HENDRY COUNTY SUSTAINABLE BIOFUELS CENTER

Sustainable Biofuel Project: Emergy Analysis of South Florida Energy crops

FINAL REPORT TO:
Intelligentsia International Inc., 132 N. Lee St., Labelle, FL 33935

BY

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List of Acronyms

ExA	Exergy Analysis
CExC	Cumulative Exergy Consumption
DDGS	Distillers Dried Grains with Solubles
EIS	Emergy Index of Sustainability
ELR	Environmental Loading Ratio
EmS	Emergy Synthesis
EP	Eutrophication Potential
Ex	Exergy
EYR	Emergy Yield Ratio
FU	Functional Unit
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LHV	Low Heating Value
NER	Net Energy Ratio
NEV	Net Energy Value
UEV	Unit Emergy Values

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This Report consists of a Literature review of Emergy Analysis (EA), Highlights on Environmental Assessment tools and software (particular attention to EA) and an Emergy Assessment or Analysis of the various farming systems for potential energy crops for South Florida - sugarcane on both organic and mineral soils, energy cane and sweet sorghum on mineral soils.

1.0 Introduction

Much of the attention directed toward renewable fuels, such as biodiesel, is focused on the perception that they have superior environmental properties compared to their petroleum fuel counterparts (*Analysis of Biodiesel Impacts on Exhaust Emissions Draft Technical Report*, 2002); (Knothe, 2010). In addition, developing renewable fuels is desirable because they are derived from sustainable sources of energy, whereas petroleum fuels come from a finite resource that is rapidly being depleted. However, the production of renewable fuels generally involves a significant amount of fossil energy (e.g., petroleum-derived diesel fuel is used to cultivate and harvest the soybeans used to make biodiesel). The amount of fossil energy used for biodiesel or bioethanol must be measured over the entire life cycle of its production to determine the extent to which it depends on petroleum fuels. The degree to which it is renewable is largely a factor of the amount of fossil energy used for its production. It is beneficial to know the renewability of a biofuel for two reasons.

First, it is useful to know how much a biofuel relies on petroleum-derived energy for its production; the less a biofuel depends on petroleum energy, the more potential it has for diversifying our total fuel supply.

Secondly, the renewability factor is one of many criteria that may be used by policymakers and others to evaluate and compare various biofuels. Renewability is a useful measurement that can be used along with other measurements, including environmental, economic, and social criteria, to assess the benefits of biofuels.

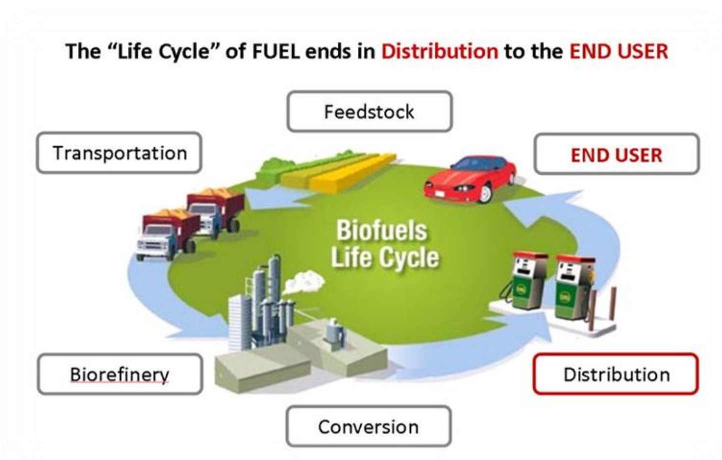


Figure 1: Typical Lifecycle of biofuel (Image Source: USDOE)

The State of Florida has a large stake in this and determines to contribute significantly in this enterprise. As the nation's third largest consumer of energy, it's imperative that

Florida's energy policy creates an environment that fosters the development of affordable, clean energy supplies to meet the state's long term needs (Adam Putnam, FL ag. commissioner, Florida Energy Summit, 2012). Businesses producing biofuels from biomass, appreciate Florida's high volume of biomass feedstock – accounting for about 7% of total U.S. biomass output, by some estimates. It is in this light that the Hendry County Sustainable Biofuels Center was set up. The goal of the Center is to foster the development of a sustainable industry for biodiesel, cellulosic ethanol, and other biofuels in south Florida by addressing some of the core needs not currently the subject of study and investment by other institutions or the private sector. The center is committed to provide regional government agencies, private companies, and other groups with independent analysis of biofuels systems, make recommendations for their enhancement and coordinate programs to develop improved biofuels systems.

1.1 Objective

The desire to have a sustainable alternative transportation fuel such as ethanol begins with sustainable agriculture. Whether it is bioethanol or more traditional agriculture on Florida lands, the desire will be to limit the use of pesticides and fertilizer, as well as the processing activities involved in the production of the biomass. This study is one amongst others, evaluating the sustainability of the various farming systems. These farming systems include: sugarcane (on organic and mineral soils), energycane and sweet sorghum, both on mineral soils.

The primary objective of the study is to compare the relative sustainability matrices of the energy crops and their respective farming systems. These matrices should guide decision and policy makers to determine the overall sustainability of an intended or proposed bioethanol project related to any of these studied crops. Several different methods of energy analysis (LCA, EA, ExA, CBA, EF, etc)[1] have been proposed to assess the feasibility or sustainability of projects exploiting natural resources. Analyses are very often performed, focusing on only one aspect of the problem: for example, maximizing energy ratios, minimizing money cost, increasing jobs, etc. Thus, the results

[1] Life Cycle Analysis (LCA), Energy Analysis (EA), Exergy Analysis (ExA), Cost Benefit Analysis (CBA), Ecological Footprint (EF).

of analysis of the same process can be significantly different depending on the method used and on the inputs and outputs identified. Furthermore, the long-term sustainability and the stability equilibria between man and the rest of the natural system are often neglected (Bastianoni & Marchettini, 1996). In these particular studies, the concept of Emergy Analysis, introduced by Odum in the 1980's was used. Results are presented here for sugarcane on both mineral (sandy) and organic (muck) soils. In summary, the main objectives are:

1) To assess and compare the sustainability levels of cultivation of sugarcane on mineral soils and organic soils for ethanol production.
2) To identify processes within the cultivation that could be targeted for improvement.

1.2 Project Scope

Though the bioethanol production path typically includes the Agricultural phase, transportation and Conversion phase (bio-refinery) to storage and distribution (see Fig 2), this study only considers the agricultural phase.

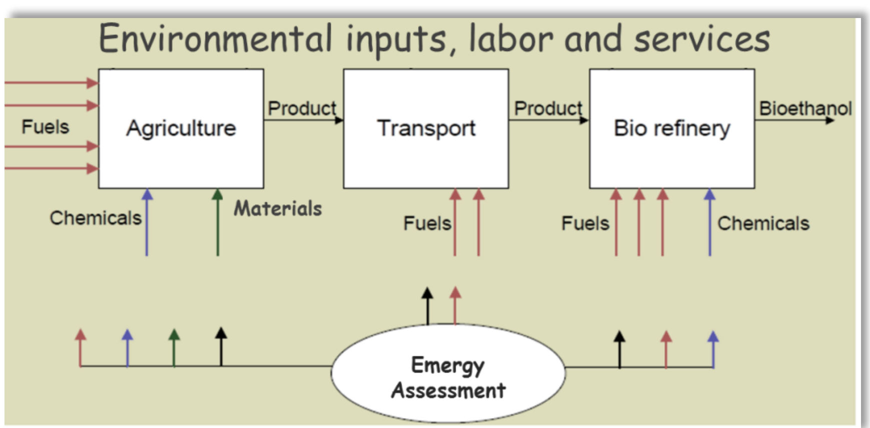


Figure 2: Major Bioethanol production phases

However, this study includes the production of feedstock or biomass without the subsequent production of bioethanol. Again, the primary crop analyzed is sugarcane (on both sandy and muck soils). Calculations are based on inputs per hectare (ha) of the sugarcane grown field. An overview of the processes included in the system evaluations are detailed in Figure 3.

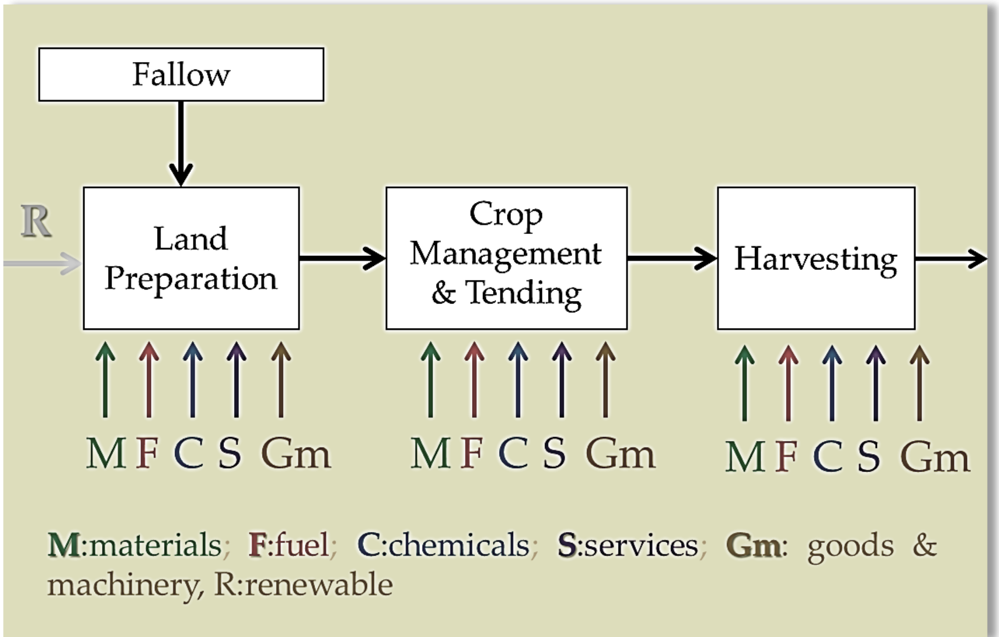


Figure 3: Agricultural Phase of Bioethanol Production

1.2.1 System Boundary

As described in Fig. 3, production pathways are evaluated beginning with Fallow, where the land is considered unused with occasional pest maintenance; Land preparation, considering equipment use, fuel consumption, and ancillary materials needed for the preparation of one hectare of land; Planting one hectare of land, including seed cane production, cane dropping and covering, and all the equipment, materials and energy needed; Cultural practices, which include all the agricultural work such as irrigation, fertilizer application, pest control, chemical application, fuel, materials and energy utilized; and Harvesting sugarcane as a final product of the feedstock production process, ending with the deposit of sugarcane billets on wagons on the harvested field.

The geographical area considered is South Florida and the data sampling included annual representative data for the crop year 2010 or best available when data for that year was not available.

1.2.2 Assumptions and Limitations

- All materials purchased for use on the farmland (e.g. fertilizers, chemicals, etc.) were assumed to be available on the farm without need to consider transportation. In some instances, transportation is considered as a component of custom rates.
- The transformities (explained later in this report) of machinery selected, makes machine production an implicit consideration within the system boundary.
- Sugarcane production is assumed to be conventional.

2.0 Environmental System Assessment tools

Just the thought of building a system would require an evaluation tool to help one choose the best path or method. Even after systems have been created and implemented, it is still necessary to evaluate their performance and consider how improvements could be made, especially in answer to the increasing challenges promoted by regulation. Models that can help decision makers toward such goals are systems assessment tools. A simple introduction and comparison on five of these methods are presented in the next section. It begins with Exergy Analysis (ExA), Life Cycle Analysis (LCA) which is obviously the most common and widely used method, Ecological Footprint (EF), Energy Analysis and Emergy Analysis.

2.1 Exergy Analysis

Exergy analysis is based upon the second law of thermodynamics, which stipulates that all macroscopic processes are irreversible. The exergy analysis method is a technique based on the concept of exergy, which is loosely defined as a universal measure of the work potential or quality of different forms of energy in relation to a given environment. It has been widely used to identify and eliminate thermodynamic imperfections of thermal processes (Szargut et al., 1988). It has also been used in Ecosystem Theory and Ecological modeling, to determine levels of organization of self-organized systems (Jorgensen, 1995). An exergy balance applied to a process or a whole plant reveals how much of the usable work potential, or exergy, supplied as the input to the system under consideration has been consumed (irretrievably lost) by the process (Kotas, 1985).

Exergy analysis is typically applied at the scale of the process or equipment, and does not account for the exergy consumed in earlier processes. Exergy analysis indicates how far a system deviates from its theoretical potential to do work. The method is useful to locate and quantify losses of energy quality in processes. This helps to optimize the use of resources with respect to their quality, in order to use energy more efficiently in a process or in the society as a whole. To estimate the total exergy input that is used in a production process it is necessary to take all the different inflows of exergy to the process into account. It is this type of budgeting which is often termed as exergy analysis.

Wall, 2010 identifies three different methods used to perform an Exergy Analysis: a process analysis, a statistical analysis or an input-output analysis. Process analysis which is focused on in this work, centers on a particular process or sequence of processes for making a specific final commodity. It evaluates the total exergy use by summing the contributions from all the individual inputs, in a more or less detailed description of the production chain. It excludes services and support facilities, such as machinery, since they are not part of the material and energy inputs to the production process. Several cases with numerical examples are given in literature (Szargut et al., 1988; Ahern, 1990; Azzarone and Sciubba, 1995; Bejan et al., 1996; Sciubba and Ulgiati, 2005). According to Sciubba et al., 2003 the basic procedure in a typical exergy analysis involves:

1) Defining the control volume to which the analysis is to be applied. This volume must include the immediate surroundings of the system.

2) Drawing a detailed flow chart of the system under consideration, paying particular attention to the proper level of aggregation at which the representation is made. Sciubba et al., 2003 add that an excessive disaggregation (i.e. too much detail) requires more extensive calculations and demands for very detailed data, often not available in practice. However, a rather low disaggregation would possibly lead to formulation of assumptions that may detract from the reliability of the analysis.

3) Constructing a data (or use an existing one) of the components chosen to represent individual processes. For each process, identify incoming and out flowing fluxes of mass and energy, separating where possible 'necessary' from 'accessory' inputs and 'useful products' from 'secondary' and 'by-products'.

4) Identifying the thermodynamic state of all fluxes, and quantifies their relevant properties (temperature, pressure, enthalpy, entropy, composition and concentration, chemical potentials, etc.)

5) Performing an exergy balance of each component to compute the exergy destruction and extend to the system level.

6) Computing the relevant efficiencies and exergetic costs.

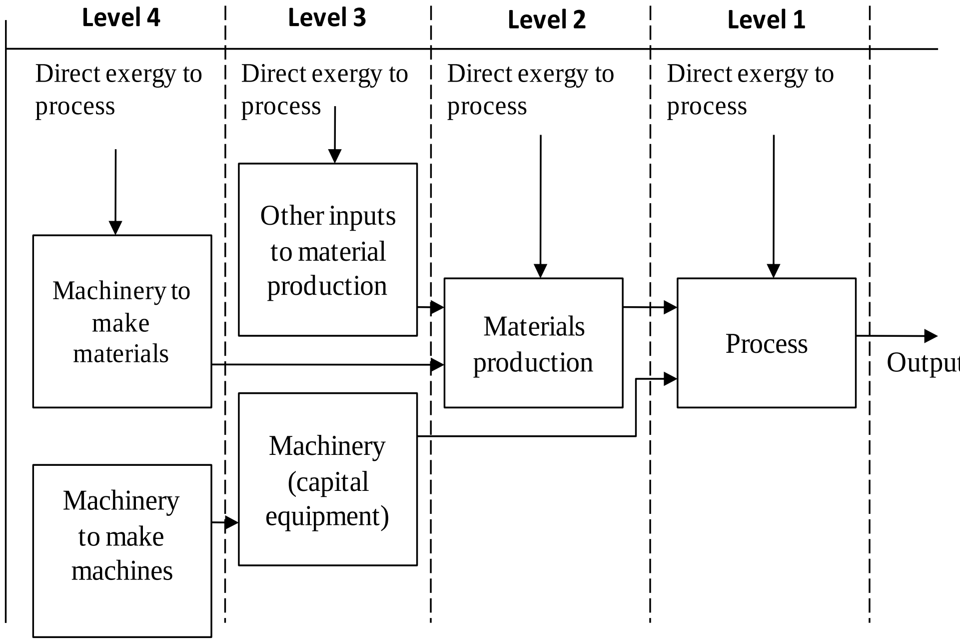


Figure 4: Levels of an exergy process analysis (Wall, 2010)

An exergy analysis offers useful insights for the correct assessment of the process itself. It identifies and quantifies the sources of irreversibility, and allows for an immediate comparison of different process structures. Furthermore, it provides a clear indication of the resource-to-end-use matching, thus allowing for a more proper resource allocation.

Its inability to account for externalities though limits its usefulness for a broader picture (Sciubba and Ulgiati, 2005). Exergy analysis has been used extensively for identifying inefficiencies and opportunities for saving energy in industrial systems. Exergy is a very useful concept and provides information only about the current state of the system and its future ability to do work.

However, it does not provide any information about the thermodynamic history or life cycle of the product or service, which is especially relevant in environmentally conscious decision-making.

Various extensions of exergy analysis such as Industrial Cumulative Exergy Consumption (ICEC) analysis (Szargut et al., 1988) and Exergetic LCA (Cornelissen and Hirs, 1997) have been developed in the past to analyze industrial systems. ICEC analysis considers cumulative exergy consumption in the industrial links of a production chain, and has a strong basis in engineering thermodynamics. Similarly Extended Exergy Accounting (EEA) proposed by Sciubba determines cumulative exergy consumption associated with not only raw material inputs but also labor and capital inputs and non-energetic externalities (Sciubba, 2001). However, all the aforementioned exergy based methods ignore the contribution of ecosystems, and the impact of emissions.

In conclusion, exergy analysis is performed in the field of industrial ecology to use energy more efficiently. The great advantage of Exergy calculations over energy calculations is that Exergy calculation pinpoints exactly where the real losses appear in processes, which is the most useful point in order to make the necessary changes in the process to improve its sustainability by reducing the Exergy consumption.

2.2 Life Cycle Analysis (LCA)

Following the energy crisis of the 1970s methods for analyzing energy requirements in production processes were developed. LCA was developed in parallel and influenced by these energy focused approaches. LCA is an ISO-standardized methodology for inventorying the material and energy inputs and emissions associated with each stage of a product or service life cycle and translating this inventory data in terms of resource dependencies (Guinee et al., 2001; Baumann and Tillman, 2005).

The tool has become very popular in the last decade to analyze environmental problems associated with the production, use and disposal or recycling of products or product systems. The technique is being standardized and adopted by many corporations to obtain more holistic and complete information about the impact of their products and processes on the environment. Every product is assumed to be divided into three main 'life processes' (or from 'cradle to grave') which includes: Production, Use and Disposal or recycling (see Fig. 5) i.e. from raw material acquisition to eventual product and waste disposal.

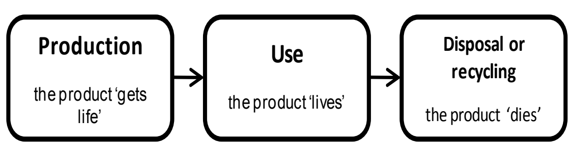


Figure 5: The life cycle 'from cradle to grave'

This analysis tool (LCA) has many uses, such as providing a means to systematically compare inputs and outputs of two products or processes; to assist in guiding the development of new products; to provide information to decision makers in industry, government, and non-governmental organizations amongst several others. It is based on the concept that, all stages of the life of a material generate environmental impacts: raw materials extraction, processing, intermediate materials manufacture, product manufacture, installation, operation and maintenance, removal, recycling, reuse, or disposal. For every 'life process' the total inflow and outflow of energy and material is computed making it very similar to exergy analysis. LCAs consist of three main stages: inventory analysis; impact assessment, and improvement analysis. The inventory analysis involves defining the LCA's purpose, boundary conditions, and assumptions and data collection. The impact analysis stage of an LCA takes these data and systematically quantifies the resulting environmental impacts. Thus, the LCA methodology yields numerical results that allow for direct, analytical comparison between the resulting impacts of the systems under study. Finally, the improvement analysis stage of the life cycle assessment is using the results[2] of the study to determine ways in which the process or product under investigation can be improved. Table 1 presents the methodology for its use.

Phase	Step	Description
Goal Definition and Scoping	Goal definition	To define goals of the analysis
	Scoping	To set up the system boundaries and functional unit
Inventory Analysis	Recording	To collect information and data, refine the system boundaries, and validate the data
	Allocation	To allocate inputs and by-products to main product and co-products
Impact Assessment	Classification	To assign the inventory input and output data to potential environmental impacts
	Characterization	To combine different stressor-impact relationships into a common framework
	Valuation	To assign weighting factors to the different impact categories
Improvement	Interpretation	To identify the ecological weaknesses and potential improvements
	Prevention Activities	To analyze the improved situation

Table 1: General Methodology of LCA

[2] It is worth to note that depending on the functional units (or reference units) chosen for the LCA the results of the study can change a lot. Thus the specifics of each variable should be considered with regards to the purpose of the study performed.

