Emergy Analysis of Food Production at S&S Homestead Farm

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Abstract

This paper uses emergy analysis to assess the ecological sustainability of a small family farm on Lopez Island, in Washington State. Emergy is defined as the available energy of one kind previously used up directly and indirectly to make a service or product, usually quantified in solar energy equivalents (Odum, H.T., 1996. *Environmental Accounting: EMERGY and Environmental Decision Making*. John Wiley & Sons, New York.). By employing a framework that emanates from ecosystem science, the success of the farm in adhering to the goal of ecological sustainability is quantitatively assessed. Emergy-based indices and ratios were calculated to estimate the sustainability of individual management areas on the farm, as well as for the farm as a whole, based on a) the emergy yield of the production process studied b) the load the production process places on the local environment and c) the overall thermodynamic efficiency of the production process. The analysis indicates that the various management areas on the farm display widely differing levels of emergy yield, environmental load, and energy transformation efficiency, and thus ecological sustainability. In general, it was found that those management areas that relied to a greater extent on locally available renewable emergy flows, and less on purchased inputs, human labor and services exhibited higher sustainability than those highly reliant on purchased and non-renewable emergy flows. While the farm exhibits relatively high levels of overall ecological sustainability as currently organized, altering management practice so that the agroecosystem relies to a greater extent on the self-organizing ability of ecosystems and less on inputs from human labor and the economy would improve the sustainability of some management areas. Finally, the analysis brought to light how the economic and ecological costs of production need to be weighed within the context of the overall holistic goals guiding a farm's operation if definitions and estimates of sustainability are to have relevance for agricultural practitioners.

Introduction

To "farm in nature's image" is a primary goal guiding many contemporary efforts to develop ecologically sustainable agricultural systems (Soule & Piper, 1992). Advocacy for this concept has been inspired by the realization that modern agricultural production systems are dependent upon large quantities of increasingly scarce non-renewable resources to maintain their high yields. Simultaneously, there is evidence that many modern, highly mechanized systems of food production can degrade soil, water and genetic resources to such a degree that when access to non-renewable resources becomes limited, the prospects of attaining even the modest yields of pre-industrial agriculture may be dim (Hall et al., 1986). Fortunately, recognition of the fact that conventional modern agriculture deviates from ecological principles has inspired a new generation of scientists and agricultural practitioners who are working to reintegrate the principles of ecology into agriculture (Altieri, 1999; Jackson, 2002). Furthermore, a committed and growing minority of people within western culture have begun to seek sustainable paths for current and future society, and in their footsteps have sprung up new concepts such as "bio-mimicry" (Benyus, 1999) and "ecological design" (Todd & Todd, 1993), which are applications of ecological principles to manufacturing and the built environment, respectively. These concepts and their associated movements have emerged as corollaries to ecological and/or sustainable agriculture, and all share a common mission of achieving a greater harmony between human society and the natural world.

While the goal of farming in a manner that is more mimetic of natural systems may be firmly incorporated into the tenets of the alternative agriculture movement, measuring the sustainability of agricultural systems by the criterion of how closely their function resembles natural systems is a relatively new area of research, and understanding how ecological principles translate into agricultural practice remains an important task. The analysis presented here endeavors to address these issues by assessing the ecological sustainability of a small family farm on Lopez Island, in Washington State; a farm that holds the goal of farming in nature's image as a fundamental organizing principle. By employing a theoretical framework emanating from ecosystem science and by using emergy analysis (Odum, 1996) as a methodological platform, the success of the farm in adhering to the goals of sustainability and eco-mimicry are quantitatively assessed. In addition, the implications of adopting different farming practices are discussed in relation to how they might help or hinder the farm to become more ecologically sustainable. The paper begins with a fairly comprehensive treatment of the conceptual and theoretical foundations of emergy analysis in order to acquaint unfamiliar readers with new concepts, and to make the analysis, results and discussion sections more meaningful.

Emergy Analysis

Emergy is defined as the available energy of one kind previously used up directly and indirectly to make a service or product (Odum, 1996). Emergy analysis has evolved from the field of "eco-energetics" (Odum, 1971) and its empirical origins stem from the study of the patterns of energy flow that ecosystems and economic systems develop during self-organization (Odum, 1988). The theoretical foundations of emergy analysis stem from the observation that both ecological systems and human social and economic systems are fundamentally energetic systems that exhibit characteristic designs and organizational patterns that reinforce energy use. Moreover, emergy analysis posits that the dynamics and performance of environmental systems are best measured and compared on an objective basis using energy metrics (Odum et al., 2000; Odum, 1988). Earlier applications of this concept used the term 'embodied energy' (Costanza, 1980; Odum & Odum, 1976) to signify that the energy expended during production in ecological and economic systems can be considered to be embodied in the system's products. Furthermore, it is held that this embodied energy informs a product's potential importance, or value, to both the production system that created the product and to its end-users. Odum (1988) later adopted the word *emergy* to differentiate the concept from other similar concepts in use in the field of ecological economics (Brown and Herendeen, 1996).

By utilizing concepts and data from many different scientific disciplines, emergy analysis is in many respects a transdisciplinary science, and can be thought of as a synthesis of systems theory, ecology and energy analysis (Odum, 1971, 1996; Hall, 1995). A number of important publications have documented the history of these concepts over the past 30 years, including: *Environment, Power and Society* (Odum, 1971), *The Energy Basis for Man and Nature* (Odum & Odum, 1976), "Self-Organization, Transformity and Information" in the journal *Science* (Odum, 1988), *Ecological and General Systems: An Introduction to Systems Ecology* (Odum, 1994), and *Environmental Accounting: EMERGY and Environmental Decision Making* (Odum, 1996), among others. Recently, emergy analyses have been used to assess the sustainability of environmental systems of all scales, from economic activity within the biosphere of the Earth (Brown & Ulgiati, 1999), to the sustainability of national economies (Ulgiati et al., 1994; Lagerberg et al., 1999), to bio-fuel production (Ulgiati, 2001; Bastianoni & Marchettini, 1996), municipal wastewater treatment (Björklund et al., 2001), and historical comparisons of industrial and pre-industrial agricultural systems (Rydberg & Jansén, 2002).

Emergy Theory of Value

The emergy theory of value states that the more work done, or energy dissipated, to produce something, the greater is its value (Odum, 1996). While the emergy theory of value is controversial (Cleveland et al., 2000), emergy analyses offer one of the only ways to objectively assess value in both ecosystems and economic systems on a common basis. Emergy values are most often quantified and expressed as solar energy equivalents (Odum, 1988, 1996), and the unit used to express emergy values is the solar emjoule (sej). By tracking all resource inputs back to the amount of solar equivalent energy required to make those inputs, emergy analysis accounts for all the entropy losses required to make a given product, and thereby allows for qualitatively different resources to be considered on a common basis. Emergy has elsewhere been referred to as the ‘memory of energy’ that was dissipated in an energy transformation process (Odum, 1996; Brown & Ulgiati, 1999). In contrast to economic valuation, which assigns value according to utility - or what one gets out of something - and uses willingness-to-pay as its sole measure, emergy offers an opposing view of value where the more energy, time and materials that are invested in something, the greater is its value (Odum, 1996; Brown & Ulgiati, 1999).

The Energy Systems Language

At the core of an emergy analysis of a given production system is a mass and energy flow analysis of that system. The boundary for the system studied is defined by the evaluator, and it is this boundary that dictates what is considered to be an indigenous resource, an input or an output for the system under study. To facilitate analysis, an energy systems diagram is drawn using the symbols of the energy language of systems ecology (after Odum, 1971, 1994) to graphically represent ecological/energy components, economic sectors and resource users, and the circulation of money through the system. Originally, the energy systems language was developed as a non-quantitative way to visually depict energy-constrained mathematical relationships. Figure 1 is an illustration and description of the energy circuit language.

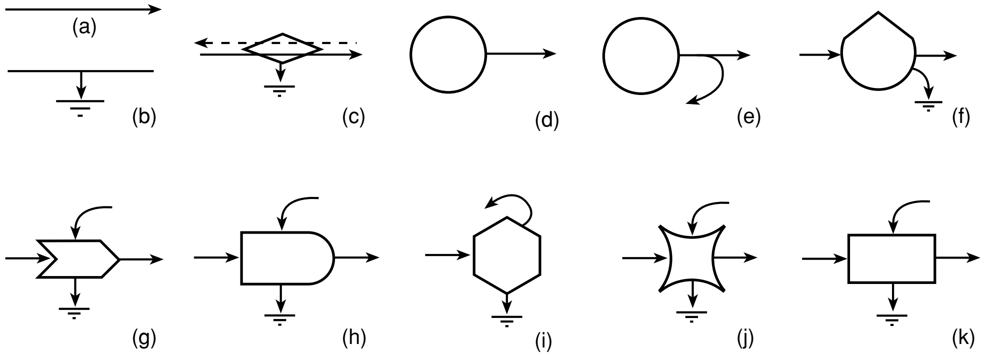


Figure 1. The Symbols of the Energy Systems Language. (a) *Energy circuit*: A pathway whose flow is proportional to the quantity in the storage or source upstream. (b) *Heat sink*: Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system. (c) *Transaction*: A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source. (d) *Force-controlled source*: External energy source with constant availability; delivering an unlimited supply in proportion to demand. (e) *Flow-controlled source/renewable source*: An energy source with only a set amount of flowing and available per unit time. (f) *Tank*: A compartment of energy storage within a system storing a quantity as the balance of inflows and outflows; a state variable. (g) *Interaction*: Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate. (h) *Producer*: Unit that collects and transforms low-quality energy under control interactions of high-quality flows. (i) *Consumer*: Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow. (j) *Switching action*: A symbol that indicates one or more switching actions. (k) *Box*: Miscellaneous symbol to use for whatever unit or function is labeled (Odum, 1996).

