequences of food production, such as soil erosion and declining water tables, must be reduced to insure that future production is not jeopardized (Pimentel et al., 1995).

Agriculture operates at the interface between nature and the human economy and combines natural resources and economic inputs to produce food. Typically, high quality, non-renewable energies from the human economy are utilized to capture and concentrate lower quality, renewable energies. 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 methods (Campbell, 1998). While the value of economic contributions is routinely quantified by economic analyses, such approaches often underestimate environmental contributions to production systems. If environmental inputs are not properly accounted for relative to economic inputs, optimum use of resources may not be achieved, and management decisions will be based on incomplete analyses (Ulgiati et al., 1994). For example, Faeth et al. (1991) analyzed the net income of a Pennsylvania, USA soybean–corn farm with and without natural resource accounting. A net annual income of US\$200 ha^{-1} without accounting for natural resources was reduced to US\$137.5 ha^{-1} when the degradation of natural resources was included, largely in the form of soil erosion. Studies of this type highlight the need for integrated approaches to quantify economic and environmental inputs, to select sustainable systems to meet future needs (Lefroy and Rydberg, 2003).

Emergy analysis, which evaluates system components on a common unit basis, is a promising tool to evaluate resource use and production of agricultural methods. Emergy analysis is a form of energy analysis that quantifies values of natural and economic resources to quantify the value of large-scale environmental support to the human economy (Odum, 1988). It is viewed a ‘donor-side’ evaluation approach because it values items based on energetic inputs as opposed to consumer preferences. Solar emergy is used to determine the value of environmental and human work within a system on a common basis: the equivalent solar energy required to produce each service or product. The fundamental assumption of emergy analysis is that the contribution of a resource is proportional to the available energy of one kind required to produce the resource (Brown and Herendeen, 1996). The solar emergy of products and services is calculated by multiplying units of energy (i.e. joules of oil) by emergy per energy ratios (transformities), units of mass (i.e. grams of corn) by emergy per mass ratios (specific emergy), and dollars by emergy per unit money. Using this technique, natural and economic contributions required to produce agricultural yields can be quantified and compared on a common basis of solar emergy-joules (emjoules). Emergy analysis has been used in a similar capacity to quantify economic and environmental inputs to water projects on the Mississippi and Mekong rivers (Martin, 2002; Brown and McClanahan, 1996), and to evaluate the sustainability of agricultural methods in Australia (Lefroy and Rydberg, 2003), Sweden (Rydberg and Jansen, 2002), Italy (Ulgiati et al., 1994), and China (Hong-fang et al., 2003).

The goal of this study was to compare three different agricultural systems with regard to their resource use, productivity, environmental impact, and overall sustainability. The three systems were corn (*Zea mays* L.) production in Kansas, United States, blackberry (*Rubus Rubus* Watson) production in Ohio, United States, and polyculture production in Chiapas, Mexico. These systems included a highly productive, conventional United States farm (Kansas corn), a family run “pick your own” fruit cultivation (Ohio blackberry), and a subsistence-based indigenous swidden system (Chiapas polyculture).

2. Methods

2.1. Site descriptions

The study site for the corn analysis was 89 ha of a furrow irrigated family owned farm located in Republic County, Kansas, USA (39°49′28″N 097°37′56″W). The corn production was rotated on a three-year cycle with sorghum. While this analysis focused only on corn production for one year, the benefits of crop rotation were accounted for by reduced annual rates of fertilizer, herbicide, and insecticide application.

The blackberry farm consisted of 0.11 ha in which blackberries grew with 1.3 m spacing in rows that were 3.3 m apart to allow for tractor access. Located near, Columbus, Ohio, USA (39°57′40″N 082°59′56″W), the family owners have successfully allowed customers to self-harvest the produce.

Traditional Lacandon Maya agroecosystems of Chiapas, Mexico (16°45′30″N, 91°30″W) cycle through three stages of production starting with the milpa (field crop stage), progressing to the acahual (bush stage), and then to the forest, before returning to the milpa. Each farmer typically divides their total area into milpas, acahuals and forests of different ages. Natural ecological succession drives the conversion between field stages (McGee, 2002, p. 82; Nations and Nigh, 1980). Polyculture is used in each field stage with as many as 60 different plant species producing resources. By directing natural succession through the control of seed banks and plantings and using resources from all stages during this progress, the Lacandon are able to reap benefits from their fields without inputs of seeds, fertilizer, herbicides, and pesticide (Levy, 2000). For this analysis a total area of 12 ha was analyzed that contained 2 ha of milpa and 10 ha divided between acahual and forest plots.