- *Goal definition and Scoping*

Scoping or defining the scope of the LCA consists of setting the limits of the assessment. In this step, which processes is included in the study is decided. It is important to choose a feasible and realistic system. The larger the system is the more complex and expensive it becomes. Complexity and costs arise mainly from collecting data. More information requires more time and money and not necessarily is available. On the other side, excluding processes drives to oversimplified systems and underestimated results. The guidelines suggest excluding processes where no data is available or whose contribution to emissions to the environment is negligible when compared to others. Very often, transportation of inputs is ignored in the LCA study. Defining a functional unit is another objective of the scoping step. This functional unit should be measurable and clearly defined. All inputs and outputs are referred to this unit. In this way, there is a reference level for comparison of many products.

- *Inventory Analysis*

This consists of collecting all data and information of each process included in the LCA study, refining the system boundaries, and validating the data. This step often requires the most effort since a lot of considerations have to be kept in mind. The data can be site specific for a company or an area, or can be more general. It also can be qualitative or quantitative. The kind of data chosen depends on the goal of the LCA study. For example:

- When the purpose is comparing two specific systems, like two companies that produce tires for cars, quantitative and site specific data from the companies is necessary.
- When the purpose is comparison of two general activities, like growing corn and sugarcane in any place of the world, quantitative but not site specific data is necessary. In this case, the sources of the data could come from public databases or even different countries. Obtaining quantitative data is very often limited by its availability. However, some LCA goals might not need quantitative data.

The performance of the LCA strongly depends on the recording step, which is a part of the inventory stage. Data that is obsolete or comes from very different places might not give reliable results. Consequently, compatibility of the data is very important. Refining the system boundaries is also part of this step. Once the data is obtained, some unit processes included in the system might turn to be irrelevant and others that are excluded may be indispensable. A common reason for excluding a process is that its data is unavailable. Sensitivity analyses are repeatedly done to determine whether it is critical or not to include or exclude a unit. A similar scenario applies for inclusion and exclusion of material flows in the system. The validation of data has to be carried on before proceeding to the next step. Mass and energy balances must agree with the final datasheet. Disagreement is very common after collecting data from different sources.

- *Allocation:* Most processes are multi-input and multi-output. In the case of more than an output analyzed, the main product refers to the specie or output of interest. Outputs different from the main product with a positive market value are called co-products. The outputs with negative or neutral market value are called by-products. Pollutants emitted to the environment and wastes are then by-products. When there are co-products in a unit process, then inputs and byproducts need to be allocated, meaning that a fraction of them has to be assigned to the main product and co-products through some rules. As pointed out by Maillefer et al., 1996, "to perform allocation in the right way is one of the biggest difficulties of life cycle inventories."

- *Impact Assessment:* This involves assigning the inventory input and output data to potential environmental impacts. This step requires considerable scientific knowledge for linking the output data to its impact. Since an output can contribute to more than one impact category, special care has to be taken to avoid double.

- *Characterization:* Characterization is the process of combining the effect of different substances on the same category of environmental impact. For example, what the environmental impact of methane is in equivalents of carbon dioxide.

- *Valuation:* Valuation is the process of assigning weighting factors to the different impact categories based on their perceived relative importance as set by social consensus. For example, an assessor or some international organization might choose to regard ozone depletion impact to be twice as important as the impact of loss of visibility, and apply weighting factors to the normalized impacts accordingly.

- *Improvement:* Interpretation and prevention activities systematically identify, qualify, check, and evaluate information from the results of the inventory analysis and impact assessment. It is the phase that often receives less attention. In this phase, extensive sensitivity and uncertainty analyses should be carried on.

- **Major Issues and Shortcomings of LCA**

Shortcomings of LCA have been motivation of many discussions and publications. Burgess and Brennan, 2001 offer a concise and complete review of these problems. Many of these shortcomings are not associated only with LCA, but to any approach that expands the scope of the unit under study to include other relevant units or activities.

Many of the problems that now face LCA are characteristic of this concept of a whole. It is important to identify them for two main reasons.

The first reason is that the solution to some of these problems may be found in other approaches.

The second reason is that some problems, like for example development of database, can be solved in collaboration with the other approaches. In any case, even if avoiding the use of LCA, these problems still come up in any other approach. Setting the boundaries of the system can be a problem. Ideally, all units involved directly or indirectly in the production chain should be included. However, including more units in the system involves collecting more data, spending more money and increasing the complexity of the system. Besides, often some units play a less important role than others and therefore they might be excluded without affecting the results.

Allocation has been one of the most discussed difficulties in LCA. Allocation is a consequence of breaking down a network in subsystems. Deciding allocation becomes critical when two systems with strong interaction are studied. Then, the rules of allocation chosen for the LCA of one subsystem can strongly affect the results of the other. Physical parameters have generally been discredited for not being able to represent the economic reality. According to Stromberg et al., 1997 and Huppes and Schneider, 1994, economic value of products should be used as a basis for allocation because they justify the existence of the industrial activity. In Lee et al., 1995 the major difficulty in assigning monetary values to environmental costs is that it is difficult to place causality on environmental effects. In general, there is no agreement on which allocation method to use. Guinee et al., 1993 have proposed to apply sensitivity analyses to all significant allocation methods in future case studies.

Another difficulty is obtaining quantitative data which is very often limited by its availability. The performance of the LCA strongly depends on the quality of the data. Data that is too old, too sparse, too averaged may not be trustworthy. The costs of collecting data can increase at a level where it is not feasible to run a LCA. It is sometimes possible to reduce these costs by using general publicly available databases. To get some good quality data requires working in collaboration with the suppliers, distributors, etc. Other situation is that the data obtained does not include some emissions or streams that are considered unimportant. Therefore, collecting such data often leads to inconsistencies like disappearance or creation of mass and energy. In such cases, LCA has no utility if physical data is wrong with respect to critical pollutants. Ayres, 1995 argues that most of the recent literature focuses on developing or finding an acceptable way to model environmental impact, i.e. to select, evaluate and compare different categories. Seldom one alternative is clearly preferable than others; they just vary from one category to another. Heiskanen, 2000 points out that LCA's results may confuse rather than enlighten the managers and therefore could make decision-making harder.

Moreover, LCA focuses mostly on the emissions from industrial processes and their impact and on consumption of nonrenewable resources. It does not account for the contribution of ecosystems to industrial activity.

- **LCA as a decision making tool**

Schaltegger, 1997 argues that from an economic point of view, today's LCA provides a small potential benefit given the high probability of potentially wrong decisions (because they are based on background inventory, unrepresentative, low quality and aggregated data) and high costs. Moreover, Heinskaken, 2000 questions whether LCA's results may be used to alleviate the pressure by spreading the impact to share it with the broader system, instead of creating a sense of responsibility. Other point of criticism in LCA is that the methodology makes the user think that it could influence environmental aspects outside their own organization, when in reality, the range of influence or decision- making potential is limited to the physical constraints of its organization. In general, the use of LCA as a decision- making tool is questionable given the facts that it can rarely point to the best technological choice and does not consider economic aspects. Moreover, LCA does not offer a compatible way to assist traditional cost-benefit analysis for decision-making. Huppes et al., 1996, argues that the "main option for expanding the domain of LCA seems to be in the combined analysis of environmental effects and costs".

2.3 Ecological Footprint Analysis

The most widely used indicator of carrying capacity in recent times is the Ecological Footprint (EF) analysis methods developed by Rees and Wackernagel, 1994. EF analysis is an accounting tool that estimates the resource consumption and waste assimilation requirements of a defined human population or economy in terms of a corresponding productive land area (Wackernagel and Rees, 1996). An Ecological Footprint is calculated by inventorying the material and energy flows required to support a given population or activity and re-expressing these flows as area of productive land required to furnish the requisite resources and absorb a subset of the resultant wastes (Wackernagel and Rees, 1996). The indicator therefore provides a measure of resource dependency expressed in a common currency, which can be used to compare performance between systems both spatially and temporally (Wackernagel et al., 2004). Complete ecological footprint analysis would include both the direct land requirements and indirect effects of all forms of material and energy consumption. It allows a cumulative approach to impact analysis. Ecological footprint method calculates the land-use implications of consumption-related resource flows and waste sinks required to support a system or a population, that is translating consumption into land areas, and simply, consumption is separated into five major categories: food, housing, transportation, consumer goods and services. Basicaly, comparison and analysis on systems could base on the calculation result of Ecological Deficit.

2.4 Energy Analysis

Energy analysis[3] according to Brown and Herendeen, 1996 is the process of determining the energy required directly and indirectly to allow a system to produce a specified good or service. The basic motivation for energy analysis is to quantify the connection between human activities and the demand for this important resource. In energy analysis the requirements of energy for production of goods or services is estimated. Generally the aim is to investigate the potential to reduce energy costs or to compare energy use in different processes giving the same product. This includes energy inputs transformed at all stages of the production process. The system perspective is described hierarchically with respect to energy requirements. Direct energy from fuels used in the processes is traced backwards to the primary energy sources so that energy used for the extraction and refining of the fuels is accounted for. The system boundaries depend on the aim of the study. One problem in energy analysis is that different forms of energy have different usability. Whether sunlight and labor should be accounted for in an energy analysis or not is a disputed question, generally it is not accounted for. Energy analysis can include renewable energy sources. However, attentive bookkeeping is required to keep them separate from non-renewable sources. While energy analysis is based on the notion that energy is more important than most people think, it typically is not used to support an energy theory of value. The more moderate view is that energy analysis is one information input, like economics, to the process of making a decision (Herendeen, 1988). The framework of input output analysis is used for mathematically sound analysis of energy flow in ecological and economic systems (Hannon, 2001). The

[3] Energy Analysis as introduced in this manuscript is the extension of the well-known concept in which "Energy analysis uses the first law of thermodynamics to track the transformations of energy and to calculate the energy losses in a process or process unit as the difference between the enthalpy leaving and entering the process."(Brown and Herendeen, 1996).

concept has also been used to study energy efficiencies in a broad range of economic activities (e.g. see Crawford et al., 2006, Giampietro et al., 1993, Kok et al., 2006).

2.5 Emergy Analysis[4]

Based on the principles of energetics (Lotka, 1922, 1945), systems theory (von Bertalanffy, 1968) and systems ecology (Odum, 1967, 1975, 1996), emergy analysis (EMA) is a quantitative analytical technique for determining the values of nonmonied and monied resources, services and commodities in common units of the solar energy it took to make them (Brown and Herendeen, 1996). Emergy analysis is based on the assumption that everything on the planet can be expressed in terms of equivalents of solar energy. The solar emergy of a resource or commodity is calculated by expressing all of the resource and energy inputs to its production in terms of their corresponding solar energy inputs (Solar emergy joules or seJ) (Odum, 1996, 2000). The resulting total can then be used to calculate the 'transformity' for the resource or commodity, which is a ratio of the total emergy used relative to the energy produced (seJ/J).

In theory, emergy analysis can be applied to systems across scales. To date, emergy analysis has been and is increasingly applied to evaluate a variety of systems including geographical regions (Pulselli et al., 2008; Lei and Wang, 2008), food production (Maud, 2007; Rotolo et al., 2007) and industrial processes (Brown and McClanahan, 1996; Min and Feng, 2008; Pulselli et al., 2008).

[4] Emergy evaluations are both synthetic and analytic. Synthesis is the act of combining elements into coherent wholes for understanding of the wholeness of systems, while analysis is the dissection or breaking apart of systems to build understanding from the pieces upward. In the emergy method of evaluation, sometimes called *emergy synthesis*, first the whole system is considered through diagramming, and then the flows of energy, resources and information that drive the system are analyzed. By evaluating complex systems using emergy methods, the major inputs from the human economy and those coming "free" from the environment are integrated to analyze questions of public policy and environmental management (Emergysystems.org, 2010).

3.0 The Emergy Concept

Definition 1 – *The First Law of thermodynamics states that the total energy of any system and its surroundings is conserved – i.e. Energy is neither created nor destroyed, it changes from one form to another.*

Preliminary Concepts

Before introducing the emergy concept, it is important to recall some general energy concepts. The theoretical and conceptual basis for the emergy methodology is grounded in thermodynamics. According to the First Law of Thermodynamics, any system in a given condition or state contains a definite quantity of energy. When this system undergoes change, any gain or loss in its internal energy is equal to the loss or gain in the energy of the surrounding systems. In differential form, this is written as in Equation 2-1, without chemical reactions.

$$dU = \delta Q + \delta W \qquad (3\text{-}1)$$

where the term U is internal energy, Q is heat and W is work (defined here as a useful energy transformation).

The symbol δ is employed to indicate that the term refers to an incremental amount of a quantity which is not a property. In contrast, dU denotes the incremental change of a property, internal energy. This is because, though we cannot measure the absolute values of either of these energy terms alone, we can and do measure their difference. Application of the First Law to a system or process is merely an accounting exercise. All the increases in the energy of the system due to all the non-thermal energy interactions are summed and this sum is the measure of the total work (available energies utilized in energy transformations) done on the system. The total energy increase due to thermal interactions is summed and this sum is the total heat absorbed by the system. This makes the accounting easier, as energy is either here or there. It does not go away.

Definition 2 – *The second law of thermodynamics states that the entropy change of any system and its surroundings, considered together, resulting from any real process, is positive and approaches a limiting value of zero for any process that approaches irreversibility.*

The first law does not account for the observation that natural processes have a preferred direction of progress. For example, spontaneously, heat always flows to regions of lower temperature, never to regions of higher temperature without external work being performed on the system. The first law is completely symmetrical with respect to the initial and final states of an evolving system. In a refrigerator, heat flows from cold to hot, but only when forced by an external agent, a compressor. The second Law of Thermodynamics is behind the separate summing of work and heat. Basically, for every transformation of energy or material into another kind, some energy is lost from the system. Every system requires this kind of 'payment' in order to be productive.

$$dS = \frac{dQ_{rev}}{T} \text{ (Clausius, 1865)} \tag{3-2}$$

$$dS = dS_{system} + dS_{surroundigs} \tag{3-3}$$

where δQ is the loss of the system's ability to do work in the form of dissipated heat;

T is the uniform temperature of the system; and

dS is the exact differential of entropy.

The second law is also known as the law of the dissipation or degradation of energy or the law of the increase in entropy (Gourgaud, 1997). Entropy (S) may be defined as a measure of the extent to which energy is degraded, dissipated, or diluted so that it becomes less able to do work. The energy contained in a system may be constant, but its utility diminishes with every increase in the entropy of the system. It is important to note here, that from the second law, it is the accumulative change in energy that takes place as a result of a change in the state of the system that is the crucial element underlying the theory of the *Emergy concept*.

Emergy (Not Energy)

Emergy is a concept conceived by Howard T. Odum, resulting from several decades of research on energy quality in ecosystems and human systems throughout the 1960's, '70's and '80's (Brown and Ulgiati, 2004). The logic behind Odum's concept of embodied energy or emergy is based on the logic behind the Second Law of Thermodynamics as stated in the previous section. This may also be known as the law of the dissipation or degradation of energy resulting in an increase in entropy. It is a measure of the recordable available energy of every process which has gone into the generation of a given product of nature or service in the economy.

Definition 3 - *The term emergy was coined by David Scienceman, a visiting scholar from Australia working with H.T. Odum, and is a contraction of the phrase "embodied energy". It is a measure of not only the measurable energy currently contained in the product or service but also the totality of the available energies that have been consumed or degraded in each energy transformation that has contributed to the development of that product or service in its current form (Gourgaud, 1997).*

Though it was conceived in the ecological sciences, proponents claim it is applicable to all forms of systems, including natural systems, human systems, and the interface of natural and human systems (Brown and Ulgiati, 2004). Emergy is defined as "available solar energy used up directly and indirectly to make a service or product" (Odum, 1996, p.8). Brown and Ulgiati, 2004, state that emergy can be thought of as "energy memory" and is a way of including all inputs to a system on a common basis. This common use of measure for emergy is the solar emjoule, abbreviated seJ. Researchers from a number of disciplines use this approach to goods and services originating from natural and human systems. It has been applied to the examination of a number of different systems, including regional development, alternative energies, building efficiency, agricultural practices and natural environments (Giannetti, et al, 2006; Lei and Wang, 2008; Meillaud et al, 2005; Menegaki, 2008; Odum, 2000a; Pulselli, 2008; Rydberg and Haden, 2006; Tilley and Swank, 2003).

As stated previously, the First Law of thermodynamics states that energy entering a system is neither created nor destroyed. According to Gourgaud, 1997, energy flowing into a system is either stored within the system or leaves the system through the appropriate pathways. Although energy is conserved within a system, useful transformations (work) necessitate that the energy as it participates in these transformations changes its essential quality. As such, energies of different qualities are not additive. This distinction is a major breakthrough by the emergy concept from that of the traditional energy analysis, sometimes used in environmental accounting techniques as described in this work, where energy of different types and qualities are deemed to be additive.

3.1 Mathematical Definition of Emergy

The concept of emergy is best understood by a clear understanding of exergy. Exergy as already defined, is the real proportion of the energy that can drive mechanical work. It could also be given as:

$$E_x = G + gz + \frac{1}{2}v^2 \qquad (3\text{-}4)$$

where *G* is Gibbs free energy, and is the available chemical energy.

In thermodynamics, the Gibbs free energy is a thermodynamic potential which measures the useful work obtainable from an isothermal, isobaric thermodynamic system. Technically, the Gibbs free energy is the maximum amount of non-pV work which can be extracted from a closed system, and this maximum can be attained only in a completely reversible process. When a system evolves from a well-defined initial state to a well-defined final state, the Gibbs free energy 'G' equals the work exchanged by the system with its surroundings, less the work of the pressure forces, during a reversible transformation of the system from the same initial state to the same final state. Gibbs defined what he called the available energy of a body as: The greatest amount of mechanical work which can be obtained from a given quantity of a certain substance in a given initial state, without increasing its total volume or allowing heat to pass to or from external bodies, except such as at the close of the processes are left in their initial condition (Gibbs, 1873). The initial state of the body, according to Gibbs, is supposed to be such that the body can be made to pass from it to states of dissipated energy by reversible processes. The *'G'* is referred to as Gibbs function or simply free energy. The Gibbs free energy is defined as:

$$G = U + PV + TS = \sum_{i=1} k\mu_i N_i \qquad (3\text{-}5)$$

Exergy power, P_x, is the rate of change of exergy with time and given as:

$$P_x = \frac{dE_x}{dt} \qquad (3\text{-}6)$$

Emergy is then defined as the integral of the exergy power over time.

$$O(t) = O_{ref} + \int_{t_0}^{t_1} P_x dt \tag{3-7}$$

i.e. the fundamental emergy of formation (O_{ref}) and the emergy from a set time t_0 to a time t. However this is only true by the introduction of a transformity factor (τ) which considers the change of energy from one form to another which makes this not usable in its present form.

3.2 Transformity (τ)

The transformity (previous name transformation ratio, Scienceman, 1987) is the ratio obtained when the total emergy used up to make a product is divided by the exergy remaining in the product. H.T. Odum defined transformity as the emergy of one type required to make a unit of energy of another type (Odum, 1996). It has the dimension of emergy/energy and measured in seJ/J. Transformity is a very important concept in Emergy Evaluation. It is used as the name implies, to 'transform' a given energy unto emergy by multiplying the energy by the transformity and hence, provides an energy quality factor (Brown and McClanahan, 1996). The transformity of a resource increases with more energy transformations contributing to the production of the resource because at each transformation, available energy is used up to produce a smaller amount of energy of another form. So, the emergy increases but the energy decreases that result in sharp increase in emergy per unit energy, i.e. transformity (Hau and Bakshi, 2004).

According to Odum, the energy flows of the universe are organized in an energy transformation hierarchy and that the position in the energy hierarchy is measured with transformities (Odum and Peterson, 1996). According to Scienceman, the concept of transformity introduces a new basic dimension into physics. However there is ambiguity in the dimensional analysis of transformity as Bastianoni et al (2007) state that transformity is a dimensionless ratio.

In any useful energy transformation, many joules of low transformity (low quality) energy are required to produce a lesser quantity of higher transformity (higher quality) energy. The energy generated by the work of transformation constitutes a higher level in the series of transformations. The output of any one energy transformation contributes and converges energy to produce an even smaller output at the nert higher level in an energy transformation chain (Figure 6, Odum, 1996).