Energy Hierarchy & Energy Quality

Odum (1988, 1994, 1996) uses the term energy hierarchy to indicate that in all systems, a greater amount of energy must be dissipated in order to produce a product containing less energy, that is of a higher "quality", suggesting that there is a natural order to how energies of differing qualities can be grouped. This idea stems from the observation that “ecosystems, earth systems, astronomical systems and possibly all systems are organized in hierarchies because this design maximizes useful energy processing” (Odum, 1988). A corollary to this statement is the theory that in open systems that exist away from thermodynamic equilibrium, such as ecological and economic systems, energy hierarchies develop as a consequence of self-organization for optimum energy use (Odum, 1995). Figure 2 illustrates this concept.

Related to the hierarchical organization of energy in systems is the notion of energy quality (Costanza, 1980; Hall et al., 1986; Odum, 1988). Energy quality refers to the observation that energies of different kinds vary in their ability to do useful work (Odum, 1996). This principle is often illustrated using the example of coal and electricity, where four joules of coal energy must be transformed to supply one joule of electric power. Because of this necessary transformation, electricity occupies a higher position in the energy transformation hierarchy than coal and is considered to be of higher quality. The tasks that coal energy and electrical energy are put to indicate how the notion of energy quality translates to the real world. Coal energy is most often transformed into low-grade thermal energy for the purposes of space heating and to create steam to turn turbines for the generation of electricity, while electricity is more versatile, is easily transported, and can power a multitude of engineered, high-technology systems. Moreover, human labor is generally of very high transformity due to the fact that human being require large emergy flows and support territories to support their work.

Transformity

When the energy used up to make a product is divided by the energy remaining in the product one derives the transformity of that product, expressed as the ratio of solar emjoules per Joule (sej/J). Transformities provide an energy quality factor in that they account for the convergence of biosphere processes required to produce something, expressed in energy units. The more energy transformations there are contributing to a product, the higher is that product's transformity, and that product therefore occupies a correspondingly higher position in the energy hierarchy (Odum, 1996). Thus, transformity can be used as energy scaling ratio to indicate energy quality and hierarchical position (Odum, 1988). Figures 2 and 3 show typical networks that includes an energy source, a producer and a consumer(s) and shows how the concepts of energy, emergy and transformity are related. The emergy is used up when the feedback from the consumer intersects with the producer, or when it "intersects its own tail" (Odum, 1996).

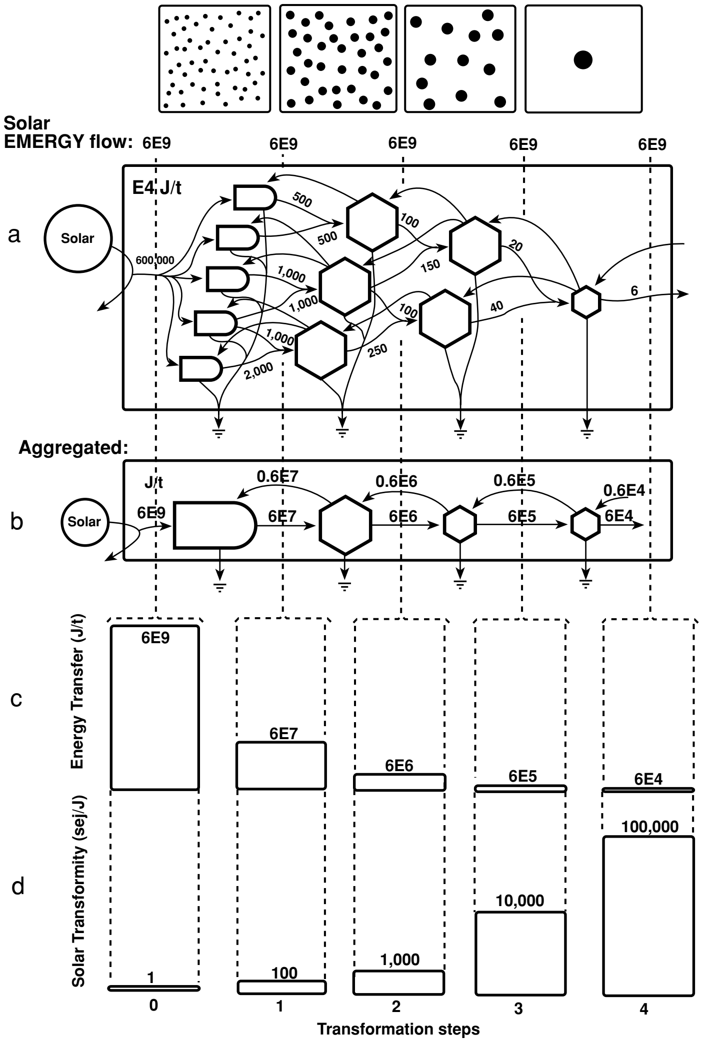


Figure 2. Diagram of the energetics of an energy transformation hierarchy. The figure shows the distribution of size and territories of units in each category. (**a**) Web with energy flows indicated in joules, (**b**) energy transformation chain formed by aggregating the web by hierarchical position, (**c**) graph of energy flows at each stage in the energy hierarchy, and (**d**) solar transformity for each level in the hierarchy (Redrawn from Odum, 1988).

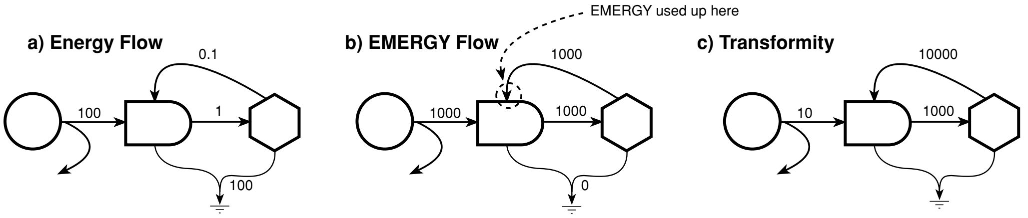


Figure 3. Energy flow, emergy flow and transformity through a typical network. The network contains one energy source, a producer, a consumer, a heat sink and the connecting pathways including a feedback reinforcement (adapted from Odum, 1996).

Simultaneously, transformity is an indicator of past environmental contributions that have combined to create a resource, and is, in theory, an indicator of the potential effect on a system that will result from the use of that resource (Brown & Ulgiati, 1997). In contrast to other forms of energy analysis which look only at the flows of heat equivalent energy to a process, emergy analysis - through the use of transformities - is able to depict the effect of system inputs with respect to the time, space and energy needed to form those inputs, thus articulating the forces driving the self-organizing processes underway in a given system better than energy analysis alone. Table 1 is a list of common transformities.

When data is not available to calculate all the transformities for the resources converging to form a given product, average transformities can be used (Brown and Ulgiati, 1999). And while static transformities are often used, there is no single transformity for most products or services. Generally, there is a range of transformities between a lower limit that is necessary to produce something and a theoretically almost-infinite upper limit (Brown & Ulgiati, 1999). A high transformity input may contribute less *energy* to a process than a low transformity input, but the overall *emergy* contribution of the two sources may be similar when adjusted for energy quality using transformities. For example, in hay production at the S&S Homestead Farm, gasoline and sunlight contributed roughly equivalent *emergy*, 5.06 E+14 sej and 5.28 E+14 sej respectively, but the *energy* contributed by sunlight was 66,000 times greater than gasoline, measured in joules and without adjusting for gasoline's concentration or energy quality with a transformity value.

Table 1. List of characteristic solar transformities of various products, resources and information. The sources of the transformities are listed in Appendix A.

Item	Solar transformity (sej/J)	Source for transformity
Sun	1	A
Wind, kinetic energy	1,496	A
Rain, chemical energy	18,199	A
Earth cycle, geological uplift	34,377	A
Coal	40,000	A
Natural gas	48,000	A
Crude oil	54,000	A
Top soil organic matter	74,000	A
Animal feed, concentrates	79,951	F
Electricity (average)	173,681	A
Fisheries production	1,200,000	H
Nitrogen, ammonium fertilizer	1,860,000	A
Phosphate, mined	10,100,000	A
Pesticides	19,700,000	B
Mechanical equipment	75,000,000	D
Genetic information, single tree species	726,000,000,000	A
Genetic information, human DNA	14,700,000,000,000,000	A

Emergy signatures

The spectrum of energy and resource flows that interact to produce an agricultural product can be thought of as representing the "emergy signature" of that product. Driving forces, or forcing functions (Odum,

1994) - which can be thought of as resources that feed, organize and constrain a system - are a key consideration when assessing the sustainability of agricultural production systems. Within an emergy signature, some flows stand out as dominant as primary driving forces. These are key flows and represent the energetic limits by which a system is constrained. Essentially, the emergy signature can be a convenient way of conceptualizing the energy and resource flows around which an agricultural system has self-organized, and may allow the energetic context of a given system to be more readily surveyed. The emergy signature is important when comparing agricultural production processes because two processes may have similar total emergy requirements, but have very different requirements in terms of the fractions of renewable to non-renewable emergy required, which the emergy signature can help to reveal (Rydberg & Jansen, 2002).