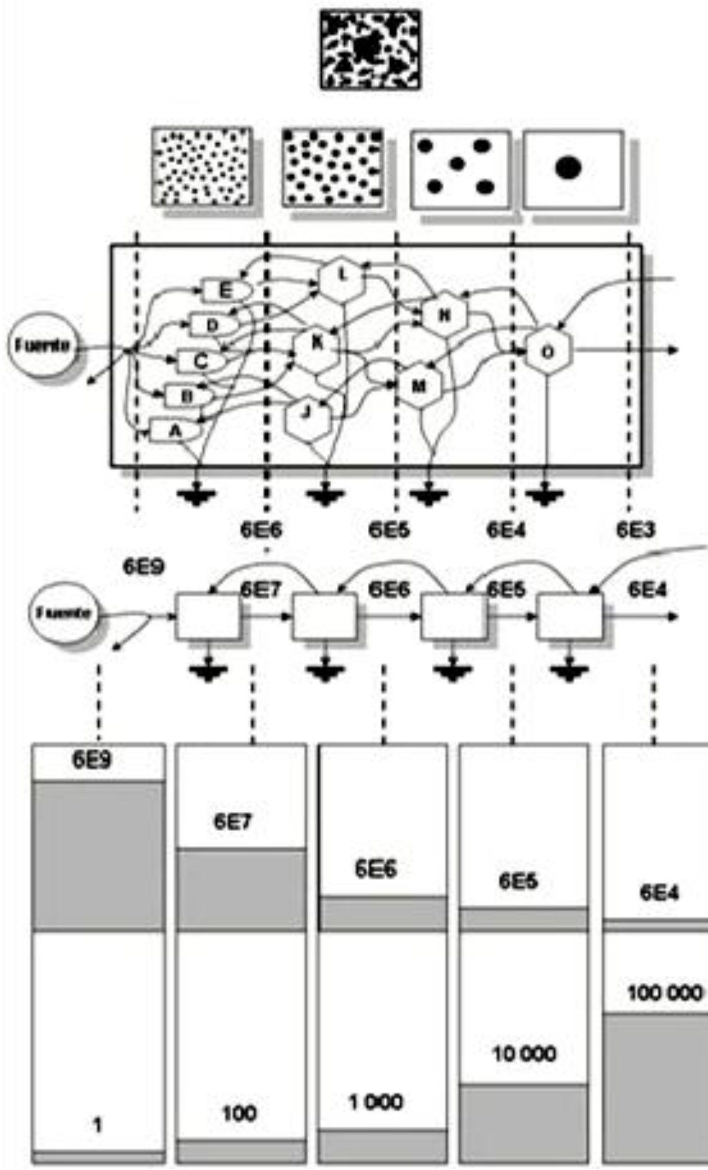


Figure 6: Energy transformation steps (Odum, 1996)

- **Definition as a ratio**

Like the efficiency ratio, transformity is quantitatively defined by a simple input-output ratio. However the transformity ratio is the inverse of efficiency and involves both indirect and direct energy flows rather than simply direct input-output energy ratio of energy efficiency. This is to say that it is defined as the ratio of emergy input to energy output.

$$\tau = \frac{O(in)}{E(out)} \tag{3-8}$$

However, it was realized that the term 'energy output' refers to both the useful energy output and the non-useful energy output (Nag, 1984). But as Sciubba and Ulgiati observed, the notion of transformity meant to capture the emergy invested per unit product, *O*, or useful output, E_x, (Sciubba and Ulgiati, 2005). The concept of transformity was therefore further specified as the ratio of input emergy dissipated (availability used up) to the unit output exergy. According to Jorgensen (2000), transformity is a strong indicator of the efficiency of the system.

$$\tau = \frac{O(in)}{E_x(out)} \tag{3-9}$$

Substituting the mathematical definition of emergy (3-7) in the above equation (3-9) gives:

$$O = \sum_i \tau_i E_{x_i} \tag{3-10}$$

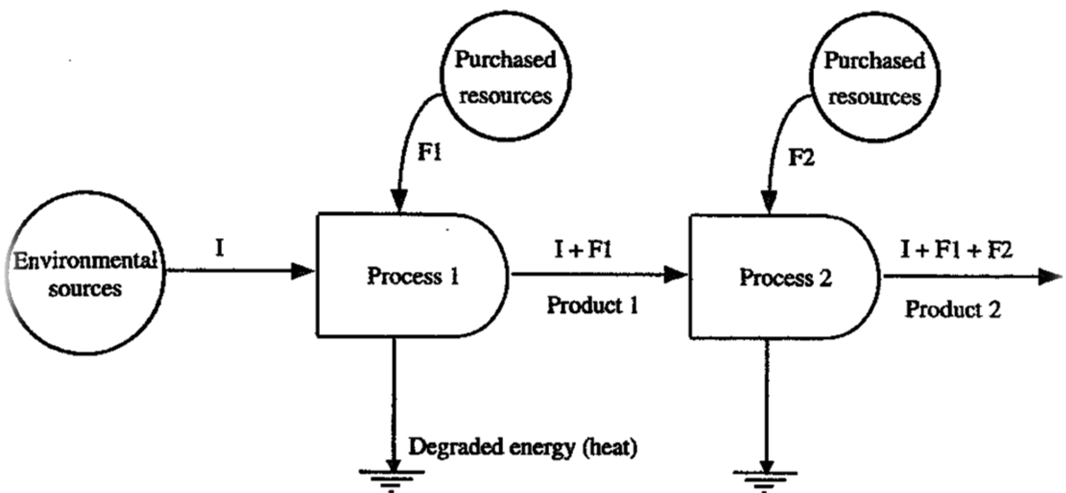
- **Calculation of Transformities**

Transformities are usually calculated by analyzing the production process for a resource or a particular item. The transformity of a particular economic or ecological products and services is determined by analyzing the production processes of the economic and environmental subsystems. Then all energy inputs required for the production are documented and converted to solar emergy joule by multiplying by the appropriate transformity. Finally, to get the transformity of the product, all the solar emergy joules for the different steps in the production process are summed up and then divided by the available energy of the product (Brown and McClanahan, 1996). Transformities are usually available from other studies (e.g. Brown and Arding, 1991; Odum, 1996). Figure 7 shows how transformities are calculated by summing all the inputs to process, direct environmental inputs as well as purchased inputs, expressed in emergy (seJ), and then dividing this total emergy by the energy content of the product of the process.

The same item may have different transformities, depending on the process that resulted in the item. This may be due to the technology involved, the year of calculation and where the process took place (country, region).

The baseline for all transformity calculations is the total emergy input to the Earth. This is the sum of the emergy of the solar insolation, deep earth heat and tidal energy. These global emergy inputs are the driving force for all planetary activities. As mentioned previously, most of the case studies that use Emergy Evaluation rely on and use transformities previously calculated. Thus, the availability of this data often determines the ease with which emergy accounting studies can be performed (Hau and Bakshi, 2004). For an in-depth description of the methodologies used to derive the transformity coefficients for various natural and human processes, see Chapters 3 and 4 in Odum's Environmental Accounting: Emergy and Environmental Decision Making.

A



$$\text{Transformity of product 1} = \frac{\text{inputs } I + F1 \text{ in emergy units}}{\text{output 1 in units of energy}}$$

$$\text{Transformity of product 2} = \frac{\text{inputs } I + F1 + F2 \text{ in emergy units}}{\text{output 2 in units of energy}}$$

Figure 7: Calculation of transformities (Lagerberg, 1999)

range of transformities usually exist for a given product. The lower limit of the transformity range represents the most efficient approach to making the product. Odum (1996) maintains then that transformities for a given product can be used to compare production efficiencies among systems.

- **Unit Emergy Values (UEVs)**

Unit Emergy Values (UEVs) are based on the emergy required to produce something. UEVs differ dependent upon whether the entity is better represented by an energy measure (joules) or a material measure (grams). According to Brown and Cohen, 2008, if the ratio compares emergy inflow to unit energy outflow, that ratio is called a 'transformity'. If it compares emergy inputs to unit material outflow, the ratio is the 'specific emergy', similar to the specific heat associated with the mass of compound or element. UEVs are calculated by dividing the sum of all emergy required by the units of product output. These values are computed based on the emergy required to generate one unit of output from a process. Transformity and specific emergy are the two types of UEVs considered in this work. However, there are several types of UEVs such as, Emergy per unit money, which is the emergy supporting the generation of one unit of economic product and emergy per unit labor defined as the amount of emergy supporting one unit of labor directly supplied to a process.

3.3 Emergy's relation with other thermodynamic quantities

There seems to be much confusion about the relationship between emergy and other thermodynamic properties, such as energy, exergy, enthalpy, etc. The qualitative difference, as pointed out by Odum and coworkers, is that unlike emergy, these thermodynamic quantities do not recognize the difference in quality of various energy sources. A common example is that `a joule of sunlight is not equivalent to a joule of fossil fuel' in the sense that they cannot do the same kind of work (Brown et al., 1995). This leads to impressions that emergy analysis is a very different approach from exergy analysis (Emblemsvag and Bras, 2001). Similarly, Ayres (2000) questions the need for emergy as opposed to standard variables of thermodynamics, namely, enthalpy and exergy. There is also some confusion about the exact definition of available energy. It is certainly not Gibbs free energy because not all of it is available for work. Odum (1995) argues that neither is it exergy because "exergy is defined to include only energy flows of similar qualities that of mechanical work, while available energy as defined in emergy analysis also considers important inflows, such as human services that require very large energy flows to maintain. On the other hand, Odum (2000b) and Campbell (2001) define available energy in emergy analysis as exergy or energy with the potential to do work. Scrutiny of transformity calculations indicates that available energy as used in emergy and exergy may indeed be equivalent. For example, for heat engines the available energy of the system is the same as exergy since it is obtained by multiplying its heat content or flow by the Carnot factor (Odum, 1996). The relationship of the transformities of fuels to their combustion efficiencies may be easily justified if available energy and exergy are equivalent. Odum uses the heat of combustion to determine available energy, which is shown to be close to exergy for fuels (Szargut et al., 1988). Moreover, the use of exergy justifies why dissipated heat carries no emergy value. This lack of formal links between emergy and other thermodynamics quantities is a significant cause of skepticism about emergy among engineers. Some efforts have been made to connect emergy with exergy (Ulgiati, 1999). Improved understanding of the relationship between emergy and exergy is essential for constructive cross-fertilization between these areas. Such insight is essential for greater use of the data and concepts of emergy analysis in evaluating the life cycle of engineering products and processes. A strong link between engineering thermodynamic concepts and emergy helps proving that many criticisms of emergy, such as its connection with economic value or the Maximum Empower Principle, are not relevant to using emergy to capture the thermodynamic aspects of ecological goods and services. More importantly, it clears up much of the confusion regarding the relation of emergy to other thermodynamic properties.

3.4 Overview of Emergy Evaluation Procedure

Emergy Evaluation of a given system is a mass and energy flow analysis where flows are transformed to emergy using transformities. Emergy evaluation allows comparison of energy flows of different forms. Emergy Evaluation like other assessment methods is guided by the research or management questions of concern. It is based on universal principles of ecological energetics and uses the Energy Systems Language to describe natural systems.

- **Summary of emergy analysis procedure**

There are five main steps required to complete an emergy evaluation (Campbell et al., 2006).

- First, a detailed systems diagram is completed.
- The second step is to translate this knowledge into an aggregated diagram of the system addressing specific questions.
- Third, descriptions of the pathways in the aggregated diagram are transferred to emergy analysis tables where the calculations needed to quantitatively evaluate these pathways are compiled.

- The fourth step in the method is to gather the raw data needed to complete the emergy analysis tables along with the conversion factors (energy contents, transformities, etc.) needed to change the raw data into emergy units.
- Finally, after the raw data has been converted into emergy units, indices are calculated from subsets of the data

3.5 Overview System Diagrams

A system diagram is drawn first to put in perspective the system of interest, combine information about the system from various sources, and to organize data gathering efforts. The process of diagramming the system of interest in overview ensures that all driving energies and interactions are included. Since the diagram includes both the economy and environment of the system, it is like an impact diagram which shows all relevant interactions. Next, a second simplified (or aggregated) diagram, which retains the most important essence of the more complex version, is drawn. This final, aggregated diagram of the system of interest is used to construct a table of data requirements for the Emergy analysis. Each pathway that crosses the system boundary is evaluated.

- **Emergy Algebra**

Rules of emergy evaluation

Since the definitions of emergy and transformity are based more on logic of memorization, than on conservation, algebra of emergy has been introduced (Brown and Herendeen, 1996). The rules of emergy evaluation are:

- all source emergy to a process is assigned to the processes output;
- by-products from a process have the total emergy assigned to each pathway;
- when a pathway splits, the emergy is assigned to each leg of the split based on its percentage of the total energy flow on the pathway;
- emergy cannot be counted twice within a system:
    - emergy in feedbacks cannot be double counted;
- By-products, when reunited, cannot be added to equal a sum greater than the source emergy from which they were derived.

3.6 Emergy allocation techniques

Figures 8(a) and 8(b) (Odum, 1996) indicate the energy, emergy and transformity relationships for the splitting of the flow via a pathway and storage respectively. In by product branching, Figure 8(c) (Odum, 1996), the flow in each resulting branch is of a different energy quality or transformity. By-product flow results from energy transformations. All by-product branches derived from an energy transformation carry the same emergy as the emergy on each pathway records the total input to the process. If these two pathways come together again in some other area of the system, they are not to be added as this would result in double counting (Gourgaud, 1997). A more detailed overview of the emergy allocation depicting the rules is discussed later in this chapter.

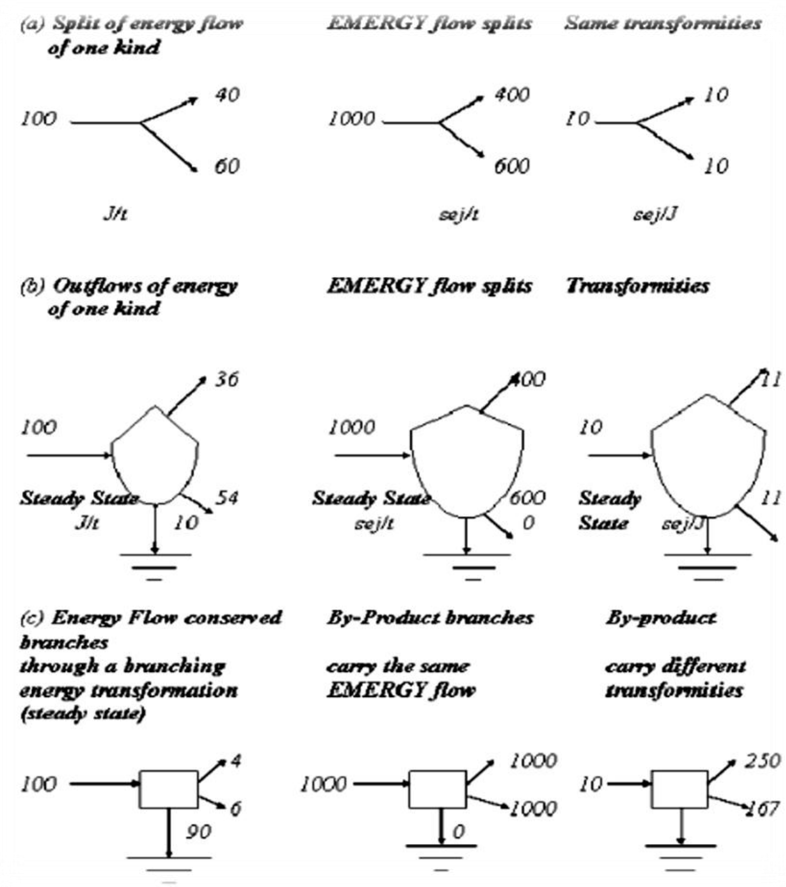


Figure 8: (a) and (b) indicate the energy, emergy and transformity relationships for the splitting of the flow via a pathway and storage respectively. In by-product branching (c) the flow in each resulting branch is of a different energy quality or transformity

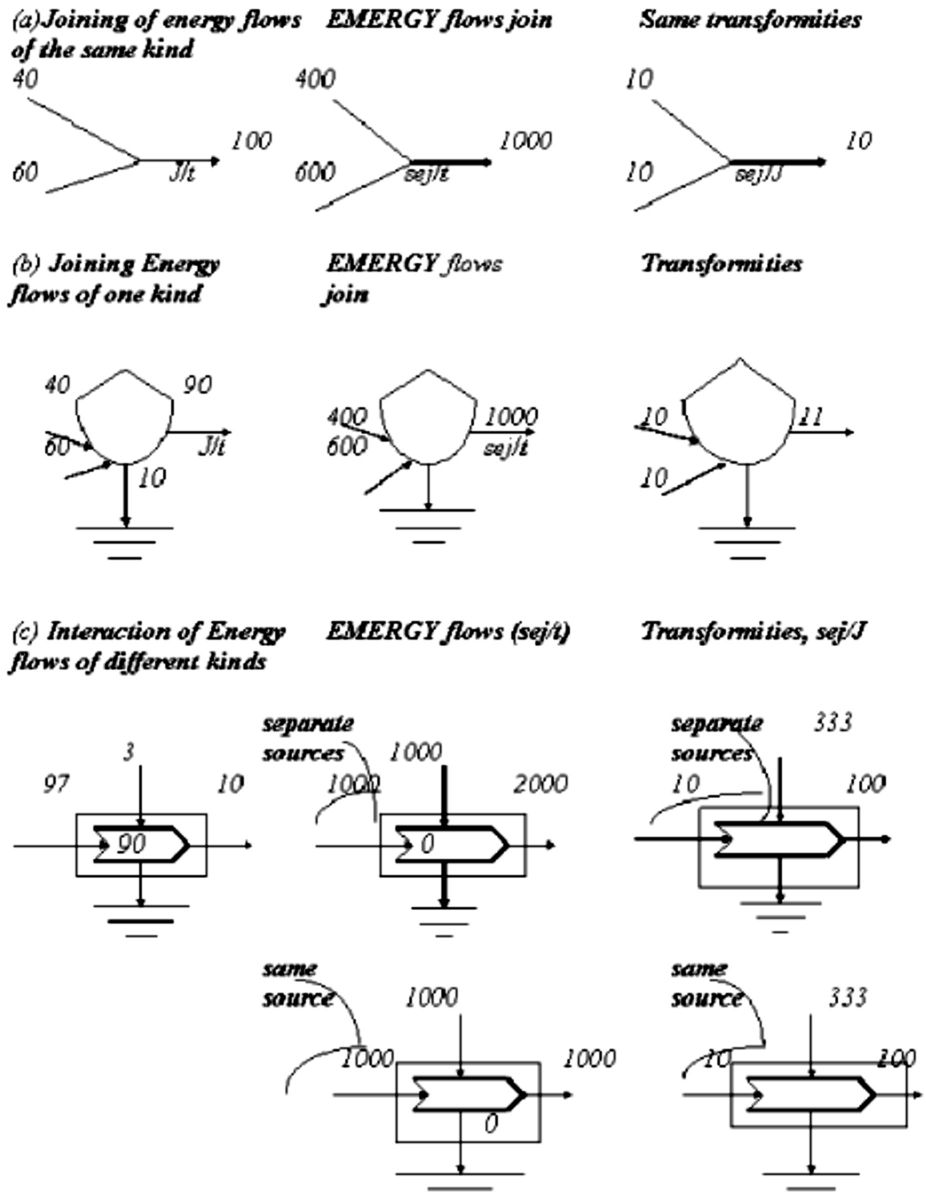


Figure 9: Interactions of flows of the same kind (a) and (b); intersection of flows of different kinds, i.e. with different transformities (c) (Odum, 1996).

In figure 9, interactions of flows of the same kind and different kinds are depicted. In figure 9(c), there is an intersection of flows of different kinds, i.e. with different transformities. In this type of intersection, interactions occur in which both inputs are required for energy transformations resulting in one more output products. Most energy transformations involve the interaction of two or more inputs of different transformity.

3.7 Emergy Evaluation Tables

Emergy analysis of a system of interest is usually conducted at two scales. First, the system within which the system of interest is embedded is analyzed and indices necessary for evaluation and comparative purposes are generated. Second, the system of interest is analyzed. Both analyses are conducted using an Emergy Analysis Table organized with the following headings:

1	2	3	4	5	6
Note	Item	Raw Units	Transformity	Solar Emergy	Macro-economic $

Each row in the table is an inflow or outflow pathway in the aggregated systems diagram; pathways are evaluated as fluxes in units per year. An explanation of each column in an Emergy Analysis Table is given next.

Column 1: The line number and footnote number that contains sources and calculations for the item.

Column 2: The item name that corresponds to the name of the pathway in the aggregated systems diagram.

Column 3: The actual units of the flow usually evaluated as flux per year. Most often the units are energy (joules/year), but sometimes are given in grams/year or dollars/year.

Column 4: Transformity of the item usually derived from previous studies.

Column 5: Solar Emergy (seJ), which is the product of the raw units in Column 3 with the transformity in Column 4.

Column 6: The result of dividing solar Emergy in Column 5 by the Emergy to money ratio (calculated independently) for the economy of the nation within which the system of interest is embedded.