The Maximum Empower Principle

In emergy analysis, the notion that self-organizing systems evolve in the direction that maximizes empower, also known as the Maximum Empower Principle (MEP), is considered to be the thermodynamic law governing self-organization in all systems (Odum, 1971, 1988, 1994, 1996; Brown & Ulgiati, 1997, 1999). The principle has been called "time's speed regulator" in that it may be the principle governing the speed at which entropy is created in open systems (Odum & Pinkerton, 1955). Following Lotka (1922a,b), the MEP is thought to be a natural selection principle operating at the level of system organization, by which system configurations are selected for or against according to their ability to acheive an optimum efficiency in competition with other systems performing similar work. Odum has offered the MEP as follows; "In competition among self-organizing processes, network designs that maximize empower will prevail." (Odum, 1996, p. 16). A statement of the MEP that is phrased in a manner more relevant to agriculture is offered by (Brown and Ulgiati, 1999, p. 488): "Systems that self-organize to develop the most useful work with inflowing emergy sources, by reinforcing productive processes and overcoming limitations through system organization, will prevail in competition with others.". Odum has offered the MEP as the fourth law of thermodynamics, positing that it is operating on all systems at all spatial and temporal scales simultaneously. The concept is key to emergy analysis in that it is on the basis of this principle that assumptions are made regarding the reliability of transformities. If the MEP is valid, then all production systems will tend towards a thermodynamically maximal operation efficiency or be selected against, and thus the transformity of the output of a time-tested system can be considered to a reliable indicator of previous energy expenditures dispersed during the work of production.

Materials and Methods

Emergy analyses examine the relationships among the components of a system's network, whereby the flows of energy and other resources converging to produce the output of a system are evaluated on a common basis of the solar equivalent energy required to do the work of production (Ulgiati & Brown, 1998). The methodology used to perform the analysis of food production at S&S Homestead Farm followed the format given by Odum (1996):

a) The system boundary was defined spatially as the area of land utilized for production, both for the farm as a whole and for the individual subsystems (management areas). The temporal dimension of the study was one calender year.
b) All major energy sources and material resources flowing into, and stored within, the farm system were identified and diagramed using the energy systems language, and the quantities were recorded and converted into energy units (Joules), mass units (grams) or monetary units (US Dollars).
c) The various resource flows were either measured directly, or estimated from production records, financial records and locally available data (e.g. weather data). To derive the emergy values of the resources flows, the quantities were tabulated and multiplied by appropriate transformities chosen from the literature.

d) The food items generated by the farm system were converted into energy units (Joules) using standard conversion factors from the USDA Nutrient Data Laboratory (USDA, 2002).

The results of the analyses are given in both diagrammatic and tabular forms. Table 2 is a sample emergy evaluation table. Column 1 of the table gives the line number of each item and is a footnote reference for the emergy calculations that are listed below the table. The name of the item and the units of raw data for that item - usually joules, grams or dollars - are recorded in Column 2. Column 3 gives the quantity of the component recorded in joules, grams or dollars. The energy, material or currency flow for each item is then multiplied by its respective transformity, which is given in column 4, along with a letter that corresponds to the reference from which the transformity was taken. The product of the raw data and the transformity equals the total emergy contribution of that component to the system. The majority of the transformities used in this study were gathered from previously published analyses (e.g., Brown et al., 1993; Doherty et al., 1993; Lagerberg et al., 1999; Odum & Odum, 1983; Odum, 1996; Ulgiati et al., 1994). The total emergy contribution of the component to the system is listed in column 6. In column 7 the macroeconomic value of the emergy flow is given as *EmDollars*. EmDollars are the emergy value of a given flow divided by the emergy/GDP ratio for the year of the study. In this study, the emdollar ratio for 1993 was used, 1.37E+12 sej/$ as this is the last year for which a complete emergy/GDP ratio was calculated for US currency (Odum, 1996). Emdollars are a non-market based indicator of the economic value of inputs to a production process both from free environmental and purchased resources.

Table 2. Sample emergy evaluation table.

Note	Item, unit	Data (units/yr)	Transformity* (sej/unit)	EMERGY (E13 sej/yr)	EmDollars (1993 USD)
1	Sun, J	7.62E+14	1.00[a]	76.18	$55.60
2	Wind, J	3.54E+09	1.50E+03 [a]	0.53	$3.87
3	Rain, J	9.81E+11	1.82E+04 [a]	1785.42	$13,032.26

Accounting for Renewable, Non-renewable, Free and Purchased Inputs

Emergy evaluations consider the following system attributes to be the decisive measures of sustainability: (a) the efficiency of resource use exhibited by a system (b) a system's net emergy yield (c) the dependency of a system on external emergy sources and (d) the overall load placed on the environment by that system (Ulgiati & Brown, 1998; Ulgiati et al., 1994). In order to assess the contribution of a production system to the long-term sustainability of society, a distinction must be made between the flows supporting a production process, and whether they are of a renewable or non-renewable character, and whether they are indigenous to the system or must be purchased. Figure 1.4 is a diagram indicating how resources are delineated and accounted for in this study using the nomenclature developed by Odum (1996) and Ulgiati and Brown (1998). Ulgiati and Brown (1998) outline the distinctions that are made between the various resource flows for purposes of emergy accounting:

a) Renewable flows (R) are: (i) flow limited (we cannot increase the rate at which they flow through the system); (ii) free (they are available at no cost); (iii) and locally available.
b) The nonrenewable flows from within (N) are: (i) stock limited (we can increase the rate of withdrawal, but the total available amount is finite in the time scale of the system); (ii) not always free (sometimes a cost is paid for their exploitation); (iii) locally available.
c) The feedback flows (F) may be: (i) stock limited (as above); (ii) never free; (iii) never locally available, always imported.

Emergy-Based Indices and Ratios

After tabulating the material and energy flow data for the farm system and adjusting for their energy qualities with transformities, a number of emergy-based ratios and indices were calculated. These aggregated indicators assist in the interpretation of the results of the analysis. For more information on emergy-based indicators, the reader is directed to a collection of papers and a book that have been published describing in detail the various emergy-based indices and ratios and what they communicate (Brown & Ulgiati, 1997, 1999; Ulgiati & Brown, 1998; Odum, 1996). The ratios and indices are useful for making comparions of the system in question to other systems yielding similar products, as well as for comparing different components of a single system, such as management areas within a farm system as a whole.

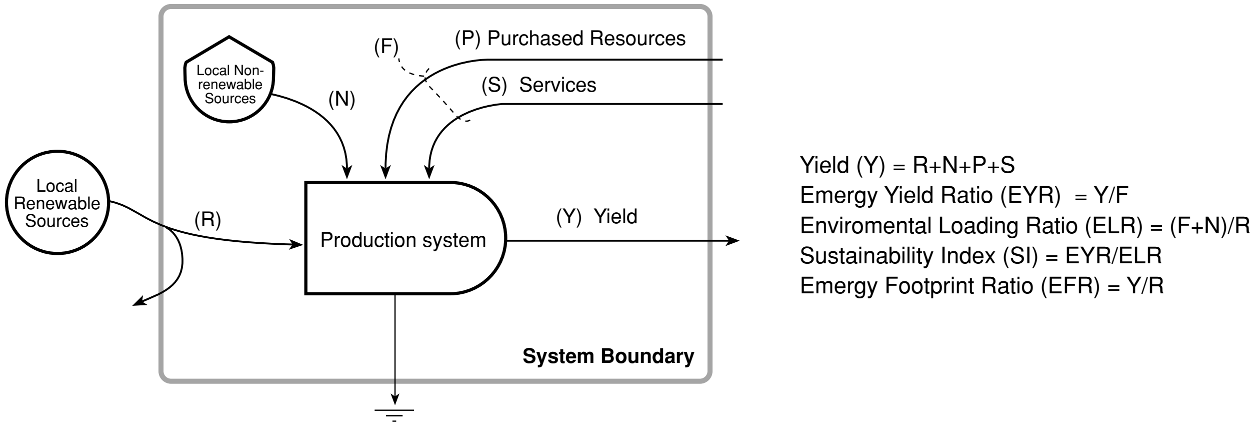


Figure 4. Diagram showing different categories of resource flows as they are accounted for in emergy evaluations of environmental systems, and the formulas used to calculate emergy-based indices and ratios (adapted from Odum, 1996 and Ulgiati and Brown, 1998).

The main indicators used in this analysis are defined as follows (after Ulgiati and Brown, 1998; Odum, 1996):

a) The Environmental Loading Ratio (ELR) is the ratio of purchased (F) and indigenous non-renewable emergy (N) to free environmental emergy (R). It is an indicator of the amount stress that a production process places on the local environment.

b) The Emergy Yield Ratio (EYR) is the ratio of the emergy of the output (Y), divided by the emergy of those inputs (F) to the process that are fed back to the system from outside. Stated otherwise: "the emergy yield ratio of each system output is a measure of its net contribution to the economy beyond its own operation" (Odum, 1996, pp. 71).

c) The Sustainability Index (SI) = EYR/ELR and is an aggregate measure of yield and sustainability that assumes that the objective function for sustainability is to obtain the highest yield ratio at the lowest environmental load.

d) The Emergy Footprint Ratio (EFR) is the ratio of the total emergy yield (Y) of a process to the amount of renewable emergy (R) supporting that process. It is a measure of the support area required to generate all the system outputs using only locally available renewable emergy flows.

Analysis and Results

Overview Analysis

By quantifying the emergy flowing to the S&S Homestead Farm, an understanding of the local and external resource base required to operate the farm system was obtained. The overview analysis is intended to give the reader a general picture of the farm system, to show how the various management areas are organized and to illustrate the connections between the various components that comprise the farm as a whole. Because all buildings on the farm perform multiple duties (excluding the greenhouse), they were counted in the overview analysis, not in analyses of the separate management areas. Therefore, the purchased inputs and services flowing into the farm as a whole will be somewhat greater than the sum of the emergy flows for the management areas. Figure 5 is an energy systems overview diagram of the S&S Homestead farm, showing all the system components that were included in the analysis.