3.8 Emergy Indices

Emergy evaluation classifies inputs into different categories – refer to Fig. 10 (i.e. local renewable, R, local non-renewable, N; and purchased, F). On the basis of these classes, some indicators can be computed in order to assess the sustainability of the use of resources. The environmental loading ratio (ELR) is the ratio of purchased (F) and non-renewable local emergy (N) to renewable environmental emergy (R). When a transformity or emergy content is assigned to a product, every input into the product can be measured in emergy terms, i.e. on a common basis. A measure of the real annual wealth of a nation is based on total annual emergy use.

Emergy availability to a nation and emergy use per person suggest a measure of the standard of living enjoyed by the population of that nation in a much more effective manner than that of fuel use per person or per capita income. This emergy-use index takes into account the different quality of input joules, by means of the transformities, and also includes renewable as well as non-renewable environmental resources, usually neglected in energy balances. In this context, standard of living refers to the availability of resources and goods and is a much more encompassing and effective measure of living standards than $GDP/capita.

The emdollar refers to the total amount of money flow generated in the entire economy by a given amount of a particular emergy input. The emdollar is defined as the emergy input divided by the emergy/$GDP ratio. A high emdollar value for a particular amount of emergy input contributes more to the economy. It has been proposed that the emdollar value of a resource could be used as a shadow price of the resource itself.

In trade analysis, the emergy exchange ratio (EER) is the ratio of emergy received for emergy delivered in a trade or sales transaction. A particular trade of one commodity for another can be expressed in emergy units. The nation receiving the higher emergy acquires a greater real value and as a consequence has its economy stimulated more than its trading partner. Unprocessed products tend to have high emergy exchange ratios for the importing nation when sold at market prices. Most technologically advanced nations exhibit a high emergy exchange ratio as they are not emergy self-sufficient. A high emergy exchange ratio contributes to the vitality of the economy of the importing nation which utilizes the unprocessed resources in its manufacturing sector making it capable of successfully competing with other nations in the overall balance of trade.

The emergy yield ratio (EYR) is the emergy of an output divided by the emergy of those inputs to the process that are fed back from the economy. "This ratio indicates whether a process is a primary energy source for the economy. Recently, the ratio for typical competitive sources of fuels has been about 6 to 1 (Lagerberg, 1999). Processes yielding less than this cannot be considered primary emergy sources. If the ratio is lower than unity, the process is not a positive source of net emergy; if the ratio is less than alternatives, less return be obtained per unit of emergy invested in comparison with alternatives Less competitive emergy sources (i.e. having a lower net emergy yield ratio) may have a lower cost, due to local conditions: costs are affected by international markets and value of currencies, which may not reflect the physical reality of a misuse of the emergy invested in comparison with actually available alternatives. Sources less competitive may become competitive when the others approach scarcity or are used up." Odum (1995) has defined an emergy investment ratio in order to account for the contributions to the productive process from the environmental inputs.

The emergy investment ratio (EIR) is the purchased emergy feedback (F) from the economy (services and other resources) divided by the free emergy inflow from the environment (I). This ratio gives an indication of whether a process is as economical as a utilizer of an economy's investments when compared with alternatives and evaluates the emergy input from the economy required to develop a unit of environmental input. Prices may be low because of the high proportion of useful work which is provided free from the environment. Ulgiati et al (1994) state that if the ratio is low then the tendency is to increase the purchased inputs so as to process more output and more money. They claim that the tendency is towards optimum resource use.

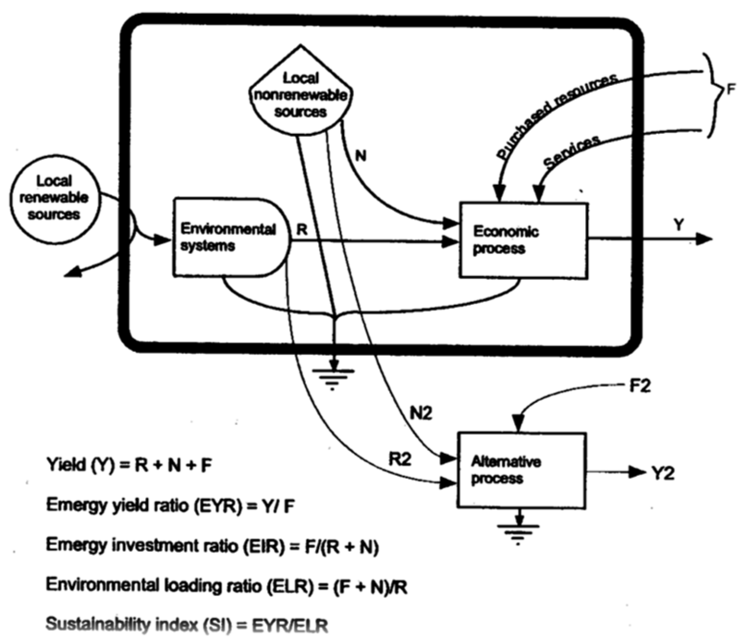


Figure 10: Representation of typical emergy indices (Lagerberg, 1999)

This ratio (EIR) is useful for the investigation of the economic viability of processes in the economy and is particularly relevant to the investigation of best alternate land use problems.

The environmental loading ratio (ELR) is the ratio of purchased and non-renewable indigenous emergy to free environmental emergy. A very high value for this ratio may be indicative that the pressure of economic activities to local environmental resources is excessive and resulting in environmental stress.

The empower density is defined as the emergy flow per unit time and unit area and is a measure of spatial concentration of emergy flow within a process or system. A high empower density can be found when emergy use is large compared with available land area. The empower density is expected to be high for highly industrialized areas and for areas of intensive crop production.

The Sustainability Index (SI) which is a composite index tracking a diverse set of socioeconomic, environmental, and institutional indicators calculated for Italy in 1989 (Ulgiati et al., 1994) was SI = 0.17. This indicates a massive use of non-renewable energy, large imports of purchased energy and materials, and large environmental stress. In contrast, the value of the sustainability index for the village under study (SI = 6.68) is indicative that the eco-village economy is a model to pursue for a more sustainable development.

3.9 General Applications of Emergy Evaluation

The concept of Emergy Analysis has been widely accepted globally and its application has spanned such global problems as population carrying capacity, greenhouse emissions, material fluxes in conventional and renewable energy production systems, and sustainable patterns of development at local, regional, national and global scales.
Emergy research has led to the development of methods for quantifying environmental values, and their application to questions of energy policy and natural resource management throughout the world, helping developing nations understand their resource issues and to evaluate alternative solutions. It has addressed resource management questions in Thailand, Papua New Guinea, Mexico, Brazil, and Ecuador, the six countries of the "southern cone" of South America and most recently the Sahel region of northern Africa.

Emergy analysis was used to compare four technological options of soybean production in Brazil (Ortega et al., 2004): chemistry and machinery intensive; herbicide and no tillage; ecological traditional and modern organic enterprise. These were divided in two main categories, the biological models (organic and ecological farms) and the industrial models (green revolution chemical farms, using herbicide without tilling). The biological options showed better environmental, economic and social performance indicators. The classic emergy analysis, point out that the biological options are the better alternatives (Hau, 2002).

The emergy analysis was also used to evaluate the sustainability of a village which aims to be ecologically friendly. The choice of focusing on the use of local resources including agriculture and farm goods, photovoltaic panels, renewable heating and cooling systems, recycled water from constructed wetlands etc., aims to obtain a sustainable village.

Another study examined and evaluated, by using emergy analysis, the use of environmental resources for wastewater treatment in a Swedish town. The study included an evaluation of the amount of emergy associated with the production of wastewater. On the basis of the analysis, it was realized that the large amount of emergy that wastewater contains are in proportion to the amount of resources employed for wastewater treatment and the extensive effects on surrounding ecosystems of discharge of untreated wastewater. The use of local renewable natural resources in Swedish municipal wastewater treatment systems is negligible compared with the use of purchased inputs, processed largely with the support of fossil energy. A drastic shift of this order would demand that extensive land areas surrounding human settlements be (indirectly or directly) devoted to wastewater treatment. These areas are not accessible today. The analysis also indicated that resource requirements from the economy in the production of electricity by the digestion of sewage sludge is about two times the total resource use for generation of the average mix of electricity used in the town. As a result, if the only reason to digest the sludge were to produce electricity, it would be more resource-efficient to purchase the electricity on the Swedish distribution net (Bjorklund et al., 2001).

4.0 Emergy Calculations for biomass production

The calculations of the energy inverted by specified agricultural resources are based on the equations described by Montesino, M., 2010 in his work *(Ecosystems services in emergy terms: Danish Energy Crops, 2010)*. Inflow energies or raw input data in grams, liters, etc., are first calculated and later transformed into solar emjoules by multiplying them by their respective transformities (Mainly from Odum, 1996).

4.1 Emergy diagram

According to Montesino, 2010, the sources of energy in agriculture can be classified in four groups:

1) Renewable sources (R): contains the sources provided by the ecosystem such as sun, wind, rain and geological inputs.
2) Non-renewable inputs (N): contains environmental sources which are mostly non-renewable, such as soil.
3) Purchased inputs (F); manmade materials such as fertilizers, pesticides and fuel.
4) Labor and Services (S): work done by farmers, contractors and farm workers.

The sum of these contributions is the energy available for a crop to grow up and produce. By definition, it constitutes the emergy of the process. At the end of the production season, biomass is harvested and traded for by money (market) as shown in Fig. 11.

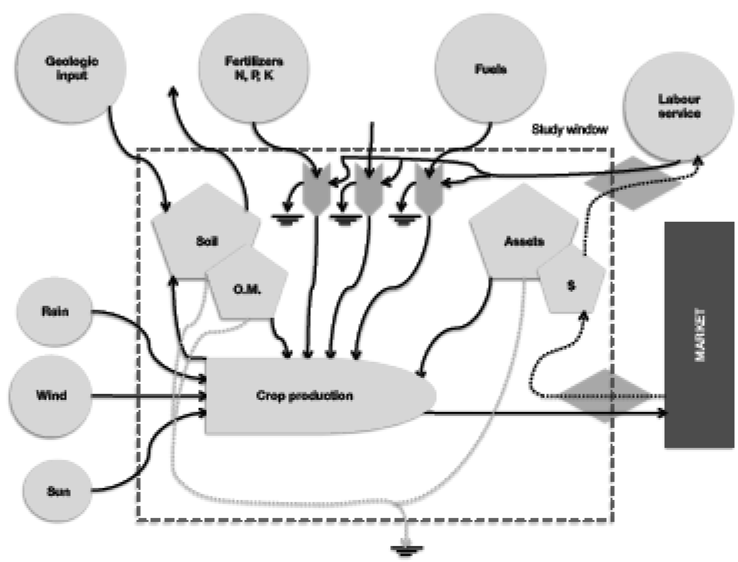


Figure 11: Emergy Systems diagram of Florida Agriculture

4.2 Emergy Formulae

Renewable emergy (R)

Solar emergy:

$$\text{Solar emergy}\left(\frac{seJ}{yr\cdot ha}\right)=\text{Solar energy}\left(\frac{J}{yr\cdot ha}\right)\times\text{ Solar transformity}\left(\frac{seJ}{J}\right)$$

$$\text{Solar energy}\left(\frac{J}{yr\cdot ha}\right)=\text{Land area dedicated for biomass production}\left(\frac{m^2}{ha}\right)\cdot\text{ Average insolation}\left(\frac{J}{yr\cdot m^2}\right)\cdot(1-\text{Albedo})$$

Wind emergy:

$$\text{Wind emergy}\left(\frac{seJ}{yr\cdot ha}\right)=\text{Wind energy}\left(\frac{J}{yr\cdot ha}\right)\cdot\text{ Wind transformity}\left(\frac{seJ}{J}\right)$$

$$\text{Wind energy}\left(\frac{J}{yr\cdot ha}\right)=\text{ Reference height (m)}\cdot\text{ Land area (ha)}\cdot\text{ Air density}\left(\frac{kg}{m^3}\right)\cdot\left[\frac{0.4\cdot\text{ Wind speed}\left(\frac{m}{sec.}\right)}{0.6}\right]^2\cdot\frac{1}{2}$$

Rain emergy:

$$\text{Rain emergy}\left(\frac{seJ}{yr\cdot ha}\right)=\text{Rain Chemical Potential Energy (CPE)}\left(\frac{J}{yr\cdot ha}\right)\cdot\text{ Rain transformity}\left(\frac{seJ}{J}\right)$$

$$\text{CPE}\left(\frac{J}{yr\cdot ha}\right)=\text{Precipitation}\left(\frac{m}{yr}\right)\cdot\text{ Land area }(m^2)\cdot\text{Water denisty}\left(\frac{g}{m^3}\right)\cdot\text{ (1-Run off coefficient)}\cdot\text{ Gibbs Free Energy}\left(\frac{J}{g}\right)$$

Geochemical emergy:

$$\text{Geochemical emergy}\left(\frac{seJ}{yr\cdot ha}\right)=\text{Geochemical energy}\left(\frac{J}{yr\cdot ha}\right)\cdot\text{ Geochemical Transformity}\left(\frac{seJ}{J}\right)$$

$$\text{Geochemical energy}\left(\frac{J}{yr\cdot ha}\right)=\text{Heat flow}\left(\frac{J}{yr\cdot m^2}\right)\cdot\text{ Land area}\left(\frac{m^2}{ha}\right)$$

After these calculations renewable emergy is written as:

$$\text{Renewable Emergy Resources}\left(\frac{seJ}{yr\cdot ha}\right)=$$
$$\text{Solar emergy}\left(\frac{seJ}{yr\cdot ha}\right)+\text{Wind emergy}\left(\frac{seJ}{yr\cdot ha}\right)+\text{Rain emergy}\left(\frac{seJ}{yr\cdot ha}\right)+\text{Geochemical emergy}\left(\frac{seJ}{yr\cdot ha}\right)$$

Purchased inputs (F)

Pesticides:

$$\text{Pesticides emergy}\left(\frac{seJ}{yr\cdot ha}\right)=\text{Average pesticides used}\left(\frac{g}{yr\cdot ha}\right)\cdot\text{ Pesticides transformity}\left(\frac{seJ}{g}\right)$$

In some cases, pesticides input amounts were quoted in their cost equivalents, in which case the appropriate transformity (sej/$) is used.

Fertilizers:

In case of fertilizers, calculations are divided according to the main elements that constitute them, i.e. Nitrogen, Phosphorus and Potassium are calculated separately:

$$\text{Nitrogen emergy}\left(\frac{\text{seJ}}{\text{yr}\cdot\text{ha}}\right) = \text{Amount of nitrogen}\left(\frac{\text{g}}{\text{yr}\cdot\text{ha}}\right)\cdot\text{ Nitrogen transformity}\left(\frac{\text{seJ}}{\text{g}}\right)$$

$$\text{Phosphorus emergy}\left(\frac{\text{seJ}}{\text{yr}\cdot\text{ha}}\right) = \text{Amount of phosphorus}\left(\frac{\text{g}}{\text{yr}\cdot\text{ha}}\right)\cdot\text{ Phosphorus transformity}\left(\frac{\text{seJ}}{\text{g}}\right)$$

$$\text{Potassium emergy}\left(\frac{\text{seJ}}{\text{yr}\cdot\text{ha}}\right) = \text{Amount of potassium}\left(\frac{\text{g}}{\text{yr}\cdot\text{ha}}\right)\cdot\text{ Potassium transformity}\left(\frac{\text{seJ}}{\text{g}}\right)$$

$$\text{Fertilizers emergy}\left(\frac{\text{seJ}}{\text{yr}\cdot\text{ha}}\right) =$$
$$\text{Nitrogen emergy}\left(\frac{\text{seJ}}{\text{yr}\cdot\text{ha}}\right) + \text{Phosphorus emergy}\left(\frac{\text{seJ}}{\text{yr}\cdot\text{ha}}\right) + \text{Potassium emergy}\left(\frac{\text{seJ}}{\text{yr}\cdot\text{ha}}\right)$$

Mechanical Equipment:

$$\text{Mechanical equpment emergy}\left(\frac{\text{seJ}}{\text{yr}\cdot\text{ha}}\right) = \frac{\text{Embodied energy}\left(\frac{\text{MJ}}{\text{yr}\cdot\text{ha}}\right)\cdot\text{ Mechanical equipment transformity}\left(\frac{\text{seJ}}{\text{kg}}\right)}{\text{Mechanical embodied transformation}\left(\frac{\text{MJ}}{\text{kg}}\right)}$$

Fuel Emergy:

$$\text{Fuel emergy}\left(\frac{\text{seJ}}{\text{yr}\cdot\text{ha}}\right) =$$
$$\text{Average hours of machinery use}\left(\frac{\text{h}}{\text{yr}\cdot\text{ha}}\right)\cdot\text{ Average motor fuel consumption}\left(\frac{\text{l}}{\text{h}}\right)\cdot\text{ Diesel energy content }\left(\frac{\text{J}}{\text{l}}\right)\cdot\text{ Motor fuel transformity}\left(\frac{\text{seJ}}{\text{J}}\right)$$

Services; Labor

$$\text{Labor emergy}\left(\frac{\text{seJ}}{\text{yr}\cdot\text{ha}}\right) = \text{Total employees in Agriculture}\left(\text{ind}\right)\cdot\text{ Average caminç}$$

5.0 Farming Systems Studied

The systems under study were a farm that grows sugarcane on organic soil, commonly referred to as "muck" and another farm that grows on mineral or sandy soil. The analysis considers the production of sugarcane without its conversion to ethanol. Production data (fertilizer inputs, pesticides demand, etc.) refer to current figures of sugarcane production in South Florida (Roka et al., 2010; Alvarez & Helsel, 2011). Whenever possible, production data have been carefully compared with results from other studies similar to the systems under study (Brandt-Williams, 2002; Campbell, 2009). Where there are significant differences due to local specificity, the most appropriate figure has been included in the calculation procedure. This is to ensure that the results might represent and reflect the exact performance of the farming systems in the area. Each data was checked with available literature to ensure it is within the acceptable range. Most of the renewable input data was based on the revised study from Brandt-Williams, 2002. This study only presents results for the first year of sugarcane harvesting (cane planting) without the additional ratoon years of production.

5.1 Boundaries

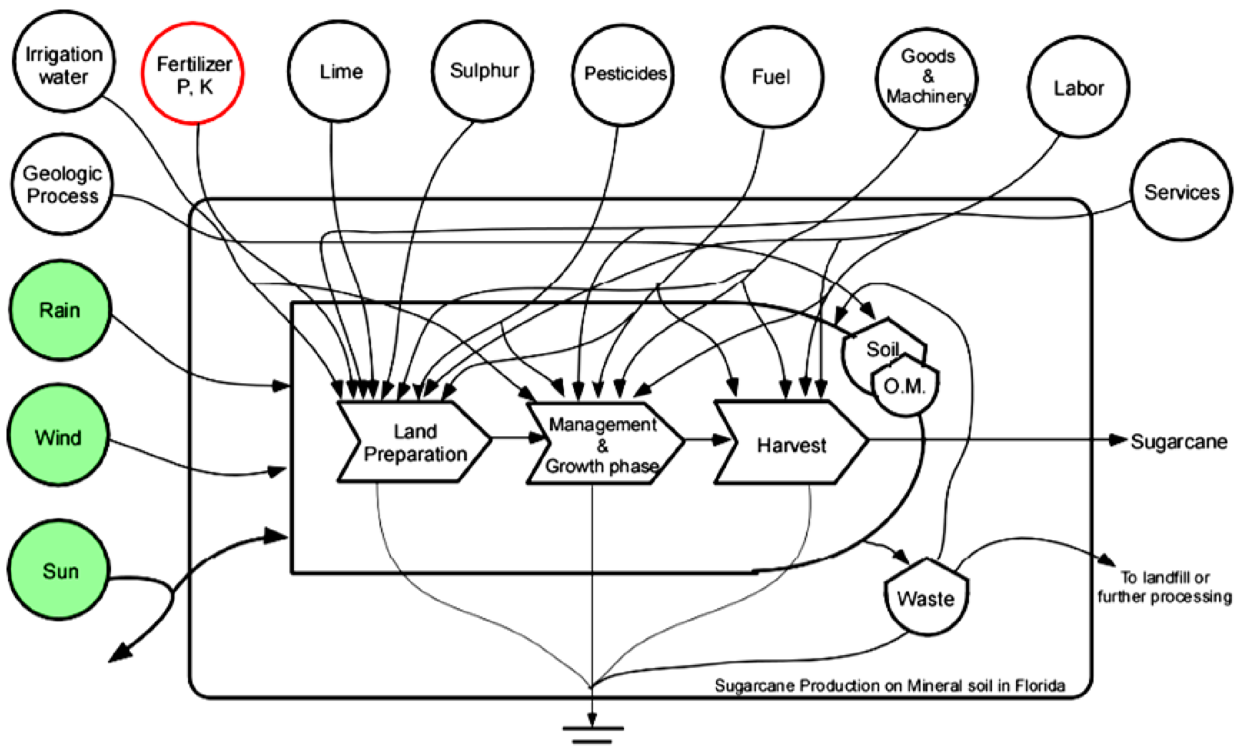
Energy systems diagrams of the investigated processes are shown in Figure 12, where all main steps are drawn from left to right and energy and material flows are indicated. The 5,000-acre farm is located in South Florida. Figure 12 shows the local boundaries of the investigated systems. It includes the Land preparation, crop management (plant tending) and the harvesting operations. Goods and energy directly supplied to the process are accounted for at this scale. In this study, inputs needed to manufacture, transport, and supply goods and energy to the process are not considered. Thus, transportation of materials to site is not included in the calculations. It is assumed that all materials needed at each stage of the production are locally available on the farm.