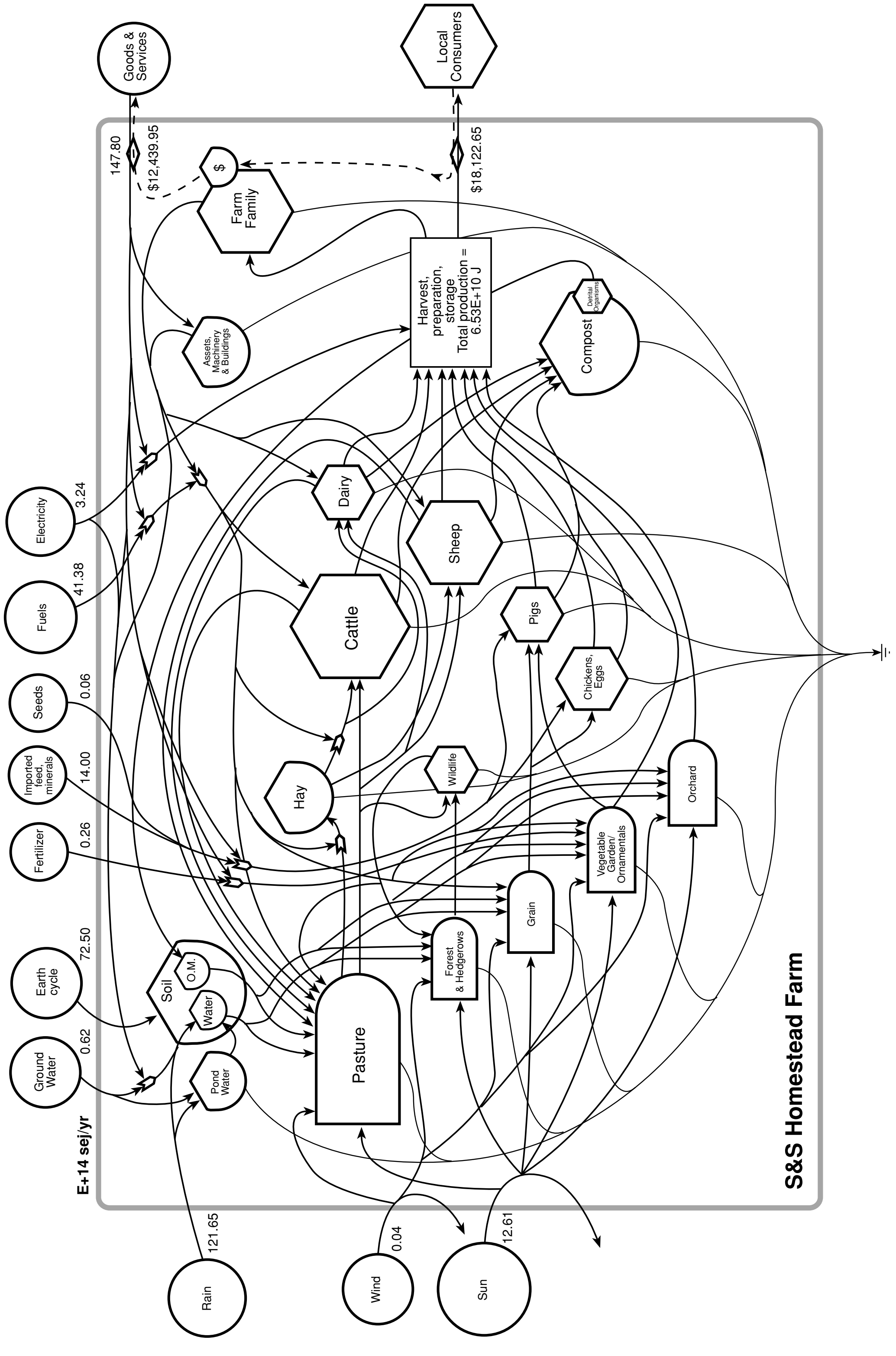


Figure 6. Energy systems diagram of the S&S Homestead Farm.

Table 3 is an emergy evaluation table of the S&S Homstead Farm. References for the transformities are given in Appendix A. The S&S Homestead Farm is a 25 hectare family farm located on Lopez Island in the San Juan Archipelago in northwest Washington State. The farm operates to provide food to members of the surrounding community, to the farmer and his family, and to the farm's interns. All produce that are sold off the farm are sold direct to customers through a Community Supported Agriculture (CSA) arrnagement (vegetables) or by contract (meat and dairy). All labor is provided by the farm family, with assistance from the 2-4 interns who join the farm during the summer each year. While the interns provide labor during the summer, the analysis presented is of a typical year and the labor requirements are estimated based on the person-hours needed to perform a given task. Therefore, a single transformity was calculated for the labor inputs, based on the emergy in the services the farmer receives from the economy. The farm strives for self-sufficiency and this is reflected in the farm's diversity.

Table 3. Emergy evaluation of S&S Homestead Farm.

Note	Item, unit	Data (units/yr)	Transformity* (sej/unit)	EMERGY (E14 sej/yr)	EmDollars (1993 USD)
RENEWABLE RESOURCES (R)					
1	Sun, J	1.26E+15	1[a]	12.61	$920.76
2	Wind, J	2.65E+09	1.50E+03 [a]	0.04	$2.90
3	Rain, evapotranspiration, J	6.68E+11	1.82E+04 [a]	121.65	$8,879.24
4	Rain, geopotential, J	9.34E+08	2.79E+04 [a]	0.26	$19.00
5	Earth Cycle, J	2.50E+11	2.90E+04 [a]	72.50	$5,291.97
6	Groundwater, J	2.73E+09	2.27E+04 [g]	0.62	$45.18
	Largest renewable input			**121.65**	$8,879.24
NONRENEWABLE STORAGES (N)					
7	Net topsoil loss, J	2.73E+09	7.38E+04 [a]	2.01	$146.89
	Sum of free inputs			**124.28**	**$9,071.31**
PURCHASED INPUTS (P)					
8	Fuels and lubricants, J	6.27E+10	6.60E+04 [a]	41.38	$3,020.29
9	Electricity, J	2.02E+09	1.60E+05 [a]	3.24	$236.39
10	Mechanical equipment, g	1.87E+05	4.10E+09 [h]	7.66	$559.04
11	Buildings, fences, tools (wood), J	1.46E+10	3.49E+04 [I]	5.09	$371.48
12	Tools, fencing, (steel), g	2.07E+05	3.20E+09 [d]	6.61	$482.80
13	Ironwood posts (fencing), g	8.50E+03	3.90E+08 [a]	0.03	$2.42
14	Insulators, ceramic (fencing), g	1.15E+03	1.00E+09 [a]	0.01	$0.84
15	Plastic (greenhouse and fencing), g	8.85E+03	3.80E+08 [d]	0.03	$2.46
16	Mineral salt, g	1.58E+05	1.00E+09 [a]	1.58	$114.96
17	Potash, g K	7.13E+02	1.10E+09 [a]	0.01	$0.57
18	Phosphate, g P	1.08E+03	1.78E+10 [a]	0.19	$13.99
19	Nitrogen, g N	1.64E+03	3.80E+09 [a]	0.06	$4.56
20	Seeds, J	1.81E+08	3.48E+04 [d]	0.06	$4.60
21	Grocery store culls , g	1.18E+05	6.31E+09 [b]	7.46	$544.43
22	Soy meal, J	1.70E+09	3.32E+05 [b]	5.64	$411.50
SERVICES and LABOR (S)					
23	Labor, J	5.77E+09	2.56E+06 [g]	147.80	$10,788.53
24	Infrastructure, service component, USD	6.88E+03	1.37E+12 [c]	94.22	$6,877.30
25	Services, yearly expenditures, USD	5.56E+03	1.37E+12 [c]	76.21	$5,562.65
	Sum of purchased inputs			**396.60**	**$28,948.86**
PRODUCTION, J					
26	Meat, J	3.01E+10			
27	Vegetables, fruit, grain, J	2.51E+10			
28	Eggs, dairy, J	1.02E+10			
28	Hay, J	3.55E+11			