Thus, transformity and specific emergy values selected for the calculations do not also include transport.

5.2 The Approach

Analysis was carried out at a 1 ha scale for each of the two farming systems. The flows of matter and energy across each system boundary are shown in Fig. 12. Using the energy systems symbols described in Odum (1994, 1996). From this perspective, agriculture is driven by two main kinds of outside sources. To the left are the free renewable emergy flows (sun, wind and rain), and to the right the purchased sources of emergy in the form of fuel, goods and services.

(a)



(b)

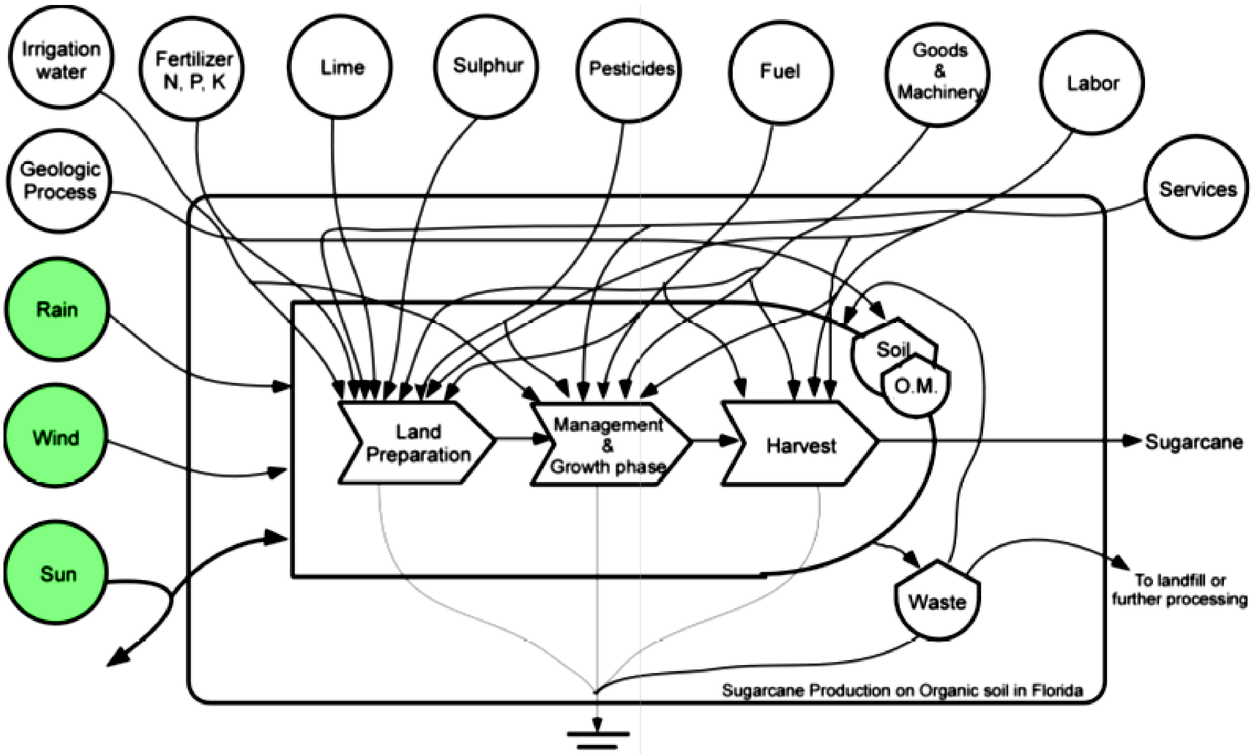


Figure 12: Energy systems diagram showing the main driving forces of sugarcane production – (a) on Mineral soil (b) Organic soil.

Fig. 12 is shown in Fig 13 aggregated into renewable environmental inputs (R), non-renewable environmental inputs (N), materials, fuels and goods (P), the service and labor components (S) and finally the total emergy (Y) being the energy required support the yield.

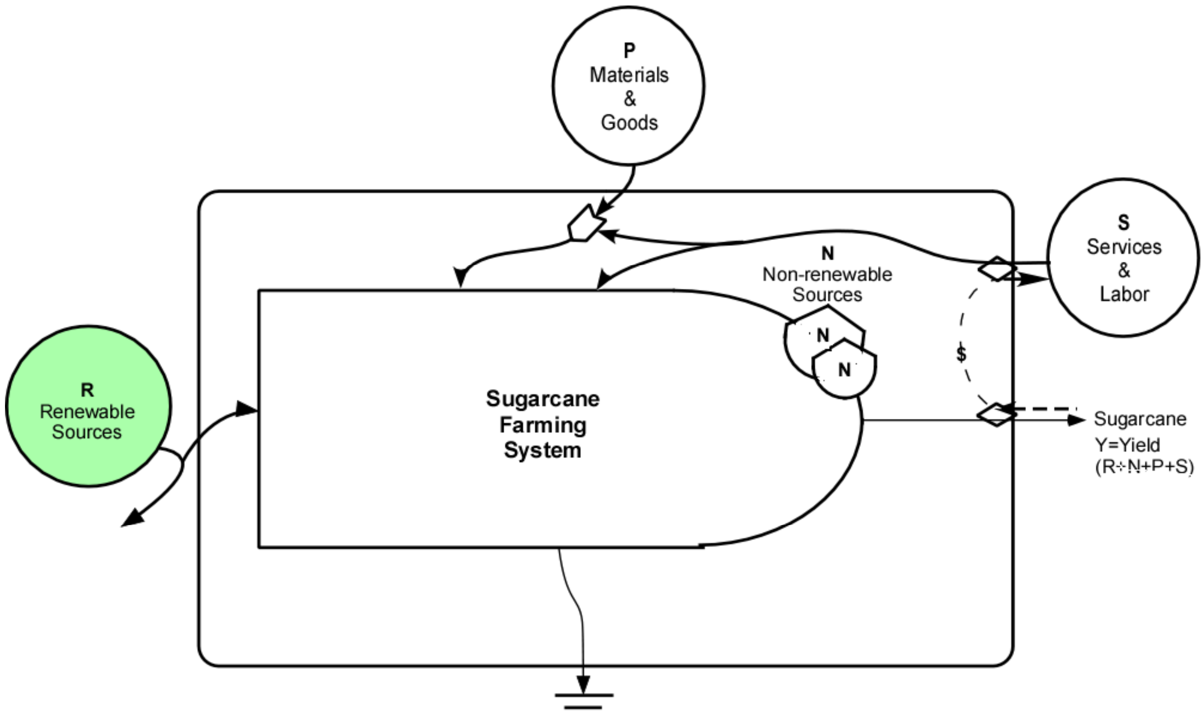


Figure 13: Systems diagram illustrating the flow of energy and materials to and from a sugarcane farming system. The aggregated flows are used to calculate emergy-based indices of sustainability.

These aggregated flows of emergy were then used to derive indices of sustainability as a basis for comparing the overall sustainability of the respective farming system. The indices used are:

- Emergy Yield Ratio (EYR) = Y/(P+S): The higher the value, the lower the system's reliance on economic investment and the higher its economic competitiveness.
- Renewable portion of total emergy (%R) = R/Y: The higher the value, the greater the sustainability of the production system.
- Environmental Loading Ratio (ELR) = (P+S+N)/R: The lower the value, the lower the environmental stress caused by the system on the surrounding areas.
- Emergy Sustainability Index (ESI) = EYR/ELR: The higher the value, the more sustainable the production system.

The emergy of each flow was calculated by multiplying the energy in Joules (or directly from its mass) by their respective transformities or specific emergies. As mentioned, these transformities are derived from previous studies that have evaluated the energy flows and conversion efficiencies involved in producing the natural resource, product or service inputs (Odum, 1996).

5.3 Data sources and emergy evaluation

The data were taken primarily from the sugarcane enterprise budgets for Southern Florida (Roka et al., 2010; Alvarez and Helsel, 2011) in which the authors presented results of a preliminary study to determine the economic potential of several types of energy crops identified as suitable for agricultural production in the state of Florida. The main basis and data sources used in the analyses are listed in Tables 2 and 3.

Table 2: Sugarcane grown on Mineral Soil data (2010). Adapted from Alvarez and Helsel, 2011.

ACTIVITY	UNIT	# YEARS	RATE	# TIMES	PRICE/ UNIT	$/ACRE/YEAR	QTY/ACRE/ YEAR
Fallow land total cost per acre:							
Herbicide + surfactant	qt	1	2.00	2	$ 7.50	$30.00	4.00
Herbicide application	$			2	$ 4.00	$8.00	
Total						$38.00	
Prorated Total		0.25				$9.50	
Land preparation total cost per acre:							
Soil testing and consulting	$	1		1	$ 1.11	$1.11	
Disking	$	1		3	$ 15.00	$45.00	
Lime (Dolomite) application	$	1		1	$ 5.00	$5.00	
Dolomite	ton	1	1.00	1	$ 28.00	$28.00	1.00
Laser Leveling	$	1		1	$ 60.00	$60.00	
Slag	ton	1	1.50	1	$ 56.00	$84.00	1.50
Slag application	$	1		1	$ 5.00	$5.00	
Total						$228.11	
Prorated Total		0.25				$57.03	
Planting							
All related activities	$/acre	1		1	$170.00	$170.00	
Seed cost	$/acre		5.00	1	$ 25.00	$125.00	
Insecticide	lb/acre	1	15.00	1	$ 2.00	$30.00	15
Micronutrients	lb/acre	1	20.00	1	$ 0.51	$10.20	20.00
Total						$335.20	
Prorated Total		0.25				$83.80	
Cultural Activities							
Fertilizer – N	lb	4	43.53	4.25	$ 0.60	$111.00	185.00
Fertilizer - P_2O_5	lb	4	50.00	1	$ 0.60	$30.00	50.00
Fertilizer - K_2O	lb	4	45.00	4.25	$ 0.60	$114.75	191.25
Chemical applications	$	4	1.00	2	$ 4.00	$8.00	
Herbicide (pre emerge herbicide)	qt	4	3.00	1	$ 3.00	$9.00	3.00
Herbicide (pre emerge herbicide)	gal	4	1.00	1	$ 16.50	$16.50	1.00
Herbicide (post emerge herbicide)	qt	4	3.00	1	$ 3.00	$9.00	3.00
Herbicide (post emerge herbicide)	pt	4	2.00	1	$ 3.00	$6.00	2.00
Oil (surfactant)	qt	4	1.00	1	$ 1.65	$1.65	1.00
Mechanical Cultivation	$	4	1.00	1	$ 6.50	$6.50	
Total						$312.40	
Miscellaneous	$					$87.57	
Interest	$					$77.06	
Harvesting activities							
Harvest, load, and haul	Gton	4	32.00	1	$ 7.00	$224.00	
Total variable costs						$851.36	
Overhead activities							
Supervising and vehicles	Gacre			1	$ 10.00	$10.00	
Road and ditch maintenance	Gacre			1	$ 5.00	$5.00	
Pumping and water control	Gacre			1	$ 50.00	$50.00	
Taxes and assessments	Gacre			1	$ 70.00	$70.00	
Land charge	Gacre			1	$ 75.00	$75.00	
Total	$					$210.00	
TOTAL COSTS						$1,061.36	

Table 3: Raw data for sugarcane grown on organic soil data (2009). Adapted from Roka et al., 2010

ACTIVITY	UNIT	RATE	TIMES	PRICE/UNIT	$/ACRE/ YEAR	QTY/ACRE /YEAR
Fallow land total cost per acre:						
Round-up + surfactant	qt	2	2	$4.00	$16.00	4
Land preparation total cost per acre:						
Soil testing [a]	$	1	1	$8.00	$8.00	
Slag	ton	3	1	$56.00	$168.00	3
Dolomite	ton	0	1	$28.00	$0.00	0
Planting and Cultural Activities:						
Fertilizer – N	lb	0	0	$0.60	$0.00	0
Fertilizer - P_2O_5 Fertilizer - K_2O	lb lb	50	1	$0.50	$25.00	50
Micronutrients	lb	15	1	$0.51	$7.65	15
Thimet (insecticide)	lb	15	0.75	$2.05	$23.06	11.25
Atrazine 4L (pre emerge herbicide)	lb	4	1	$3.00	$12.00	4
Evik (pre emerge herbicide)	lb	1	0.5	$3.00	$1.50	0.5
2,4-D Amine 4 (post emerge herbicide)	qt	2	1	$3.00	$6.00	2
Asulox LA (post emerge herbicide)	gal	1	0.5	$25.00	$12.50	0.5
oil (surfactant)	qt	2	2	$1.65	$6.60	4
Harvesting (weighted) cost per acre						
Cane cutting PC (gt = gross tons)	Gton	50	1,144	$6.50	$325.00	
Cane cutting 1st R	Gton	40	1,300	$6.50	$260.00	
Cane cutting 2nd R	Gton	35	1,000	$6.50	$227.50	
Cane cutting 3rd R	Gton	30	500	$6.50	$195.00	
Cane hauling	mile	0	0	$0.25	$0.00	

Summary versions of the enterprise budgets as shown in the Tables (2 & 3) show the costs for fallow land maintenance, land preparation, planting activities, cultural activities and harvesting. The overhead expenses include supervision, vehicles, farm maintenance, irrigation, taxes and assessment, and a land charge. The relative importance of total costs provides insights into the future economic potential of sugarcane as an energy crop. However, the data also serves as a useful source for the emergy analysis, as it provides raw input values for various material and service inputs.

Most of the renewable input (sun, rain, etc.) data were based on the revised study from Brandt-Williams, 2002. This study only presents results for the first year of sugarcane harvesting (cane planting) without the additional ratoon years of production.

6.0 Results and Discussion

The emergy flows with accompanied footnotes calculated for the two farming systems are itemized in Tables 4-7.

Table 4: Emergy Evaluation of Sugarcane on mineral soil, per ha per year (2010)

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY* (sej/unit)	Solar EMERGY (E13 sej/yr)
RENEWABLE RESOURCES					
1	Sun	J	6.35E+13	1	6
2	Rain	J	6.18E+10	3.02E+04	187
3	Et	J	5.48E+10	2.59E+04	142
4	Water (irrigation)	l	9.63E+06	2.25E+05	0.2
NONRENEWABLE STORAGES					
5	Net Topsoil Loss	J	6.33E+08	1.24E+05	8
	Sum of free inputs (sun, rain omitted)				150
PURCHASED INPUTS					
Operational inputs					
6	Fuel (diesel, gasoline, lubricants)	J	1.99E+10	1.11E+05	221
7	Electricity	J	0.00E+00	2.69E+05	0
8	Machinery	g	5.54E+04	1.12E+10	62
9	Potash	g K	1.78E+05	1.85E+09	33
10	Dolomite (Lime)	g	2.24E+06	1.68E+09	377
11	Slag	g	3.36E+06	6.01E+06	2.0
12	Pesticides (insecticides, herbicides)	$	2.32E+02	2.30E+12	53
13	Phosphate	g P	1.32E+04	3.70E+10	49
14	Nitrogen	g N	4.40E+04	4.05E+10	178
15	Micronutrients (Fe, Mg, Mn, Zn)	g	2.24E+04	1.45E+10	33
16	Labor	J	2.71E+08	4.45E+06	120
17	Services	$	5.19E+02	4.03E+12	209
	Sum of purchased inputs				1337
	Total Emergy				1487

Table 5 presents numbers and description for each item calculated in Table 4.

Table 5: Footnotes to the Emergy Analysis in Table 4

Item no.	Item description				Source
1	**Sun, J**				
		Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)		
		Insolation:	6.90E+09	$J/m^2/yr$	[a]
		Area:	1.00E+04	m^2	
		Albedo:	0.08		[a]
		Annual energy:	6.35E+13	J	
		Emergy per unit input =	1	sej/J	[b]
2	**Rain, J**				
		Annual energy =	(in/yr)(Area)(0.0254 m/in)(1E6g/m^3)(4.94J/g)(1 - runoff)		
		in/yr:	53		[c]
		Area, m^2:	10000		
		runoff coefficient:	7.00E-02		[a]
		Annual energy:	6.18E+10	J	
		Emergy per unit input =	1.80E+04	sej/J	[b]
3	**Evapotranspiration, J**				
		Annual energy =	(Evapotranspiration)(Land area)(Density)(Gibb's free energy)		
		Evapotranspiration	1.11E+00	m/y	[g]
		Area:	10000	m^2	
		Density:	1.00E+06	g/m^3	
		Gibbs free energy:	4.94E+00	J/g	
		Annual energy:	5.48E+10	J	
		Emergy per unit input =	1.54E+04	sej/J	[b]
4	**Surface water irrigation, J**				
		Annual consumption, l:	9.63E+06	l	
		Emergy per unit input =	2.25E+05	sej/l	KHALAF, 2007
5	**Net Topsoil Loss, J**				
		Erosion rate =	70	g/m2/yr	[a]
		% organic in soil =	0.04		[a]
		Energy cont./g organic=	5.40	kcal/g	
	Net loss of topsoil = (farmed area)(erosion rate)				
	Organic matter in topsoil used up= (total mass of topsoil)(% organic)				
	Energy loss= (loss of organic matter)(5.4 kcal/g)(4186 J/kcal)				
		Annual energy:	6.33E+08	J	
		Emergy per unit input =	7.38E+04	sej/J	[b]
6	**Fuel, J per ha** (includes diesel, gasoline, lubricants)				
	(gallons fuel) * (1.32E8 J/gal)				
		Gallons:	1.51E+02		[a]
		Annual energy:	1.99E+10	J	
		Emergy per unit input =	6.60E+04	sej/J	[b]
7	**Electricity, J**				
		Annual energy = KWh*3.6E6 J/KWh			
		KWh:	0.00E+00		[a]
		Annual energy:	0.00E+00	J	
		Emergy per unit input =	1.60E+05	sej/J	[b]
8	**Machinery, g (assuming 10 year life)**				
			5.54E+01	kg	[a]

Item no.	Item description			Source
	Emergy per unit input =	1.12E+10	sej/g	
9	**Potash, g K per ha**			
	(g fertilizer active ingredient)(78 gmol K/94 gmol K2O)			
	g:	2.14E+05	g K	[d]
	Annual consumption:	1.78E+05		
	Emergy per unit input =	1.10E+09	sej/g	[b]
10	**Dolomite, g per ha**			
	Annual consumption, g:	2.24E+06	g	[a]
	Emergy per unit input =	1.68E+09	sej/g	[b]
11	**Slag, g per ha**			
	Annual consumption, g:	3.36E+06	g	
	Emergy per unit input =	6.01E+06	sej/g	[h]
12	**Pesticides, $ per ha** (includes pesticides, fungicides, herbicides)			
	Annual consumption, $:	$231.82	$	[d]
	Emergy per unit input =	2.30E+12	sej/$	[f]
13	**Phosphate, g P per ha**			
	(g fertilizer active ingredient)(31 gmol P/132 gmol DAP)			
	g:	5.60E+04		[d]
	Annual consumption:	1.32E+04	g P	
	Emergy per unit input =	2.20E+10	sej/g	[e]
14	**Nitrogen, g N per ha**			
	(g fertilizer active ingredient)(28 gmol N/132 gmol DAP)			
	g:	2.07E+05		[d]
	Annual consumption:	4.40E+04	g N	
	Emergy per unit input =	2.41E+10	sej/g	[e]
15	**Micronutrients, g**			
	Annual consumption, g:	2.24E+04	g	
	Emergy per unit input =	1.45E+10	sej/g	USEPA, 2010
16	**Labor, J**			
	(pers-hours/ha/yr)*(2500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)			
	pers-hours:	2.07E+02		[a]
	Annual energy:	2.71E+08	J/yr	
	Emergy per unit input =	4.45E+06	sej/J	[a]
17	**Services, $ per ha**			
	$/yr:	5.19E+02		[d]
	Annual emergy =	($ /yr)(sej/$)		
	Emergy per unit input =	2.40E+12	sej/$, 1983	[b]

References for Table 5

[a] Brandt-Williams, 2002
[b] Odum, 1996
[c] Abtew et al., 2010
[d] Alvarez and Helsel, 2011
[e] Brandt-Williams, 1999
[f] Brown et al., 1991

The emergy flows for sun and rain were omitted since they are captured within the process of evapotranspiration to avoid double counting. Evapotranspiration depends on the solar radiation (sun) to obtain the required temperature to vaporize the moisture (rain) in both soil and plant. Tables 6 and 7 present results and notes, respectively, for production in organic (muck) soil.

Table 6: Emergy Evaluation of sugarcane on organic soil, per ha per year (2009)

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY* (sej/unit)	Solar EMERGY (E13 sej/yr)
RENEWABLE RESOURCES					
1	Sun	J	6.35E+13	1	6
2	Rain	J	6.18E+10	3.02E+04	187
3	Et	J	5.48E+10	2.59E+04	142
4	Water (irrigation)	l	9.63E+06	2.25E+05	0.2
NONRENEWABLE STORAGES					
5	Net Topsoil Loss	J	4.25E+10	1.24E+05	527
	Sum of free inputs (sun, rain omitted)				669
PURCHASED INPUTS					
Operational inputs					
6	Fuel (diesel, gasoline, lubricants)	J	1.99E+10	1.11E+05	221
7	Electricity	J	0.00E+00	2.69E+05	0
8	Machinery	g	5.54E+04	1.12E+10	62
9	Potash	g K	3.26E+04	1.85E+09	6
10	Dolomite (Lime)	g	0.00E+00	1.68E+09	0
11	Slag	g	6.73E+06	6.01E+06	4
12	Pesticides (insecticides, herbicides)	g	1.76E+02	2.30E+12	40
13	Phosphate	g P	3.95E+03	3.70E+10	15
14	Nitrogen	g N	0.00E+00	4.05E+10	0
15	Micronutrients (Fe, Mg, Mn, Zn)	g	1.68E+04	1.45E+10	24
16	Labor	J	2.71E+08	4.45E+06	120
17	Services	$	4.32E+02	4.03E+12	174
	Sum of purchased inputs				667
	Total Emergy				1336

Table 7 presents numbers and description for each item calculated in Table 6.

Table 7: Footnotes to the Emergy Analysis in Table 6.

Item no.	Item description			Source
1	**Sun, J**			
	Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)		
	Insolation:	6.90E+09	$J/m^2/yr$	[a]
	Area:	1.00E+04	m^2	
	Albedo:	0.08		[a]
	Annual energy:	6.35E+13	J	
	Emergy per unit input =	1	sej/J	[b]
2	**Rain, J**			
	Annual energy =	(in/yr)(Area)(0.0254 m/in)(1E6g/m^3)(4.94J/g)(1 - runoff)		
	in/yr:	53		[c]
	Area, m^2:	10000		
	runoff coefficient:	7.00E-02		[a]
	Annual energy:	6.18E+10	J	
	Emergy per unit input =	1.80E+04	sej/J	[b]
3	**Evapotranspiration, J**			
	Annual energy =	(Evapotranspiration)(Land area)(Density)(Gibb's free energy)		
	Evapotranspiration:	1.11E+00	m/y	[g]
	Area:	10000	m^2	
	Gibb's free energy number:	4.94	J/g	
	Density:	1.00E+06	g/m^3	
	Annual energy:	5.48E+10	J	
	Emergy per unit input =	1.54E+04	sej/J	[b]
4	**Surface water irrigation, J**			
	Annual consumption, l:	9.63E+06	l	
	Emergy per unit input =	2.25E+05	sej/l	KHALAF, 2007
5	**Net Topsoil Loss, J**			
	Erosion rate =	4700	g/m2/yr	[a]*
	% organic in soil =	0.04		[a]
	Energy cont./g organic=	5.40	kcal/g	
	Net loss of topsoil = (farmed area)(erosion rate)			
	Organic matter in topsoil used up= (total mass of topsoil)(% organic)			
	Energy loss= (loss of organic matter)(5.4 kcal/g)(4186 J/kcal)			
	Annual energy:	4.25E+10	J	
	Emergy per unit input =	7.38E+04	sej/J	[b]
6	**Fuel, J per ha** (includes diesel, gasoline, lubricants)			
	(gallons fuel) * (1.32E8 J/gal)			
	Gallons:	1.51E+02		[a]
	Annual energy:	1.99E+10	J	
	Emergy per unit input =	6.60E+04	sej/J	[b]
7	**Electricity, J**			
	Annual energy = KWh*3.6E6 J/KWh			
	KWh:	0.00E+00		[a]
	Annual energy:	0.00E+00	J	
	Emergy per unit input =	1.60E+05	sej/J	[b]
8	**Machinery, g (assuming 10 year life)**			
		5.54E+01	kg	[a]
	Emergy per unit input =	1.12E+10	sej/g	

Item no.	Item description			Source
9	**Potash, g K per ha**			
	(g fertilizer active ingredient)(78 gmol K/94 gmol K2O)			
	g:	3.92E+04	g K	[d]
	Annual consumption:	3.26E+04		
	Emergy per unit input =	1.10E+09	sej/g	[b]
10	**Dolomite, g per ha**			
	Annual consumption, g:	0.00E+00	g	[a]
	Emergy per unit input =	1.00E+09	sej/g	[b]
11	**Slag, g per ha**			
	Annual consumption, g:	6.73E+06	g	
	Emergy per unit input =	6.01E+06	sej/g	[h]
12	**Pesticides, g per ha** (includes pesticides, fungicides, herbicides)			
	Annual consumption, $:	$175.60	$	[d]
	Emergy per unit input =	2.30E+12	sej/$	[f]
13	**Phosphate, g P per ha**			
	(g fertilizer active ingredient)(31 gmol P/132 gmol DAP)			
	g:	1.68E+04		[d]
	Annual consumption:	3.95E+03	g P	
	Emergy per unit input =	2.20E+10	sej/g	[e]
14	**Nitrogen, g N per ha**			
	(g fertilizer active ingredient)(28 gmol N/132 gmol DAP)			
	g:	0.00E+00		[d]
	Annual consumption:	0.00E+00	g N	
	Emergy per unit input =	2.41E+10	sej/g	[e]
15	**Micronutrients, g**			
	Annual consumption, g:	1.68E+04	g	
	Emergy per unit input =	1.45E+10	sej/g	USEPA, 2010
16	**Labor, J**			
	(pers-hours/ha/yr)*(2500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)			
	pers-hours:	2.07E+02		[a]
	Annual energy:	2.71E+08	J/yr	
	Emergy per unit input =	4.45E+06	sej/J	[a]
17	**Services, $ per ha**			
	$/yr:	4.32E+02		[d]
	Annual emergy	= ($ /yr)(sej/$)		
	Emergy per unit input =	2.40E+12	sej/$	[b]

References for Table 7

[a] Brandt-Williams, 2002; [b] Odum, 1996; [c] Abtew et al.,2010; [d] Alvarez and Helsel., 2011; [e] Brandt-Williams, 1999; [f] Brown et al., 1991

The bar histogram in Fig. 14 (also known as emergy signature) shows the relative importance of the main emergy flows supporting the sugarcane production process for both farming systems. The information collected covers one year (2009) for organic soil and two different years (2008 and 2010) for mineral soil.Page: 63

The 2009 data runs from the 2008/9 season and as such has similar conditions as that of mineral soil 2008 crop season. Comparing the results of the mineral soil 2008 data to an updated data for 2010 was to observe any significant impacts for mineral soil sugarcane feedstock production as a result of production modifications. The results clearly show that the largest emergy flows for organic soil sugarcane production were associated with soil erosion or subsidence (Table 6, item 5) and services (Table 6, item 17).

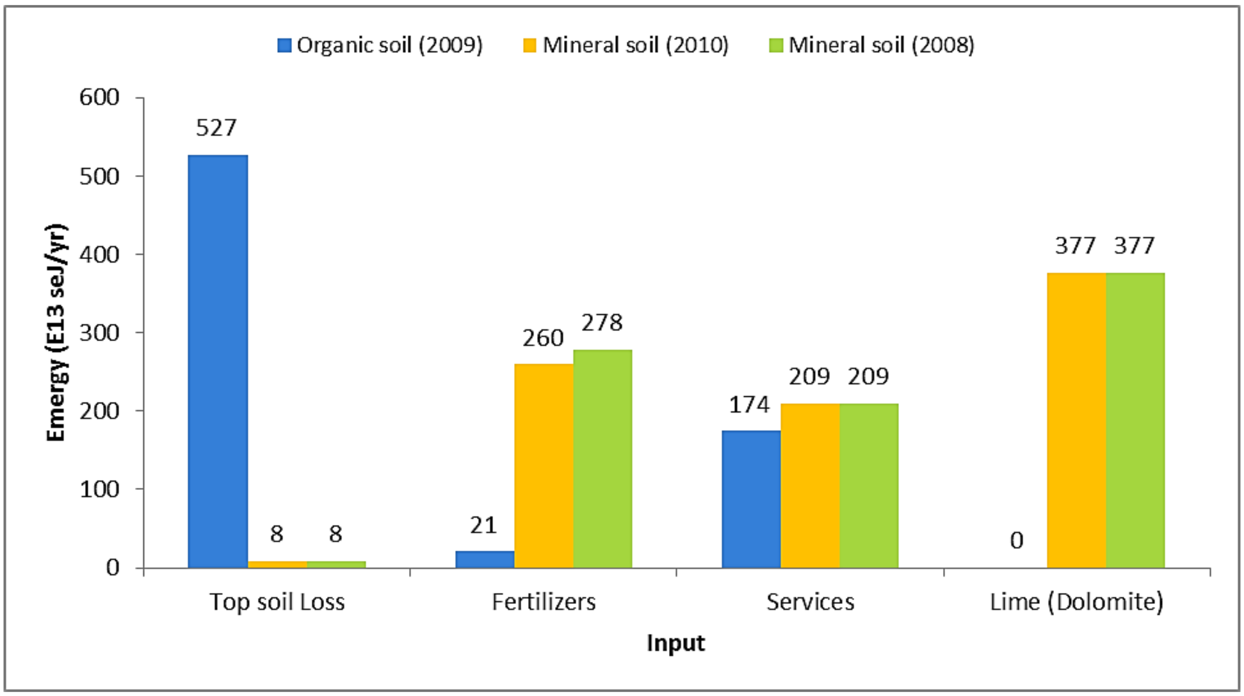


Figure 14: Emergy Signature for Sugarcane Production on Mineral and Organic soils.

However, for mineral soil sugarcane production, the largest contributions were lime (dolomite) (item 10), fertilizers, and services. The results of mineral soil sugarcane production show a drastic reduction of soil loss due to the absence of enriched organic material coupled with other factors that are the main causes of soil subsidence in the Everglades Agricultural Area (EAA) of South Florida. Soil loss, the highest emergy flow in the sugarcane organic soil system, had an annual flow of 527E13 sej/yr, almost 70 times larger than in the mineral soil system.

Purchased energy was dominated by fuel (diesel, gasoline, oil) for both organic and mineral soils. Again, the current practice of adding lime to enhance the soil quality (pH) of mineral soils introduced a significant impact on the results. With the same production rate, the difference in total emergy flows show that mineral soil sugarcane required a slightly higher (1487E13 sej/yr) than organic soil sugarcane production (1336E13 sej/yr). The results contradicted the initial hypothesis, which expected a higher total emergy input due to the enormous amount of soil subsidence. The results follow reason as the additional fertilizer and lime inputs needed to condition the soil, as well as the additional services required to have soil conditioning done, impacts directly on additional energy input into the mineral soil farming system. As a result, the effect of less required inputs places organic soil sugarcane production slightly higher in 'production efficiency' in South Florida compared to mineral soil production. However, due to the fact that soil subsidence takes years or forever to replenish, soil loss raises a major environmental (renewability) concern. One may then suggest that organic soil sugarcane production has economic advantages but a 'deceptive' renewability benefit. According to Lefroy and Rydberg, 2003, in the long run, processes with a high percentage of renewable emergy are likely to be more sustainable than those with a high proportion of non-renewable emergy. Fig. 15 shows a comparative view of the sustainability ratios for the two farming systems.

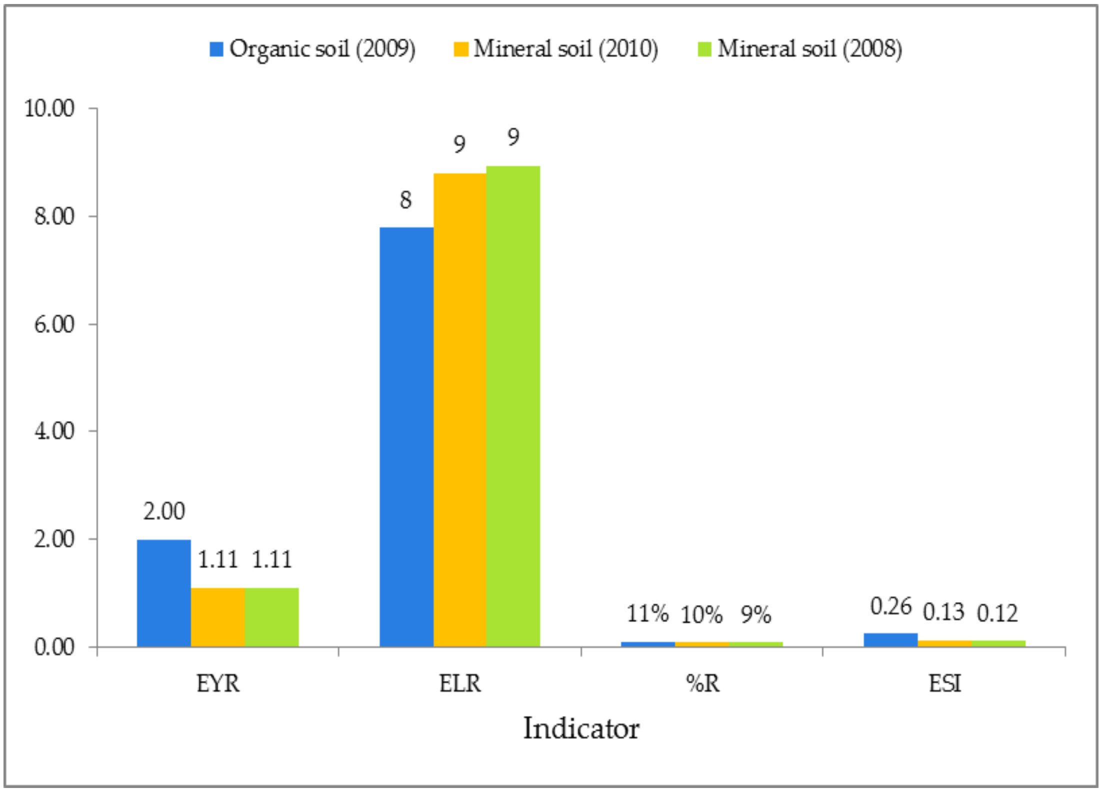


Figure 15: Emergy Indicators for mineral and organic soil sugarcane production.

The % renewable emergy flows were 11% for organic soil, 10% for mineral soil sugarcane production in 2010 and 9% in 2008. The high purchased input flow for mineral soil production reflects in its EYR value as more inputs from the economy are required by the system than it gives back as energy. The Emergy Yield Ratio (EYR) gives organic soil sugarcane production an edge in its economic competiveness compared to mineral soil production. The environmental loading ratio (ELR) is a direct inverse function of the fraction renewable (Ulgiati and Brown, 1998). The closeness in the ELR values is depicted in their closeness in percentage renewability. The two systems relatively provide similar environmental stress. However, the Emergy Sustainability Index (ESI), indicate that the organic soil sugarcane system had the greatest level of sustainability followed by the mineral soil sugarcane system (2010).

This measure assumes that the objective function for sustainability is to obtain the highest EYR while minimizing ELR (Ulgiati and Brown, 1998). The EYR and low ELR produced a sustainability index of 0.26 for the organic soil sugarcane system, while the low EYR and high ELR of the 2010 and 2008 mineral soil sugarcane system produced a sustainability index of 0.13 and 0.12 respectively (Fig. 15). This result indicated that when considering environmental loading and yield ratios, the organic soil sugarcane system performed slightly better than the mineral soil sugarcane feedstock production systems. However, since the inputs for the mineral soil are quite available and copious compared with the annual loss of organic soil (which is not replaceable) organic soil sugarcane feedstock production remains environmentally unfavorable. Throughout the years, research and development has contributed to help reduce or solve continuous soil subsidence in the EAA in Florida.

6.1 Organic soil Emergy inputs demand Timeline

Fig. 16 provides a snap shot of main emergy inputs demand for muck soils throughout the last decade for sugarcane feedstock production as studied by Bastianoni and Marchettini (1996).

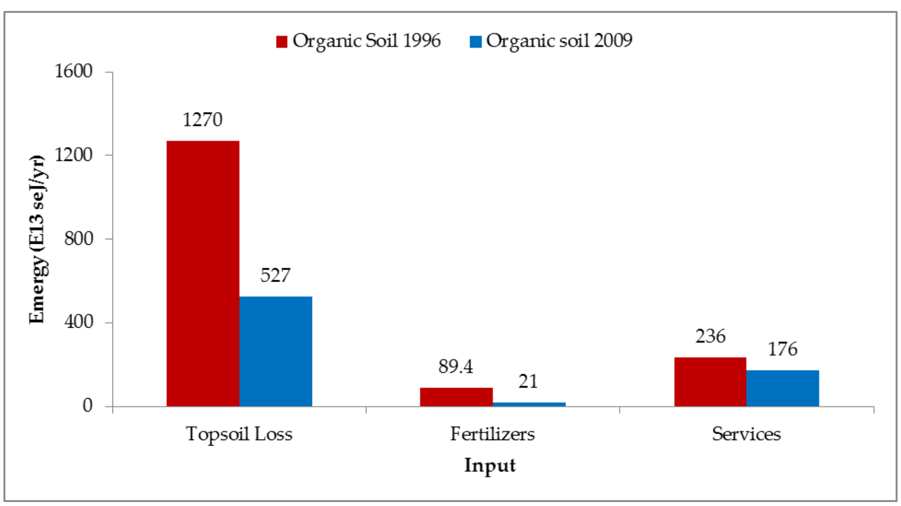


Figure 16: Organic soil main emergy inputs timeline.

As a result of continuous improvements in farming methods, regulations, and equipment efficiency in several farming practices including sugarcane in the area in the last decade, the sustainability levels have tremendously changed with time. The results show a significant reduction and control of soil subsidence in the EAA (Wright, 2008). Again, reduction in both fertilizers and required services on sugarcane farms in the EAA has been observed. Soil erosion, loss, or subsidence emerged as a significant contributor to the energy flow and sustainability for organic soil sugarcane biomass farming. In the mineral soil farming system, the increase in purchased inputs and services contributed significantly to its overall reduced sustainability. The relative importance placed on soil subsidence compared to water use in this analysis contrasts with the perceived impact of these two processes in the real world. From the perspective of emergy analysis, a smaller total energy flow is involved in returning water to the atmosphere than in producing soil organic matter. The higher value placed on soil loss compared to water management also reflects the supply-driven nature of the emergy method, whereby processes are valued according to the number and kind of energy transformations involved, rather than their consequences or utility as seen from a human perspective (Lefroy and Rydberg, 2003).

6.2 Alternative, Sustainable Sugarcane Farming System

In South Florida, new and modified sugarcane farming systems are moving ahead with funding from the U.S. Department of Energy, but far more research support is needed to quickly and fully realize this option in light of sugarcane biomass as feedstock to the increasing bioethanol industry.

The new farming system should aim to provide multiple benefits, to balance various economic, social, and ecological needs, address water storage, water flow, water quality, biodiversity, soil subsidence, carbon emissions, and biofuel production. The challenges are to fully redesign the land preparation, planting, harvesting, and all other farming operations so that schedules, methods, and capital resources work in a scientific and cost-effective manner with total sustainability goals. As discussed in previous sections, expanding mineral soil sugarcane biomass production will significantly reduce soil subsidence and the resulting carbon loss to the atmosphere may be eligible for credit sales on already-existing carbon markets. This gradual expansion of sugarcane production on mineral soils would require focused and consistent application of measures to achieve a balance of high yields with environmental sustainability. Recycling some of the nutrients to reduce costs and thus energy inputs might be an option. Continuous surface water run-off could be stored on fields to reduce additional water use. Fuel-driven pumps could be modified or replaced with electric pumps to reduce fossil emissions to the environment.