RENEWABLE RESOURCES (R): (1) ***Sun***: average insolation 6.31E+03 MJ/m^2/yr (estimate from Hendersen-Sellers & Robinson, 1994). Solar energy received on land = 2.50E+05 m^2 (land area) x 6.31E+03 MJ/m^2/yr x (1-0.2) (1-albedo) x 1,000,000 J/MJ = 1.26E+15 J/yr. **(2)** ***Wind***: average wind speed at ground based on estimated wind speed of 2.5 m/s at 1000 m. Energy from wind received on land = 1000 m (height of boundary layer) x 1.23 kg/m^3 (density of air) x 2.50E+05 m^2 (land area) x (0.4 x 2.5 m/s / 0.6)^2 / 2 = 2.65E+09 J/yr. **(3)** ***Rain, evapotranspiration***: average annual precipitation received on Lopez Island 636.5 mm/yr (Mayo, 2002 pers. comm.). Energy in rain = 636.5 mm/yr x 2.50E+05 m^2 (land area) x .001 m/mm x 1E6 g/m^3 x 4.94 J/g x (1-0.15) (runoff coefficient, from Orr, et al., 2002) = 6.68E+11 J/yr. **(4)** ***Rain, geopotential:*** energy in geopotential = 2.50E+05 m^2 (land area) x 0.15% (runoff coefficient, Orr, et al., 2002) x 0.64 m (rainfall) x 4 m (avg elevation) x 9.8 m/s^2 (gravity) = 9.34E+08 J/yr. **(5)** ***Earth cycle*:** energy contribution of deep earth heat = 2.50E+05 m^2 (land area) x 1.00E+06 J/m^2, (heat flow, Odum, 1996) = 2.50E+11 J/yr. **(6)** ***Groundwater:*** 100300 gal./yr (estimate from total use of house and barn) x .00379 m^3/gal x 1E6 g/m^3 x 4.94 J/g = 1.88E+09 J. **NONRENEWABLE STORAGES (N): (7)** ***Net topsoil loss***: based on erosion rates calculated with the Revised Universal Soil Loss Equation (RUSLE) (erosion rate = R*K*LS*C*P), using estimates from (Brady & Weil, 2000, pp.482-88). Erosion rate calculated as 40*17.02 (factor R) * 0.063 (factor K) * 0.75 (factor LS) * 0.003 (factor C) * 1.0 (factor P) * 1000000 g/Mg = 96,503 g/ha/yr. Net loss of topsoil = 96,503 g/ha/yr * 25 ha (farmed area) = 2.41E+06 g/yr. Loss of organic matter = 2.41E+06 g (topsoil loss) x 0.05% (organic matter) = 5.05E+04 g, organic matter/yr. Energy loss = 5.05E+04 g (org. matter) x 5.4 kcal/g (Odum, 1996) x 4186 [J/kcal] = 2.73E+09 J/yr. **PURCHASED INPUTS (P): (8)** ***Fuels and lubricants***: 1620 liters used. Energy content = 1620 l x 3.87E+07 J/l (U.S. Department of Energy, 2000) = 6.27E+10 J. **(9)** ***Electricty***: energy use = 2.02E+09 J. Data for electricity use available from subsystem analyses. **(10)** ***Machinery***: Tractor, John Deere 770 (20 hp) = 8.75E+02 kg steel. Mower = 2.31E+02 kg, steel. Bush hog (auger) = 8.90E+01 kg, steel. Truck = 1,000 kg, steel. Hay rake = 3.25E+02 kg, steel. Sicklebar mower = 1.95E+02 kg, steel. Chipper/shredder = 5.70E+01 kg, steel. Lawn mower = 30 kg, steel. Total yearly contribution from machinery, g, steel = 1,195 kg x 1000 g/kg = 1,195,000 g x 0.0667 (15 year depreciation rate) = 186,800 g. **(11)** ***Buildings, fences, tools (wood)***: amount of wood = 83.25 m^2 x 450,000 g/m^3 x 3.6 kcal/g x 4186 J/kcal = 564,544,890,000 J. Yearly contribution = 564,544,890,000 J x 0.02 (50 year depreciation rate, as decimal) = 1.46E+10 J. **(12)** ***Tools, fencing (steel)***: Yearly contribution = 2.07E+05 g. Data for steel available from subsystem analyses. **(13)** ***Ironwood posts***: Yearly contribution = 8.50E+03 g, wood. **(14)** ***Insulators, ceramic***: Yearly contribution = 1.15E+03 g, ceramic. Data available in subsystem analyses. **(15)** ***Plastic***: Yearly contribution = 8,851.44 g, plastic. Data available in subsystem analyses. **(16)** ***Mineral salt***, 1.58E+05 g. Data available in subsystem analyses. **(17)** ***Potash*** = 712.7 g, K. Data available in vegetable analysis. **(18)** ***Phosphate*** = 1,076.7 g, P. Data available in vegetable analysis. **(19)** ***Nitrogen*** = 1,643.4 g, N. Data available in vegetable analysis. **(20)** ***Seeds*** = 1.81E+08 J. Data available in vegetable analysis. **(21)** ***Grocery store culls*** = 1.18E+05 g. Data available in subsystem analyses. **(22)** ***Soy meal*** = 1.70E+09 J. Data available in subsystem analyses. **SERVICES and LABOR (S): (23)** ***Labor***: total person-hours for farm operation = 3,150.25 hours/yr. Energy contribution of labor = (3,150.25 person-hours x 3500 kcal/day x 4186 J/kcal) / 8 person-hours/day = 5.77E+09 J. Transformity of labor based on expenditure of $10,000 USD for services for the farmer. Thus 10,000 x 1.37E+12 sej/USD (1993 dollars) = 1.37E+16 sej / 5.35E+09 J/yr (metabolism) = 2.56E+06 sej/J of labor **(24)** ***Infrastructure, service component, USD***: purchased services for infrastructure and equipment based on federal asset report prepared for tax purposes = $138,000 USD x 0.05 (20 year depreciation rate) = $6,877.30 yearly contribution. **(25) Services, yearly expenditures, USD**: $3,562.65, yearly operating cost + $2,000 misc. (taxes, insurance, supplies, etc.) = $5,562.65 total. **PRODUCTION**: data for production can be found in subsystem analyses. **(26)** ***Meat***: total energy content = 3.01E+10 J. **(27)** ***Vegetables, fruit, grain***: total energy content = 2.51E+10 J. **(28)** ***Eggs, dairy***: total energy content = 1.02E+10 J. **(29)** ***Hay***: total energy content = 3.55E+11 J.

Hay Production

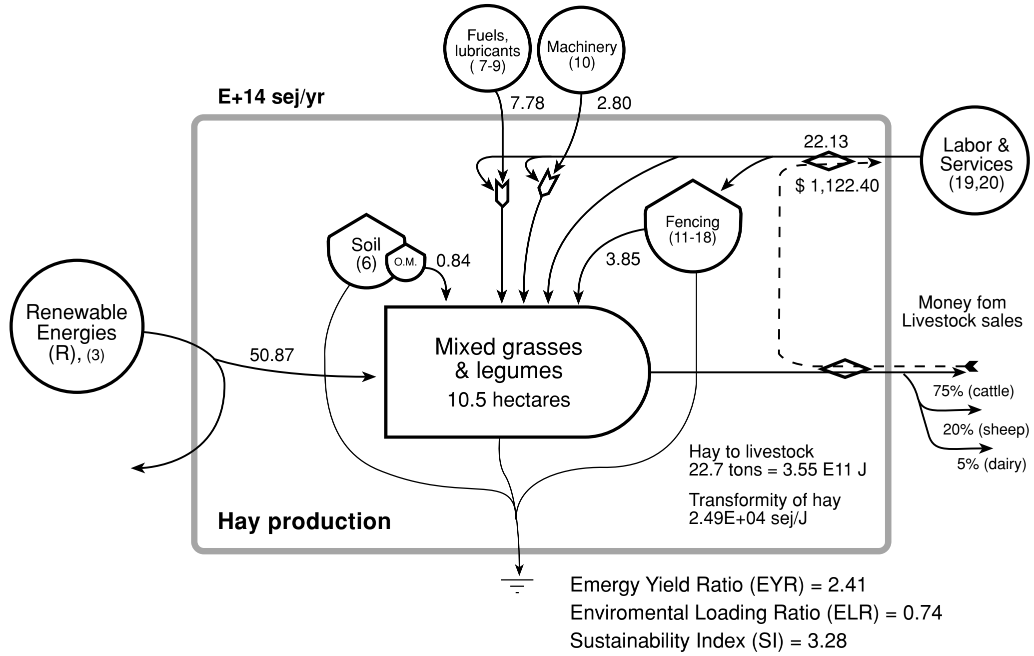


Figure 7. Energy systems diagram of hay production.

In emergy terms, the hay fields and pasture are the power base of the farm system as they are the primary means of solar energy capture, and solar energy storage, used to provide energy for the farm animals throughout the winter. The hay is composed of naturalized grasses and legumes, and the following species can be found in the fields harvested for hay: bentgrass (*Agrostis capillaris*), crabgrass (*Digitaria sanguinalis*), tall fescue (*Festuca arundinacea*), meadow foxtail (*Alopecurus pratensis*), orchardgrass (*Dactylis glomerata*), quackgrass (*Elytrigia repens*), reed canarygrass (*Phalaris arundinacae*), annual ryegrass (*Lolium perene multiflorum*), timothy (*Phleum pratense*), Alsike clover (*Trifolium hybridum*), white clover (*Trifolium repens*), red clover (*Trifoliu pratense*), birdsfoot trefoil (*Lotus corniculatus*). The fields are harvested for hay one time per year, usually in late June and early July. The hay is cut, raked, baled and stacked in the field for curing before being stored in the barn to provide winter feed for the cattle and sheep. Labor is provided by the farmer and farm interns, and it requires the labor of approximately six people working eight hours a day for three days to bring the hay in. 1000 bales are usually stored, corresponding to approximately 22.7 tons of hay, with an energy content of 3.55 E+11 Joules. Figure 7 is a energy systems diagram of hay product on the S&S Homestead Farm. While the hay is shown here as a separate analysis, the analyses of cattle, lamb and dairy production, presented subsequently, include hay in their respective analyses. Therefore, hay is not counted as an output in the final overall analysis, as to do so would be double counting. Table 4 is an emergy evaluation of hay production, prior to its consumption by livestock.

Table 4. Emergy evaluation of hay production, prior to use by livestock.

Note	Item, unit	Data (units/yr)	Transformity* (sej/unit)	EMERGY (E14 sej/yr)	EmDollars (1993 USD)
RENEWABLE RESOURCES (R)					
(1)	Sun, J	5.28E+14	1.00[a]	5.28	$385.04
(2)	Wind, J	1.11E+09	1.50E+03[a]	0.02	$1.21
(3)	Rain, evapotranspiration, J	2.80E+11	1.82E+04[a]	50.87	$3,713.14
(4)	Rain, geopotential, J	3.91E+08	2.79E+04[a]	0.11	$7.95
(5)	Earth Cycle, J	1.05E+11	2.90E+04[a]	30.32	$2,213.01
	Largest of the renewable inputs (rain)			**50.87**	**$3,713.14**
NONRENEWABLE STORAGES (N)					
(6)	Net topsoil loss, J	1.14E+09	7.38E+04[a]	0.82	$61.43
	Sum of free inputs (R+N)			**50.95**	**$3,774.56**
PURCHASED INPUTS (P)					
(7)	Diesel, J	7.66E+09	6.60E+04[a]	5.06	$369.15
(8)	Lubricants, J	2.55E+08	6.60E+04[a]	0.17	$12.30
(9)	Gasoline, J	3.87E+09	6.60E+04[a]	2.55	$186.44
(10)	Machinery, g	6.83E+04	4.10E+09[h]	2.80	$204.35
(11)	Wood posts, J	4.11E+08	3.49E+04[I]	0.14	$10.46
(12)	Iron posts, g	2.48E+04	3.20E+09[d]	0.79	$57.96
(13)	Barb wire, galv. steel, g	1.49E+04	3.20E+09[d]	0.48	$34.79
(14)	Electric wire, galv. steel, g	2.44E+03	3.20E+09[d]	0.08	$5.70
(15)	Ironwood posts, g	3.41E+03	3.90E+08[a]	0.01	$0.97
(16)	Insulators, ceramic, g	4.24E+02	2.00E+09[a]	0.01	$0.62
(17)	Insulators, plastic, g	8.23E+01	3.80E+08[d]	0.00	$0.02
(18)	Cattle gates, iron, g	8.80E+04	2.65E+09[h]	2.33	$170.22
SERVICES and LABOR (S)					
(19)	Labor, J	2.64E+08	2.56E+06[g]	6.76	$493.15
(20)	Services, USD	$1,122.40	1.37E+12[c]	15.38	$1,122.40
	Sum of purchased inputs			**36.56**	**$2,668.53**
PRODUCTION, J					
(21)	Hay production, J =	3.55E+11			