7.0 Concluding Remarks

The aim of this study was to use Odum's (1996) emergy method to compare the resource use and environmental impact of two alternative farming systems by measuring their relative sustainability. The results provide as much insight into the assumptions inherent in this approach as they do into the farming systems in this study. As discussed, the sugarcane industry in South Florida is moving towards a more sustainable production system in terms of both on- and off - farm considerations. At this stage, alternative farming system practices as outlined above (expansion on mineral soils with modified practices) have not been fully adapted to a great extent, but growers are rapidly adopting components of the system. For example, the past few years have seen large increases in the area sown to fallow legumes, substantial increases in the area using reduced tillage for the establishment of both legumes and plant cane crops, and a realization that controlled traffic is essential to overcome the adverse effects of compaction. Initiatives in terms of improved water use efficiency, nutrient management, and integrated pest control are all being discussed and implemented. Most importantly, with the potential expansion of biofuel industries, the sugarcane industry has realized that it cannot continue to survive with a system based on yesterday's value in terms of production strategies and environmental responsibility. Excessive tillage, high inputs of chemicals and fertilizers, and long-term monoculture must pass into history. It will obviously take time to get appropriate systems in place but steps in the correct direction are certainly being taken and these positive actions should be acknowledged.

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APPENDIX A: Additional notes to Emergy Evaluation

1 SUN

The annual energy value (J) used in this study was from Brandt-Williams, 2002 in which the author conducted an emergy analysis on sugarcane production in Florida. In this case, this value could be used directly from the reference without recalculation. The emergy per unit value (transformity) was from Odum's book (1996) on Environmental Accounting. However, the approach in arriving at that value is below:

Annual energy = (Avg. Total Annual Insolation J/yr)(Area)(1-albedo)
Insolation: 6.90E+09 $J/m^2/yr$
Area: 1.00E+04 m^2
Albedo: 0.08
Annual energy: 6.35E+13J [From Brandt-Williams, 2002]
Emergy per unit input = 1sej/J

$Emergy = 6E13sej$

2 RAIN

Annual energy = (in/yr)(Area)(0.0254 m/in)(1E6g/m3)(4.94J/g)(1 - runoff)

The main input here is to determine the average annual rainfall (in/yr) in South Florida for the specific year under review. Abtew et al, 2010 puts it at 53in/yr. As such, it follows as:

Rainfall: 53in/yr:
Land Area, m^2: 10000m^2
Runoff coefficient: 7.00E-02
Annual energy: 6.18E+10J
Emergy per unit input = 1.80E+04sej/J

$Emergy = 6.18E10J\left(\frac{1.80E4sej}{J} * 1.68\right) = 187E13sej$ [5]

3 EVAPOTRANSPIRATION

Evapotranspiration (ET) is a term used to describe the water loss from land on which vegetation is growing. Values of ET for a crop (e.g. sugarcane) are expressed as the amount of water lost (inches, cm, mm, m) per unit of time (hour, day, week, month, season, or year). The average ET for sugarcane in South Florida according to Lang et al., 2002 is 1.11m/yr. As such the annual energy of ET is expressed as:

Annual energy = (Evapotranspiration)(Land area)(Density)(Gibb's free energy)

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[5] You only use the 1.68 factor when you use any transformity value calculated prior to yr 2000 based on a previous baseline of 9.44E24 solar Joules/yr. The current baseline is 15.83E24.

Evapotranspiration: 1.11E+00m/yr
Land Area: 10000m^2
Density: 1.00E+06g/m^3
Gibbs free energy: 4.94E+00J/g
Annual energy: 5.48E+10J
Emergy per unit input = 1.54E+04sej/J

$$Emergy = 5.48E10J\left(\frac{1.54E4sej}{J} * 1.68\right) = 142E13sej$$

4 SURFACE WATER IRRIGATION

Considering the water requirements of sugarcane, there are two factors to consider: one is the actual amount of water required to produce the sugarcane, the other is the management of the water table in the cane field (Wright et al., 2011).

In a U.S. Geological Survey document, Marella (2008), reports that irrigation for Florida sugarcane in 2005 withdrawn 875 x 10^6 gallons per day (1.21 x 10^{12} liters per year). Considering that during the year 2012 Florida has 410,000 acres (166,000 ha) planted with sugarcane (ERS, 2012) and that mineral soils represent 20% of sugarcane crop in Florida, water withdrawals for irrigation of Florida sugarcane in mineral soils are determined to be 36.4 x 106 liters/ha-year (3.89 x 106 gal/acre-year).

Based on Marella, 2008 and ERS, 2012

IRRIGATION				
Water used in FL Ag/day	8.75E+08	gal/day	3.31E+09	l/day
Water used in FL Ag/year	3.19E+11	gal/year	1.21E+12	l/year
Total sugarcane crop	4.10E+05	acres	1.66E+05	ha
Water used per area/year	7.79E+05	gal/acre/year	7.29E+06	l/ha/year

As such, the emergy calculation is based on:
Annual consumption, l/ha/yr: 7.29E+06l
Emergy per unit input = 2.25E+05sej/l

$$Emergy = 7.29E6l * \frac{2.25E5sej}{l} = 0.2sej$$

5 NET TOPSOIL LOSS

An average inventory of topsoil loss for sugarcane produced in mineral soils was not found. As such, the topsoil loss (70g/m2/yr) for oranges produced in South Florida was used. This is assumed to be in range of similar values for sugarcane produced in mineral soils. However, the topsoil loss for sugarcane produced from organic soils in Florida was found to be 4700g/m2/yr (Brandt-Williams, 2002). The energy loss is calculated based on the amount of organic matter contained in the soil (in which case the topsoil loss). Thus, the calculations are as follows:

Erosion rate = 70g/m2/yr
% organic in soil = 0.04
Energy cont./g organic= 5.40 kcal/g
Net loss of topsoil = (farmed area)(erosion rate)
Organic matter in topsoil used up= (total mass of topsoil)(% organic)
Energy loss= (loss of organic matter)(5.4 kcal/g)(4186 J/kcal)
Annual energy: 6.33E+08J
Emergy per unit input = 7.38E+04sej/J

$$Emergy = 6.33E8J\left(\frac{7.38E4sej}{J} * 1.68\right) = 8E13sej$$

6 FUEL

Diesel used for farm machinery was taken from Brandt-Williams, 2002 as no other current data for Florida sugarcane was available. Annual energy was calculated as follows:

Fuel, J per ha (includes diesel, gasoline, lubricants)
Annual Energy = (gallons fuel) * (1.32E8 J/gal)
Where an estimation of 1.32E8J of energy is contained in a gallon of diesel (Brandt-Williams, 2002):
Gallons: 1.51E+02
Annual energy: 1.99E+10J
Emergy per unit input = 6.60E+04sej/J

$$Emergy = 1.99e10J\left(\frac{6.6E4sej}{J} * 1.68\right) = 221E13sej$$

7 ELECTRICITY

Since almost all pumps and equipment on farms used as our case study run on fuel, input from electricity was neglected. However, if necessary to calculate, the annual energy would be as follows:

Annual energy (Electricity, J) = KWh*3.6E6 J/KWh
KWh: 0.00E+00 (Value to find)
Annual energy: 0.00E+00J
Emergy per unit input = 1.60E+05sej/J

8 AGRICULTURAL MACHINERY (assuming a 10 years life span)

Total weight of machinery used in sugarcane crop production in South Florida was assumed to follow a standard weight of machinery for agricultural production in Florida (http://www.cep.ees.ufl.edu/emergy/resources/templates.shtml). This assumption was made since specific current information on equipment such as number of tractors used, sprayers, tillers, etc were not available. As such, assuming a life of 10 years = 5.54E+01kg/ha per year. Transformity for steel machinery as calculated by Brandt-Williams, 2001, folio #4 is 1.12E10sej/g.

$$Emergy = 5.54E4g * \frac{1.12E10sej}{g} = 62E13sej$$

9 POTASH FERTILIZER

According to Rice et al., 1993 (Revised 2010), sugarcane utilizes large quantities of potassium. Deficiencies are commonly observed on well-drained, coarse, sandy soils. In comparison to other nutrients, sugarcane response to K fertilization is usually most immediately apparent. Fertilizer K recommendations by the Everglades Soil Testing Laboratory range from 0 to 208 lb K/A (0 to 250 lb K2O/A) for plant cane and first ratoon crops, and 0 to 125 lb K/A (0 to 150 lb K2O/A) for second ratoon and all subsequent ratoon crops. (g fertilizer active ingredient)(78 gmol K/94 gmol K2O). The value used in this study (191.25Ib/acre/yr) was from the 2010 sugarcane enterprise budget (Alvarez and Helsel, 2011). The calculations are as follows:

K2O	pound	191.25	g/acre	8.68E+04	g/ha	2.14E+05

Potash, g K per ha

Annual consumption = (g fertilizer active ingredient)(78 gmol K/94 gmol K2O)

K2O g: 2.14E+05gK

Annual consumption: 1.78E+05gK

Emergy per unit input = 1.10E+09sej/g

$$Emergy = 1.78E5g\left(\frac{1.1E9sej}{g} * 1.68\right) = 33E13sej$$

10 DOLOMITE

Rice et al., 1993 stated that because Mg was determined to be a major limiting factor on sandy mineral soils in a recent leaf nutrient survey of commercial sugarcane fields in Florida, a Mg amendment such as dolomite (or calcium silicate containing Mg) should also be considered at planting for fields with low soil-test Mg or for fields with plants exhibiting low leaf tissue Mg concentrations in the previous season's crop. Furthermore,

they stated that Liming with dolomite effectively raises soil pH and supplies plant available Mg. A 2 ton/A application of dolomite (broadcast applied and disk incorporated prior to planting) should increase soil pH by approximately one pH unit.
The source for this study's input value (1 ton/A) was the 2010 enterprise budget (Alvarez and Helsel, 2011). Typically, since a sandland field would have 3 crops and then a fallow year, planting would be done about every 4 years. Thus the dolomite input is divided by 4. The calculations are as follows:

Dolomite (Lime)	ton	1.00	g/acre	9.07E+05	g/ha	5.60E+05

Dolomite, g per ha
Annual consumption: 5.60E+05g
Emergy per unit input = 1.68E+09sej/g

$$Emergy = 5.6E5g * \frac{1.68E9sej}{g} = 94E13sej$$

11 SLAG

According to Rice et al., 1993, calcium silicate slag, which is a popular Si source, tends to have low solubility under high soil pH conditions. The Everglades Soil Testing Lab offers a Si soil-test but does not offer specific Si application recommendations since the Si soil-test has not been calibrated for sugarcane production. Nonetheless, growers have experimented with Ca-silicate slag applications for many years. This collective experience suggests that when soils test low for acetic acid extractable Si (less than 10 ppm in the soil extract), a 3 ton/A application of Ca-silicate slag will likely support favorable yield improvements over a three-crop cycle. The Si source is generally broadcast applied and disked into the soil prior to planting. Leaf Si analysis is very useful in combination with soil test Si values in determining the need for calcium silicate application. The source for our value is from Alvarez and Helsel, 2011. Again, just as in the case of dolomite, since a sandland field would have 3 crops and then a fallow year, planting would be done about every 4 years. Thus the slag input is divided by 4. The calculations are as ff:

Slag	ton	1.50	g/acre	1.36E+06	g/ha	8.41E+05

Slag, g per ha
Annual consumption: 8.41E+05g
Emergy per unit input = 6.01E+06sej/g

$$Emergy = 8.41E5g * \frac{6E6sej}{g} = 0.5E13sej$$

12 PESTICIDES

The source for our values was again the 2010 enterprise budget. Since the various insecticides and pesticides were in in different units and some of which density values were unknown, it was difficult to use mass (g) or volume (l) units. As such, I resulted using cost values to make it simpler in which case a corresponding transformity value for pesticides should be sej/$ and not sej/g or sej/l. The calculations were as follows:

Pesticides, $ per ha (includes pesticides, fungicides, herbicides)
Annual consumption: $231.82
Emergy per unit input = 1.95E+12sej/$

$$Emergy = \$231.82 * \frac{1.95E12sej}{\$} = 45E13sej$$

13 PHOSPHATE

According to Rice et al., 1993, phosphorus is likely to be deficient in organic and mineral soils in Florida. Careful control of available P levels is essential for high yields of sugarcane and sucrose. Root development is slow when P is limited and results in inadequate utilization of available moisture and nutrients. Deficiency is much more common in ratoon crops, and deficiency symptoms tend to increase with crop age. Amounts of P recommended by the Everglades Soil Testing Laboratory range from 0 to 33 lb P/A (0 to 75 lb P2O5/A) for plant cane and first ratoon crops, 0 to 31 lb P/A (0 to 70 lb P2O5/A) for second ratoon, and 18 lb P/A (40 lb P2O5/A) for subsequent ratoons. In determining the energy content in the fertilizer, it is important to consider the active ingredient (P) in the compound. From the source (Alvarez and Helsel, 2011) the calculations are as follows:

P2O5	pound/acre	50.00	g/acre	2.27E+04	g/ha	5.60E+04

Phosphate, g P per ha
Annual consumption = (g fertilizer active ingredient)(31 gmol P/132 gmol DAP)
Phosphate, g: 5.60E+04
Annual consumption: 1.32E+04g P
Emergy per unit input = 2.20E+10sej/g

$$Emergy = 1.32E4gP\left(\frac{2.2E10sej}{g} * 1.68\right) = 49E13sej$$

14 NITROGEN (N)

According to Rice et al., 2011, no N fertilizer is recommended for sugarcane grown on muck soils. Under south Florida growing conditions on organic soils, N deficiencies are rarely seen in sugarcane. On the other hand, N deficiencies can readily occur in sugarcane grown on sandy soils. Multiple applications of N fertilizer are often required during the growing season to sustain adequate sugarcane production on mineral (sandy) soils, which lack the high organic N contents of muck soils. Failing to supply adequate N during critical growth periods can result in stunted plants, premature ripening, and reduced biomass and sugar yields. In the meantime, current UF/IFAS nitrogen fertilizer recommendations during a 1-year crop cycle for sugarcane grown on south Florida sandy soils is 180 lb N/A. From the same source as above, the calculations are as follows:

Nitrogen	pound	185.00	g/acre	8.39E+04	g/ha	2.07E+05

Nitrogen, g N per ha
Annual consumption = (g fertilizer active ingredient)(28 gmol N/132 gmol DAP)
Nitrogen input: 2.07E+05g/ha
Annual consumption: 4.40E+04g N
Emergy per unit input = 2.41E+10sej/g

$$Emergy = 4.4E4gN\left(\frac{2.41E10sej}{g} * 1.68\right) = 178E13sej$$

15 MICRONUTRIENTS

Since relatively large quantities of N, P, K, S, Mg, and Ca are needed by plants, these are referred to as "macronutrients." The remainder of the required plant elements are usually called "micronutrients." According to Rice et al., 1993 (revised 2010), no suitable soil tests have been developed for accurate micronutrient recommendations. High soil pH (pH > 6.6) levels are often associated with a range of micronutrient deficiencies. As such, some experts may recommend micronutrients as additional inputs for sugarcane production. Alvarez and Helsel, 2011 stated 20Ib/acre for Florida sugarcane. The calculations are as ff:

micronutrients	pound	20.00	g/acre	9.07E+03	g/ha	2.24E+04

Micronutrients, g
Annual consumption: 2.24E+04g
Emergy per unit input = 1.45E+10sej/g

$$Emergy = 2.24E4g * \frac{1.45E10sej}{g} = 33E13sej$$

16 LABOR

The labor (both manual or unskilled labor and skilled labor) required on the farm was based on Brandt-Williams, 2002 in which a similar analysis was carried out. The calculation as in the reference is as follows:

Labor, J = (pers-hours/ha/yr)*(2500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)

pers-hours: 2.07E+02

Annual energy: 2.71E+08J/yr

Emergy per unit input = 4.45E+06sej/J

$$Emergy = \frac{2.7E8J}{yr} * \frac{4.45E6sej}{J} = 120E13sej/yr$$

17 SERVICES

These services sourced from the 2010 enterprise budget include (soil testing and consulting, road and ditch maintenance, taxes and assessments, etc). These at best do not include field operation costs (custom rates) such as disking, chemical application, fertilizer application, harvesting, etc). These field operations mentioned have already been taken to account in fuel consumption, labor, machinery etc. As such, reconsidering them as services will amount to a double count. Therefore, the services calculations are as follows:

Services, $ per ha

Annual Service emergy = ($ /yr)(sej/$)

$/yr: 5.21E+02

Emergy per unit input = 1.95E+12sej/$

$$Emergy = \frac{5.21E2\$}{yr} * \frac{1.95E12sej}{\$} = 102E13sej/yr$$

EMERGY YIELD RATIO (EYR)

- Total emergy divided by total economic inputs.
- The higher the value, the lower the system's reliance on economic investment and the higher its economic competitiveness

As such, assuming the total emergy into the system is Y and the economic input emergy or the emergy from purchased sources or what you pay for (fuel, fertilizers, labor, chemicals etc) is F, then:

$$EYR = \frac{Y}{F}$$

Total emergy (Y) from this analysis = 1087E13sej; Purchased emergy (F) = 937E13sej

As such, $EYR = \frac{1087E13sej}{937E13sej} = 1.16$

ENVIRONMENTAL LOADING RATIO (ELR)

- Non-renewable resources from the economy and from the environment divided by the renewable Inputs.
- A lower value favors a higher sustainability process.

With purchased emergy input as F, Nonrenewable emergy inputs (soil, etc) as N and renewable emergy inputs (rain, sun, etc) as R, ELR can be defined as: $ELR = \frac{N+F}{R}$

From this analysis, F =937E13sej, N=8E13sej, and R=142E13sej[6]

Therefore, $ELR = \frac{(8+937)}{142} = 6.7$

% RENEWABLE (%R)

- Renewable Input divided by total emergy.
- Higher value, greater the sustainability of the production system

As such, $\%R = \frac{142}{1087} = 13\%$

EMERGY SUSTAINABILITY INDEX (ESI)

- Ratio of the EYR to ELR. To be sustainable the process must obtain the highest yield ratio (EYR) at the lowest ELR.

Therefore ESI from this analysis with an EYR = 1.16 and ELR = 6.7 results in:

$$ESI = \frac{1.16}{6.7} = 0.17$$

[6] The sum of emergy values for evapotranspiration (ET) and water for irrigation is used as the total renewable input (R) in this case. Sun and Rain are omitted since they both are functions of ET. This is to avoid double counting.

APPENDIX B: Emergy Analysis of Energy cane on Sandy soils in South Florida

Energy cane is genetically modified sugarcane specially created at the University of Florida for cellulosic ethanol production. Sugarcane, a grass native to Asia of the genus Saccharum, has been cultivated more than 4,000 years (Baucum, 2009). Sugars in the cane can be used to create crystallized sugar, molasses, syrup, and rum, among other products. Because of this usage, sugarcane lines with higher sugar content, as compared to other lines, have historically been preferred. However, when producing cellulosic ethanol, the fiber (known as cellulose) is more valuable, therefore, a special hybrid, energy cane, was created to meet the desire for higher cellulose content.

Energy cane hybrids released in 2007 by the Agricultural Research Service, showed increased cellulose content as well as increased tolerance to cold, as compared to commercial varieties. It is hoped that energycane can be grown in the South where corn yields are not as great as those in the Midwest. This crop could also give growers a higher ethanol yield than corn in some of our Southern states and would not compete with food as in the case of corn.

Energy cane is currently being grown at university test plots in the South, to see how well it produces (and how it fares in hurricanes). Verenium[7] (has leased 20,000 acres to begin growing the crop on a large scale.

Every acre of energy cane, said Mr. Riva (a representative of Verenium), should yield on the order of 1,800 to 2,000 gallons of ethanol annually (compared with 800 gallons for conventionally produced ethanol from sugar cane in countries like Brazil).

This work analyzed the environmental/economic pros and cons of energy cane production in South Florida using the emergy methodology. The calculations and data sources follow a similar path as in the case of sugarcane described in previous sections, since energy cane production sequence follows that of sugarcane very closely.