RENEWABLE RESOURCES: notes (1-5) are based identical calculations as table 3, substituting 1.05E+05 m^2 as the land area of the hay fields. **NONRENEWABLE STORAGES (N): (6)** ***Net topsoil loss***: is based on identical calculations to table 3, substituting 1.05E+05 m^2 as the land area. **PURCHASED INPUTS (P): (7)** ***Diesel***: 198 liters used during mowing, cutting, raking, and baling. Energy content = 198 l x 3.87E+07 J/l (U.S. Department of Energy, 2000) = 7.66E+09 J. **(8)** ***Lubricants***: 6.6

liters used. Energy content = 6.6 l x 3.87E+07 J/l (U.S. Department of Energy, 2000) = 2.55E+08 J. **(9)** ***Gasoline***: estimated 100 liters used. Energy content = 100 l x 3.87E+07 J/l (U.S. Department of Energy, 2000) = 3.87E+09 J. **(10)** ***Machinery***: Tractor, John Deere 770 (20 hp) = 8.75E+02 kg steel x 0.33 (use factor, portion used for haymaking) = 288.75 kg, steel. Mower = 2.31E+02 kg, steel x 0.5 (use factor) = 115.5 kg, steel. Hay rake = 3.25E+02 kg, steel. Sicklebar mower = 1.95E+02 kg, steel. Truck = 1,000 kg, steel x 0.10 (use factor) = 100 kg. Total yearly contribution from machinery, g, steel = 1,024.25 kg x 1000 g/kg = 1,024,250 g x 0.0667 (15 year depreciation rate) = 68,283.33 g. **(11)** ***Wood posts***: energy contribution of posts = 30 posts x 13630 g/post x 3.6 kcal/g x 4186 J/kcal = 6,161,959,440 J. Yearly contribution = 6,161,959,440 J x 0.067 (15 year depreciation rate, as decimal) = 4.11E+08 J. **(12)** ***Iron posts***: 91 posts x 4090 g/post = 372,190 g, total. Yearly contribution = 372,190 g x 0.067 (15 year depreciation rate) = 2.48E+04 g, iron. **(13)** ***Barbed wire***: 5656 ft x 39.5 g/ft = 223,412 g, galvanized steel. Yearly contribution = 223,412 g x 0.067 (15 year depreciation rate) = 1.49E+04 g, galvanized steel. **(14)** ***Electric wire***: 3210 ft x 11.4 g/ft = 36,594 g, galv. steel. Yearly contribution = 36,594 g x 0.067 (15 year depreciation rate) = 2.44E+03 g, galv. steel. **(15)** ***Ironwood posts***: 53 posts x 966 g, wood/post = 51,198 g, total. Yearly contribution = 51,198 g x 0.067 (15 year depreciation rate) = 3.41E+03 g, wood. **(16)** ***Insulators, ceramic***: 60 insulators x 106 g/insulator = 6,360 g, ceramic. Yearly contribution = 6,360 g x 0.067 (15 year depreciation rate) = 4.24E+02 g, ceramic. **(17)** ***Insulators, plastic***: 65 insulators x 19 g/insulator = 1,235 g, plastic. Yearly contribution = 1,235 g x 0.067 (15 year depreciation rate) = 8.23E+01g, plastic. **(18)** ***Cattle gates***, iron: 4 gates x 330,000 g/gate = 1,320,000 g, iron. Yearly contribution = 1,320,000 g x 0.067 (15 year depreciation rate) = 8.80E+04 g, iron. **SERVICES and LABOR (S): (19)** ***Labor***: total person-hours for cut and harvest = 144 hours. Energy contribution of labor = (144 person-hours x 3500 kcal/day x 4186 J/kcal) / 8 person-hours/day = 2.64E+08 J. **(20)** ***Services***: purchased services for haymaking (baling, fuels, portions of respective machinery and infrastrcuture) = $1,122.40 USD. (**21**) ***Hay production***: 1000 bales x 50 lb/bale x 0.46 kg/lb x 1000 g/kg = 2.27E+07 g. Energy in forage based on 85% DM and 1.84E+04 J/g/DM (Rydberg & Jansen, 2002). Energy content = 2.27E+07 g x 0.85 x 1.84E+04 J/g = 3.55E+11 J.

Beef Cattle Production

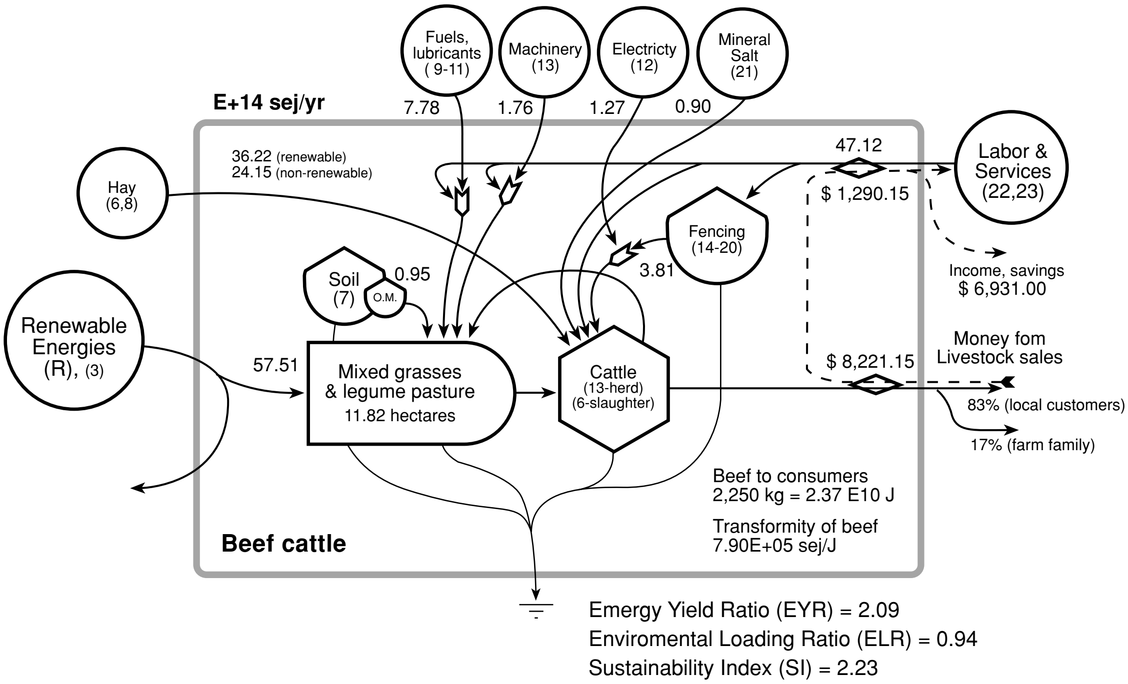


Figure 8. Energy systems diagram of beef cattle production.

The beef cattle are a genetic cross of Simental, Hereford, Angus and Scottish Highland breeds. The cattle graze on grass pasture throughout the spring and summer months, and are fed hay throughout the late fall and winter seasons. The breeds were selected for their ability to transform grass into high quality protein, as the cattle are never fed grain. A system of intensive rotational grazing is employed where the cattle are kept on paddocks 0.18 ha in area for 1-2 days before being rotated to fresh pasture. In this way, the cattle are on fresh pasture every day or two and do not return to a paddock until after at least 25-30 days. This keeps parasite loads very low. In addition, this pulsing of the system may work to maximize the total productivity of the pastures, based on the concept that pulsing maximizes power (Odum, 1994). Figure 8 is an energy systems diagram of beef production and table 5 is a corresponding emergy evaluation.

Table 5. Emergy evaluation of beef cattle production, icluding hay.

Note	Item, unit	Data (units/yr)	Transformity* (sej/unit)	EMERGY (E14 sej/yr)	EmDollars (1993 USD)
RENEWABLE RESOURCES (R)					
1	Sun, J	5.96E+14	1[a]	5.96	$435.27
2	Wind, J	1.25E+09	1.50E+03[a]	0.02	$1.37
3	Rain, evapotranspiration, J	3.16E+11	1.82E+04[a]	57.51	$4,197.46
4	Rain, geopotential, J	4.41E+08	2.79E+04[a]	0.12	$8.98
5	Earth Cycle, J	1.18E+11	2.90E+04[a]	34.27	$2,501.66
6	Hay, J (renewable portion, 60%)	1.60E+11	2.27E+04[a]	39.72	$2,643.82
	Sum of renewable inputs (rain) + hay			**93.73**	$6,841.28
NONRENEWABLE STORAGES (N)					
7	Net topsoil loss, J	1.29E+09	7.38E+04[a]	0.95	$69.44
	Sum of free inputs			**94.68**	**$6,910.71**
PURCHASED INPUTS (P)					
8	Hay, J (non-renew. portion, 40%)	1.06E+11	2.27E+04[g]	24.15	$1,762.54
9	Diesel, J	7.66E+09	6.60E+04[a]	5.06	$369.15
10	Lubricants, J	2.55E+08	6.60E+04[a]	0.17	$12.30
11	Gasoline, J	3.87E+09	6.60E+04[a]	2.55	$186.44
12	Electricity, J	7.93E+08	1.60E+05[a]	1.27	$92.60
13	Mechanical equipment, g	4.29E+04	4.10E+09[h]	1.76	$128.34
14	Wood posts (fencing), J	1.08E+09	3.49E+04[i]	0.38	$27.56
15	Iron posts (fencing), g	6.84E+04	3.20E+09[d]	2.19	$159.86
16	Ironwood posts (fencing), g	3.99E+03	3.90E+08[a]	0.02	$1.14
17	Barb wire, galvanized steel (fencing), g	3.10E+04	3.20E+09[d]	0.99	$72.51
18	Electric wire, galvanized steel (fencing), g	2.49E+04	3.20E+09[d]	0.23	$16.77
19	Insulators, ceramic (fencing), g	2.19E+02	1.00E+09[a]	0.00	$0.16
20	Plastic (fencing), g	1.16E+03	3.80E+08[d]	0.00	$0.32
21	Mineral salt blocks, g	9.00E+04	1.00E+09[a]	0.90	$65.69
SERVICES and LABOR (S)					
22	Labor, J	1.15E+09	2.56E+06[g]	29.44	$2,148.97
23	Services, USD	1.29E+-03	1.37E+12[c]	17.68	$1,290.15
	Sum of purchased inputs			**86.78**	**$6,334.50**
PRODUCTION, J					
24	**Beef, J**	**2.37E+10**			

RENEWABLE RESOURCES (R): (notes 1-5) renewable resource data based on identical calculations as for the farm analysis substituting 1.18E+05 m^2 as the land area. **(6)** ***Hay (renewable portion)***: 75% of hay yield is fed to cattle, and 60% of hay emergy is renewable = 3.55E+11 J x 0.75 x 0.60 = 1.60E+11 J **NONRENEWABLE STORAGES (N): (7)** ***Net topsoil loss***: based on identical calculations as for hay using 1.18E+05 m^2 as the land area. **PURCHASED INPUTS (P): (8)** ***Hay (non-renewable portion)***: 75% of hay yield is fed to cattle, and 40% of hay emergy is non-renewable (purchased) = 3.55E+11 J x 0.75 x 0.40 = 1.06E+11 J **(9)** ***Diesel***: estimated 198 liters used to mow after cattle graze a pasture. Energy content = 198 l x 3.87E+07 J/l (U.S. Department of Energy, 2000) = 7.66E+09 J. **(10)** ***Lubricants***: estimated 6.6 liters used. Energy content = 6.6 l x 3.87E+07 J/l (U.S. Department of Energy, 2000) = 2.55E+08 J. **(11)** ***Gasoline***: estimated 100 liters used. Energy content = 100 l x 3.87E+07 J/l (U.S. Department of Energy, 2000) = 3.87E+09 J. **(12)** ***Electricity***: energy use based on Gallagher M1500 fence charger = 120V x 0.2 Amp x 24 hr/day x 365 day/yr = 220.24 kWh/r * 3.6E+06 J/kWh = 7.93E+08 J. **(13)** ***Machinery***: Tractor, John Deere 770 (20 hp) = 8.75E+02 kg steel x 0.33 (use factor, portion used for haymaking) = 288.75 kg, steel. Mower = 2.31E+02 kg, steel x 0.5 (use factor) = 115.5 kg, steel. Bush hog (auger) = 8.90E+01 kg, steel. Truck = 1,000 kg, steel x 0.15 (use factor) = 150 kg. Total yearly contribution from machinery, g, steel = 643.25 kg x 1000 g/kg = 643,250 g x 0.0667 (15 year depreciation rate) = 42,883.33 g. **(14)** ***Wood posts***: energy contribution of posts = 79 posts x 13630 g/post x 3.6 kcal/g x 4186 J/kcal = 16,226,493,192 J. Yearly contribution = 16,226,493,192 J x 0.067 (15 year depreciation rate, as decimal) = 1.08E+09 J. **(15)** ***Iron posts***: 251 posts x 4090 g/post = 1,026,590 g, total. Yearly contribution = 1,026,590 g x 0.067 (15 year depreciation rate) = 6.84E+04 g, iron. **(16)** ***Ironwood posts***: 62 posts x 966 g, wood/post = 59,892 g, total. Yearly contribution = 59,892 g x 0.067 (15 year depreciation rate) = 3.99E+03 g, wood. **(17)** ***Barbed wire***: 11,788 ft x 39.5 g/ft = 465,626 g, galvanized steel. Yearly contribution = 465,626 g x 0.067 (15 year depreciation rate) = 3.10E+04 g, galvanized steel. **(18)** ***Electric wire***: 9447 ft x 11.4 g/ft = 107,696 g, galv. steel. Yearly contribution = 107,696 g x 0.067 (15 year depreciation rate) = 7.18E+03 g, galv. steel. **(16)** ***Insulators, ceramic***: 31 insulators x 106 g/insulator = 3,286 g, ceramic. Yearly contribution = 3,286 g x 0.067 (15 year depreciation rate) = 2.19E+02 g, ceramic. **(20)** ***Plastic***: (116 insulators x 19 g/insulator = 2,204 g) + (14 portable fence handles x 114 g/handle = 1,596 g) + (4 electro-tape reels x 3410 g/reel = 13,640 g) Yearly contribution = 17,440 g x 0.067 (15 year depreciation rate) = 1.16E+03g, plastic. **(21)** ***Mineral salt blocks***,g: 4 blocks x 22,500 g/block = 90,000 g, minerals. **SERVICES and LABOR (S): (22)** ***Labor***: total person-hours for management = 144 hours. Energy contribution of labor = (627.5 person-hours x 3500 kcal/day x 4186 J/kcal) / 8 person-hours/day = 1.15E+09 J. **(23)** ***Services***: purchased services for cattle (slaughter fees, mineral blocks, fencing repair, respective portions of machinery and fencing infrastructure) = $1,290.15 USD. **(24)** ***Beef production***: energy in meat = 4,950 lbs (hanging weight) x 453.6 g/lb x 2.52 kcal/g (based on wet weight, from Holland et al., 1993) x 4186 J/kcal = 2.37E+10 J.

Lamb Production

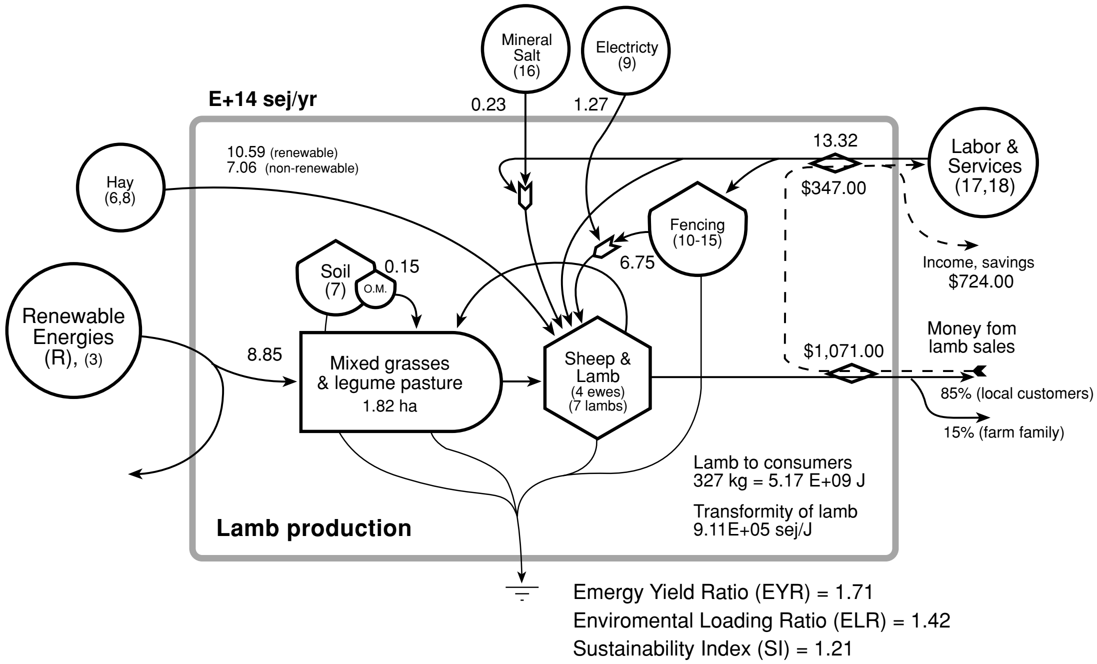


Figure 9. Energy systems diagram of lamb production.

The sheep and lamb are a cross of Romney and Suffolk breeds and are primarily raised for meat, although their skins and fleece are retained for use on the farm, and for sale. The sheep generally graze the margins of the farm, are rotated primarily on the forest edge, and are not on any one pasture for more than 1-2 weeks. The estimated total land used for sheep was 1.82 ha (4 acres). Figure 8 is an energy systems diagram for lamb production. Table 6 is a corresponding emergy evaluation table.

Table 6. Emergy evaluation of sheep.

Note	Item, unit	Data (units/yr)	Transformity* (sej/unit)	EMERGY (E14 sej/yr)	EmDollars (1993 USD)
RENEWABLE RESOURCES (R)					
1	Sun, J	9.17E+13	1[a]	0.92	$66.96
2	Wind, J	1.38E+08	1.50E+03[a]	0.00	$0.15
3	Rain, evapotranspiration, J	4.86E+10	1.82E+04[a]	8.85	$645.76
4	Rain, geopotential, J	6.79E+07	2.79E+04[a]	0.02	$1.38
5	Earth Cycle, J	1.82E+10	2.90E+04[a]	5.27	$384.87
6	Hay, J (renewable portion, 66%)	4.26E+10	2.27E+04[a]	10.59	$773.17
	Sum of renewable inputs (rain) + hay			**19.44**	**$1,418.93**
NONRENEWABLE STORAGES (N)					
7	Net topsoil loss, J	1.09E+08	7.38E+04[a]	0.15	$10.68
	Sum of free inputs			**19.59**	**$1,429.62**
PURCHASED INPUTS (P)					
8	Hay, J (non-renew. portion, 40%)	2.84E+10	2.27E+04[g]	7.06	$515.45
9	Electricity, J	7.93E+07	1.60E+05[a]	0.13	$9.26

Table 6 continued.