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[7] Verenium Corporation is a recognized pioneer in the development and commercialization of high-performance enzymes for use in industrial processes. Verenium sells enzymes developed using its unique R&D capabilities to a global market. The company harnesses the power of nature and, leveraging unique, patented technology, creates products that maximize efficiency while improving environmental performance. (http://www.verenium.com/index.html)

Costs and Returns for Energy cane Production on Mineral soils in South Florida (2010)

ACTIVITY	UNIT	# YEARS	RATE	# TIMES	PRICE/ UNIT	$/ACRE/ YEAR	QTY/ACRE /YEAR
Fallow land total cost per acre:							
Herbicide + surfactant	qt	1	2.00	2	$ 7.50	$30.00	4.00
Herbicide application	$			2	$ 4.00	$8.00	
Total						$38.00	
Prorated Total		0.166				$6.31	
Land preparation total cost per acre:							
Soil testing and consulting	$	1		1	$ 1.11	$1.11	
Disking	$	1		3	$ 15.00	$45.00	
Lime (Dolomite) application	$	1		1	$ 5.00	$5.00	
Dolomite	ton	1	1.00	1	$ 28.00	$28.00	1.00
Laser Leveling	$	1		1	$ 60.00	$60.00	
Slag	ton	1	1.50	1	$ 56.00	$84.00	1.50
Slag application	$	1		1	$ 5.00	$5.00	
Total						$228.11	
Prorated Total		0.166				$37.87	
Planting							
All related activities	$/acre	1		1	$170.00	$170.00	
Seed cost	$/acre		3.00	1	$ 25.00	$75.00	
Insecticide	lb/acre	1	15.00	1	$ 2.00	$30.00	15
Micronutrients	lb/acre	1	20.00	1	$ 0.51	$10.20	20.00
Total						$285.20	
Prorated Total		0.166				$47.34	
Cultural Activities							
Fertilizer – N	lb	6	44.00	4.17	$ 0.60	$110.09	183.48
Fertilizer - P_2O_5	lb	6	50.00	1	$ 0.60	$30.00	50.00
Fertilizer - K_2O	lb	6	45.00	4.17	$ 0.60	$112.59	187.65
Chemical applications	$	6	1.00	2	$ 4.00	$8.00	
Herbicide (pre emerge herbicide)	qt	6	3.00	1	$ 3.00	$9.00	3.00
Herbicide (pre emerge herbicide)	gal	6	1.00	1	$ 16.50	$16.50	1.00
Herbicide (post emerge herbicide)	qt	6	3.00	1	$ 3.00	$9.00	3.00
Herbicide (post emerge herbicide)	pt	6	2.00	1	$ 3.00	$6.00	2.00
Oil (surfactant)	qt	6	1.00	1	$ 1.65	$1.65	1.00
Mechanical Cultivation	$	6	1.00	1	$ 6.50	$6.50	
Total						$309.33	
Miscellaneous	$					$82.26	
Interest	$					$72.39	
Harvesting activities							
Harvest, load, and haul	Gton	6	30.00	1	$ 7.00	$210.00	
Total variable costs						$765.50	
Overhead activities							
Supervising and vehicles	Gacre			1	$ 10.00	$10.00	
Road and ditch maintenance	Gacre			1	$ 5.00	$5.00	
Pumping and water control	Gacre			1	$ 40.00	$40.00	
Taxes and assessments	Gacre			1	$ 70.00	$70.00	
Land charge	Gacre			1	$ 75.00	$75.00	
Total	$					$200.00	
TOTAL COSTS						$965.50	

Emergy Evaluation of Energycane on mineral soil, per ha per year

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY* (sej/unit)	Solar EMERGY (E13 sej/yr)
RENEWABLE RESOURCES					
1	Sun	J	6.35E+13	1	6
2	Rain	J	6.18E+10	3.02E+04	187
3	Et	J	5.48E+10	2.59E+04	142
4	Water (irrigation)	l	9.63E+06	2.25E+05	0.2
NONRENEWABLE STORAGES					
5	Net Topsoil Loss	J	6.33E+08	1.24E+05	8
	Sum of free inputs (sun, rain omitted)				150
PURCHASED INPUTS					
Operational inputs					
6	Fuel (diesel, gasoline, lubricants)	J	5.46E+09	1.11E+05	61
7	Electricity	J	0.00E+00	2.69E+05	0
8	Machinery	g	5.54E+04	1.12E+10	62
9	Potash	g K	1.75E+05	1.85E+09	32
10	Dolomite (Lime)	g	5.60E+05	1.68E+09	94
11	Slag	g	8.41E+05	6.01E+06	0.5
12	Pesticides (insecticides, herbicides)	$	2.32E+02	1.95E+12	45
13	Phosphate	g P	1.32E+04	3.70E+10	49
14	Nitrogen	g N	4.36E+04	4.05E+10	177
15	Micronutrients (Fe, Mg, Mn, Zn)	g	2.24E+04	1.45E+10	33
16	Labor	J	2.71E+08	4.45E+06	120
17	Services	$	4.94E+02	4.03E+12	199
	Sum of purchased inputs				872
	Total Emergy				1022

Notes:

*Unless otherwise noted, unit emergy ratios in notes are original values. For final valuation, these have been multiplied by 1.68 to normalize them to the current standard global emergy flow.

Item no.	Item description				Source
1	**Sun, J**				
		Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)		
		Insolation:	6.90E+09	$J/m^2/yr$	[a]
		Area:	1.00E+04	m^2	
		Albedo:	0.08		[a]
		Annual energy:	6.35E+13	J	
		Emergy per unit input =	1	sej/J	[b]
2	**Rain, J**				
		Annual energy =	(in/yr)(Area)(0.0254 m/in)(1E6g/m^3)(4.94J/g)(1 - runoff)		
		in/yr:	53		[c]
		Area, m^2:	10000		
		runoff coefficient:	7.00E-02		[a]
		Annual energy:	6.18E+10	J	
		Emergy per unit input =	1.80E+04	sej/J	[b]
3	**Evapotranspiration, J**				
		Annual energy =	(Evapotranspiration)(Land area)(Density)(Gibb's free energy)		
		Evapotranspiration	1.11E+00	m/y	[g]
		Area:	10000	m^2	
		Density:	1.00E+06	g/m^3	
		Gibbs free energy:	4.94E+00	J/g	
		Annual energy:	5.48E+10	J	
		Emergy per unit input =	1.54E+04	sej/J	[b]
4	**Surface water irrigation, J**				
		Annual consumption, l:	9.63E+06	l	
		Emergy per unit input =	2.25E+05	sej/l	KHALAF, 20(
5	**Net Topsoil Loss, J**				
					[a]
		% organic in soil =	0.04		[a]
		Energy cont./g organic=	5.40	kcal/g	
	Net loss of topsoil = (farmed area)(erosion rate)				
	Organic matter in topsoil used up= (total mass of topsoil)(% organic)				
	Energy loss= (loss of organic matter)(5.4 kcal/g)(4186 J/kcal)				
		Annual energy:	6.33E+08	J	
		Emergy per unit input =	7.38E+04	sej/J	[b]
6	**Fuel, J per ha** (includes diesel, gasoline, lubricants)				
	(gallons fuel) * (1.32E8 J/gal)				
		Gallons:	4.14E+01		[a]
		Annual energy:	5.46E+09	J	
		Emergy per unit input =	6.60E+04	sej/J	[b]
7	**Electricity, J**				
		Annual energy = KWh*3.6E6 J/KWh			
		KWh:	0.00E+00		[a]
		Annual energy:	0.00E+00	J	
		Emergy per unit input =	1.60E+05	sej/J	[b]
8	**Machinery, g (assuming 10 year life)**				
			5.54E+01	kg	[i]
		Emergy per unit input =	1.12E+10	sej/g	
9	**Potash, g K per ha**				
	(g fertilizer active ingredient)(78 gmol K/94 gmol K2O)				
		g:	2.10E+05	g K	[d]
		Annual consumption:	1.75E+05		
		Emergy per unit input =	1.10E+09	sej/g	[b]
10	**Dolomite, g per ha**				
		Annual consumption, g:	5.60E+05	g	[a]
		Emergy per unit input =	1.68E+09	sej/g	[b]
11	**Slag, g per ha**				
		Annual consumption, g:	8.41E+05	g	
		Emergy per unit input =	6.01E+06	sej/g	[h]
12	**Pesticides, $ per ha** (includes pesticides, fungicides, herbicides)				
		Annual consumption, $:	$231.82	$	[d]
		Emergy per unit input =	1.95E+12	sej/$	[i]

Item no.	Item description			Source
13	**Phosphate, g P per ha**			
	(g fertilizer active ingredient)(31 gmol P/132 gmol DAP)			
	g:	5.60E+04		[d]
	Annual consumption:	1.32E+04	g P	
	Emergy per unit input =	2.20E+10	sej/g	[e]
14	**Nitrogen, g N per ha**			
	(g fertilizer active ingredient)(28 gmol N/132 gmol DAP)			
	g:	2.06E+05		[d]
	Annual consumption:	4.36E+04	g N	
	Emergy per unit input =	2.41E+10	sej/g	[e]
15	**Micronutrients, g**			
	Annual consumption, g:	2.24E+04	g	
	Emergy per unit input =	1.45E+10	sej/g	EPA report
16	**Labor, J**			
	(pers-hours/ha/yr)*(2500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)			
	pers-hours:	2.07E+02		[a]
	Annual energy:	2.71E+08	J/yr	
	Emergy per unit input =	4.45E+06	sej/J	[a]
17	**Services, $ per ha**			
	$/yr:	4.94E+02		[d]
	Annual emergy =	($ /yr)(sej/$)		
	Emergy per unit input =	2.40E+12	sej/$, 1983	[b]

Name of Index	Expression	Quantity
% Renewability	(R)/(Y)	14%
Emergy Yield Ratio	Y/(P + S)	1.17
Environmental Loading Ratio	(N + F)/R	6
Emergy Sustainability Index	EYR/ELR	0.21

APPENDIX C: Emergy Analysis of Sweet sorghum on Mineral soils in South Florida

Sweet sorghums have generated interest as a feedstock for ethanol production since the 1970s. Juice from sweet sorghum can be converted to ethanol using currently available, conventional fermentation technology (similar to ethanol produced from sugarcane juice in Brazil). The bagasse (crushed stalks) that remains after removal of the juice can be burnt to generate electricity or steam as part of a co-generation scheme. Additionally, the bagasse could be utilized as a feedstock if the technology for cellulosic ethanol production becomes viable on a commercial scale.

Currently, sweet sorghum is not produced in Florida on a commercial basis, so there is limited information on production costs. However, grain and silage/forage sorghum are produced in North Florida and their production costs are likely similar. Information can be found at http://nfrec.ifas.ufl.edu/programs/enterprise_budgets.shtml#field_crops.

Compared to many other crops, sweet sorghum has high water- and nutrient-use efficiencies and is considered environmentally sustainable. Unlike some proposed high biomass energy crops, sweet sorghum is not a threat to become an invasive weed in Florida.

Outline of Events Sequence and Protocol for Sweet Sorghum[8] Production

1. Land Preparation: January through to mid-March
   a) Occurs prior to planting or after ratoon (usually, only 1)/crop rotation
   b) Soil tests conducted to determine soil fertility requirements
   c) Disking
   d) Lime application for soils with pH below 6.0 to correct soil acidity
   e) Laser leveling done on half of the acreage each year
   f) Secondary tillage
      i. Disc harrow for shallow tillage, cultivates the soil and chops up unwanted weeds or crop remainders
   g) Row and beds Formation
      (1) Row plow
         a) Designed to till soil within a narrow band (single row)
         b) Tandem disc for fine finish seed beds

[8] Drought resistant, water efficient crop, efficient in fertilizer consumption

Material and Energy Inputs

- Light disc
- Tandem disc
- Laser leveler
- Row plow
- Tractor(s)
- Fuel and lubricants
- Specialized labor
- Operators of equipment

2. Planting: Late March – Mid-June
   a) Optimal planting times in Florida will vary between locations. However, in all cases, soil temperatures at planting should be above 65°F.
   b) Mechanical planting: Sweet sorghum is largely by mechanical cultivation.
   c) Typically seeded in widely spaced rows (30-40in)
   d) Ideal seeding rate for most sweet sorghum varieties is 3-4 seeds per linear ft of row.
   e) Fertilizer and pesticide operations to ensure effective crop field maintenance.

Material and Energy Inputs

- Tinned cultivator (for seed drilling)
- Seeds (for first year crops)
- Corn planter for seeding
- Soil insecticide
- Nitrogen
- P_2O_5
- K_2O
- Micronutrients
- Herbicide
- Insecticide
- Fungicide
- Tractor(s)
- Fuel and lubricants
- Labor
- Operators of equipment

3. Harvesting: July to October
   a) Currently, the only commercially viable harvest method for sweet sorghum is removing the entire crop with a forage harvester.
   b) Usually deheaded prior to harvesting for the purpose of boosting sugar yields.

<u>Material and Energy Inputs</u>

- Forage Harvester
- Mechanical deheader
- Tractor(s)
- Wagons
- Fuel and lubricants
- Labor
- Operators of equipment

4. The Farming Cycle

a) Sweet sorghum is grown 4-5 months before either:
   i. The stalks regrow;
   ii. Rotated with another crop;
   iii. Ratooned; or
   iv. Left fallow

Costs & Returns for Sweet sorghum Production on Mineral soils in South Florida (2010)

ACTIVITY	UNIT	RATE	# TIMES	PRICE/ UNIT	$/ACRE/YEAR	QTY/ACRE/ YEAR
Fallow land total cost per acre:						
Herbicide + surfactant	qt	0.00	0	$ 7.50	$0.00	0.00
Herbicide application	$		0	$ 4.00	$0.00	
Total					$0.00	
Land preparation total cost per acre:						
Soil testing and consulting	$/acre		1	$ 1.11	$1.11	
Disking	$/acre		2	$ 15.00	$30.00	
Lime (Dolomite) application	$/acre		1	$ 5.00	$5.00	
Lime Material	ton/acre	2.00	1	$ 28.00	$56.00	2.00
Laser Leveling	$/acre		0.5	$ 60.00	$30.00	
Secondary tillage	$/acre		1	$ 12.00	$12.00	
Slag	ton/acre	0.00	0	$ 56.00	$0.00	0.00
Slag application	$/acre		0	$ 5.00	$0.00	
Total					$134.11	
Planting						
Plant drilling	$/acre		1	$ 12.00	$12.00	
Seed cost	$/acre	3.00	1	$ 9.00	$27.00	
Soil Insecticide	lb/acre	3.00	1	$ 9.00	$27.00	3
Total					$66.00	
Cultural Activities						
Fertilizer application	$/acre		2	$ 6.00	$12.00	2.00
Fertilizer – N	lb/acre	90.00	2	$ 0.60	$108.00	180.00
Fertilizer - P_2O_5	lb/acre	60.00	2	$ 0.60	$72.00	120.00
Fertilizer - K_2O	lb/acre	90.00	2	$ 0.60	$108.00	180.00
Micronutrients	lb/acre	15.00	2	$ 0.51	$15.30	30.00
Chemical applications	$	1.00	2	$ 4.00	$8.00	2.00
Herbicide	pt/acre	1.50	1	$ 2.20	$3.30	1.50
Herbicide	qt/acre	2.00	1	$ 1.50	$3.00	2.00
Insecticide	oz/acre	2.80	6	$ 2.75	$46.20	16.80
Fungicide	oz/acre	4.00	4	$ 4.00	$64.00	16.00
Mechanical Cultivation	$/acre	1.00	4	$ 6.50	$26.00	
Total					$465.80	
Miscellaneous	$				$66.56	
Interest	$				$58.60	
Harvesting activities						
Harvesting	$/ton	22.50	2	$ 9.00	$405.00	
Deheading	$/acre		2	$ 8.00	$16.00	
Transporting	10 miles	22.50	2	$ 93.62	$187.24	
Total					$608.24	
Overhead activities						
Supervising and vehicles	$/acre		1	$ 10.00	$10.00	
Road and ditch maintenance	$/acre		1	$ 5.00	$5.00	
Irrigation	$/acre		1	$ 76.00	$76.00	
Taxes and assessments	$/acre		1	$ 55.00	$55.00	
Land charge	$/acre		1	$ 75.00	$75.00	
Total	$				$221.00	
TOTAL COSTS					$1,620.31	

Emergy Evaluation of Sweet sorghum on mineral soil, per ha per year

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY* (sej/unit)	Solar EMERGY (E13 sej/yr)
RENEWABLE RESOURCES					
1	Sun	J	6.35E+13	1	6
2	Rain	J	6.18E+10	3.02E+04	187
3	Et	J	1.48E+10	2.59E+04	38
NONRENEWABLE STORAGES					
4	Net Topsoil Loss	J	9.92E+08	1.24E+05	12
	Sum of free inputs (sun, rain omitted)				51
PURCHASED INPUTS					
Operational inputs					
5	Fuel (diesel, gasoline, lubricants)	J	2.99E+09	1.11E+05	33
6	Electricity	J	4.68E+08	2.69E+05	13
7	Machinery	J	5.27E+08	1.09E+05	6
8	Potash	g K	1.36E+04	1.85E+09	3
9	Dolomite (Lime)	g	7.26E+05	1.68E+09	122
10	Slag	g	0.00E+00	6.01E+06	0.0
11	Pesticides (insecticides, herbicides)	g	5.45E+02	2.52E+10	1
12	Phosphate	g P	2.56E+03	3.70E+10	9
13	Nitrogen	g N	3.46E+03	4.05E+10	14
14	Labor	J	2.71E+08	4.45E+06	120
15	Services	$	8.84E+01	4.03E+12	36
	Sum of purchased inputs				357
	Total Emergy				407

Name of Index	Expression	Quantity
% Renewability	(R)/(Y)	9%
Emergy Yield Ratio	Y/(P + S)	1.14
Environmental Loading Ratio	(N + F)/R	9
Emergy Sustainability Index	EYR/ELR	0.12

Notes:
*Unless otherwise noted, unit emergy ratios in notes are original values. For final valuation, these have been multiplied by 1.68 to normalize them to the current standard global emergy flow.

Item	Item description			Source
1	**Sun, J**			
	Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)		
	Insolation:	6.90E+09	$J/m^2/yr$	[a]
	Area:	1.00E+04	m^2	
	Albedo:	0.08		[a]
	Annual energy:	6.35E+13	J	
	Emergy per unit input =	1	sej/J	[b]
2	**Rain, J**			
	Annual energy =	(in/yr)(Area)(0.0254 m/in)(1E6g/m^3)(4.94J/g)(1 - runoff)		
	in/yr:	53		[c]
	Area, m^2:	10000		
	runoff coefficient:	7.00E-02		[a]
	Annual energy:	6.18E+10	J	
	Emergy per unit input =	1.80E+04	sej/J	[b]
3	**Evapotranspiration, J**			
	Annual energy =	(Evapotranspiration)(Land area)(Density)(Gibb's free energy)		
	Evapotranspiration		m/y	[g]
	Area:		m^2	
	Density:		g/m^3	
	Gibbs free energy:		J/g	
	Annual energy:	1.48E+10	J	Odum et al., 1998
	Emergy per unit input =	1.54E+04	sej/J	[b]
4	**Net Topsoil Loss, J**			
	Erosion rate =		g/m2/yr	[a]
	% organic in soil =			[a]
	Energy cont./g organic=		kcal/g	
	Net loss of topsoil = (farmed area)(erosion rate)			
	Organic matter in topsoil used up= (total mass of topsoil)(% organic)			
	Energy loss= (loss of organic matter)(5.4 kcal/g)(4186 J/kcal)			
	Annual energy:	9.92E+08	J	Odum et al., 1998
	Emergy per unit input =	7.38E+04	sej/J	[b]
5	**Fuel, J per ha** (includes diesel, gasoline, lubricants)			
	(gallons fuel) * (1.32E8 J/gal)			
	Gallons:			[a]
	Annual energy:	2.99E+09	J	Odum et al., 1998
	Emergy per unit input =	6.60E+04	sej/J	[b]
6	**Electricity, J**			
	Annual energy = KWh*3.6E6 J/KWh			
	KWh:	1.30E+02		[a]
	Annual energy:	4.68E+08	J	
	Emergy per unit input =	1.60E+05	sej/J	[b]
7	**Machinery, J, Oil Equivalent (assuming 10 year life)**			
		5.27E+08	J	Odum et al., 1998
	Emergy per unit input =	6.47E+04	sej/J	Odum et al., 1998
8	**Potash, g K per ha**			
	(g fertilizer active ingredient)(78 gmol K/94 gmol K2O)			
	g:	1.63E+04	g K	[d]
	Annual consumption:	1.36E+04		
	Emergy per unit input =	1.10E+09	sej/g	[b]
9	**Dolomite, g per ha**			
	Annual consumption, g:	7.26E+05	g	[a]
	Emergy per unit input =	1.00E+09	sej/g	[b]
10	**Slag, g per ha**			
	Annual consumption, g:	0.00E+00	g	
	Emergy per unit input =	6.01E+06	sej/g	[h]
11	**Pesticides, g per ha** (includes pesticides, fungicides, herbicides)			
	Annual consumption, g:	5.45E+02	g	[d]
	Emergy per unit input =	1.50E+10	sej/g	[f]

Item	Item description			Source
12	**Phosphate, g P per ha**			
	(g fertilizer active ingredient)(31 gmol P/132 gmol DAP)			
	g:	1.09E+04		[d]
	Annual consumption:	2.56E+03	g P	
	Emergy per unit input =	2.20E+10	sej/g	[e]
13	**Nitrogen, g N per ha**			
	(g fertilizer active ingredient)(28 gmol N/132 gmol DAP)			
	g:	1.63E+04		[d]
	Annual consumption:	3.46E+03	g N	
	Emergy per unit input =	2.41E+10	sej/g	[e]
14	**Labor, J**			
	(pers-hours/ha/yr)*(2500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)			
	pers-hours:	2.07E+02		[a]
	Annual energy:	2.71E+08	J/yr	
	Emergy per unit input =	4.45E+06	sej/J	[a]
15	**Services, $ per ha**			
	$/yr:	8.84E+01		[d]
	Annual emergy = ($ /yr)(sej/$)			
	Emergy per unit input =	2.40E+12	sej/$, 1983	[b]