10	Batteries, lead (fencing), g	9.08E+03	7.30E+10 [a]	6.64	$484.41
11	Wood posts (fencing), J	8.22E+07	3.49E+04 [i]	0.03	$2.09
12	Ironwood posts (fencing), g	8.37E+02	3.90E+08 [a]	0.00	$0.24
13	Electric wire, galvanized steel (fencing), g	1.98E+03	3.20E+09 [d]	0.06	$4.63
14	Insulators, ceramic (fencing), g	1.41E+02	1.00E+09 [a]	0.00	$0.10
15	Plastic (temp fencing), g	5.00E+03	3.80E+08 [d]	0.02	$1.39
16	Mineral salt, g	2.25E+04	1.00E+09 [a]	0.23	$16.42
SERVICES and LABOR (S)					
17	Labor, J	3.34E+08	2.56E+06 [g]	8.56	$625.00
18	Services, USD	3.47E+02	1.37E+12 [c]	4.75	$347.00
	Sum of purchased inputs			**27.48**	**$2,005.99**
PRODUCTION, J					
19	**Lamb, J**	**5.17E+09**			

RENEWABLE RESOURCES (R): (notes 1-5) renewable resource based on identical calculations as for the farm analysis substituting 1.82E+04 m^2 as the land area. **(6)** ***Hay (renewable portion)****:* 20% of hay yield is fed to sheep, and 60% of hay emergy is renewable = 3.55E+11 J x 0.20 x 0.60 = 4.26E+10 J **NONRENEWABLE STORAGES (N): (7)** ***Net topsoil loss***: based on identical calculations as for hay using 1.18E+05 m^2 as the land area. **PURCHASED INPUTS (P): (8)** ***Hay (non-renewable portion)****:* 20% of hay yield is fed to sheep, and 40% of hay emergy is non-renewable (purchased) = 3.55E+11 J x 0.20 x 0.4 = 2.84E+10 J **(9)** ***Electricity***: energy use based on Gallagher M1500 fence charger = 120V x 0.2 Amp x 24 hr/day x 365 day/yr = 220.24 kWh/r x 3.6E+06 J/kWh x 0.10 (use for sheep) = 7.93E+07 J. **(10)** ***Batteries***: Total yearly contribution from batteries g, lead = 100 lbs. x .454 kg/lb x 1000 g/kg = 45,400 g x 0.2 (5 year depreciation rate) = 9080 g. **(11)** ***Wood posts***: energy contribution of posts = 6 posts x 13630 g/post x 3.6 kcal/g x 4186 J/kcal = 1.23E+09 J. Yearly contribution = 1.23E+09 J x 0.067 (15 year depreciation rate, as decimal) = 8.22E+07 J. **(12)** ***Ironwood posts***: 13 posts x 966 g, wood/post = 12,558 g, total. Yearly contribution = 12,558 g x 0.067 (15 year depreciation rate) = 8.37E+02 g, wood. **(13)** ***Electric wire***: 2608 ft x 11.4 g/ft = 29,731 g, galv. steel. Yearly contribution = 29,731 g x 0.067 (15 year depreciation rate) = 1.98E+03 g, galv. steel. **(14)** ***Insulators, ceramic***: 20 insulators x 106 g/insulator = 2,120 g, ceramic. Yearly contribution = 2,120 g x 0.067 (15 year depreciation rate) = 1.41E+02 g, ceramic. **(15)** ***Plastic***: 5 temporary fences x 5000 g/insulator = 25,000 g. Yearly contribution = 25,000 g x 0.067 (15 year depreciation rate) = 5.00E+03g, plastic. **(16)** ***Mineral salt***: 1 bag x 22,500 g/bag = 22,500 g, minerals. **SERVICES and LABOR (S): (17)** ***Labor***: total person-hours for management = 182.5 hours. Energy contribution of labor = (182.5 person-hours x 3500 kcal/day x 4186 J/kcal) / 8 person-hours/day = 3.34E+08 J. **(18*****)*** ***Services***: purchased services for cattle (slaughter fees, mineral blocks, fencing repair, respective portions of machinery and fencing infrastructure) = $347.00 USD. (**24**) ***Lamb production***: energy in meat = 720 lbs (hanging weight) x 453.6 g/lb x 3.78 kcal/g (based on wet weight, from Holland et al., 1993) x 4186 J/kcal = 5.17E+09 J.

Pork Production

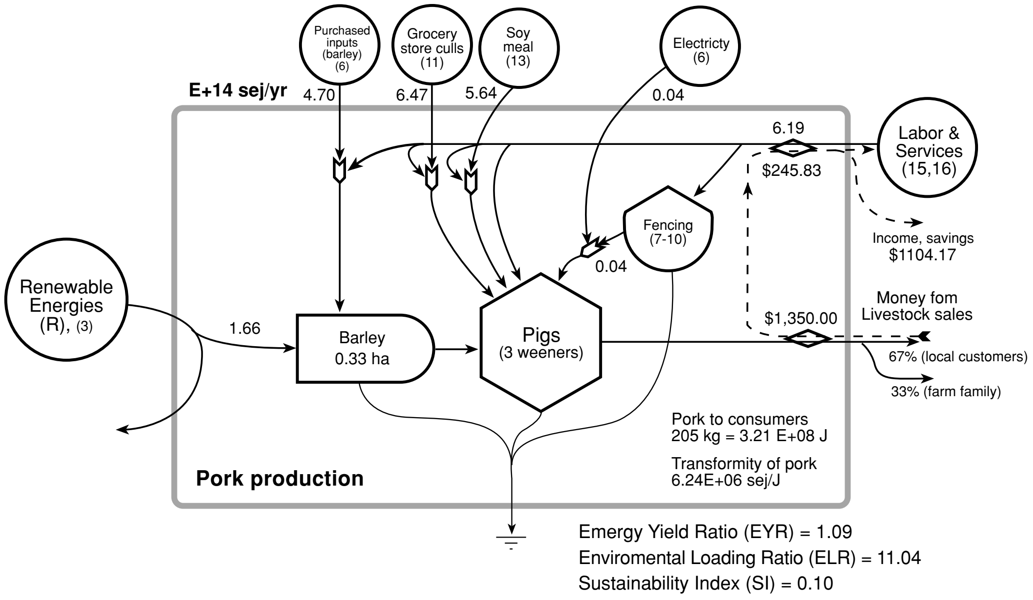


Figure 10. Energy systems diagram of pork production.

The pigs at the S&S Homestead farm are bought as piglets and raised on the farm in a 120 m^2 pen where they are fed barley grown on the farm, purchased soy meal, as well as fruits and vegetables brought to the farm as culls from the local grocery store. The pigs are kept for 120 days and then they are slaughtered and sold to local customers, with one pig being kept by the farm family. Figure 10 is an energy systems diagram of pork production and Table 7 is its corresponding emergy evaluation table.

Table 7. Emergy evaluation of pork production.

Note	Item, unit	Data (units/yr)	Transformity* (sej/unit)	EMERGY (E14 sej/yr)	EmDollars (1993 USD)
RENEWABLE RESOURCES (R)					
1	Sun, J	6.05E+11	1[a]	0.17	$12.60
2	Wind, J	9.09E+05	1.50E+03[a]	0.00	$0.03
3	Rain, chemical energy, J	3.21E+08	1.82E+04[a]	1.66	$121.47
4	Rain, geopotential, J	4.48E+05	2.79E+04[a]	0.00	$0.26
5	Earth Cycle, J	1.20E+08	2.90E+04[a]	0.03	$72.39
	Sum of largest renewable inputs (rain) + hay			**1.66**	$121.47
PURCHASED INPUTS (P)					
6	Purchased inputs for barley	5.10E+09	9.22E+04	4.70	$343.11
7	Electricity, J	2.38E+07	1.60E+05[a]	0.04	$2.78
8	Wood posts (fencing), J	6.85E+07	3.49E+04[I]	0.02	$1.74
9	Ironwood posts (fencing), g	2.58E+02	3.90E+08[a]	0.00	$0.07
10	Electric wire, galvanized steel (fencing), g	4.92E+02	3.20E+09[d]	0.02	$1.15
11	Insulators, ceramic (fencing), g	5.65E+01	1.00E+09[a]	0.00	$0.04
12	Grocery store culls , g	1.03E+05	6.31E+09[b]	6.47	$472.56
13	Soy meal, J	1.77E+09	3.32E+05[b]	5.64	$411.50
SERVICES and LABOR (S)					
14	Labor, J	1.10E+08	2.56E+06[g]	2.82	$205.48
15	Services, USD	2.46E+02	1.37E+12[c]	3.37	$245.83
	Sum of purchased inputs			**18.37**	**$1,341.16**
PRODUCTION, J					
16	**Pork, J=**	**3.21E+08**			

RENEWABLE RESOURCES (R): (notes 1-5) renewable resource data based on identical calculations as for the farm analysis substituting 3.30E+03 m^2 as the land area (pig pen and 36% of area used for barley). **PURCHASED INPUTS (P): (6)** ***Purchased input for barley:*** 1.86E+10 J (total energy in barley) x 0.36 (% used for pigs) x 0.75 (% purchased inputs) = 5.10E+09 J **(7)** ***Electricity***: energy use based on Gallagher M1500 fence charger = 120V x 0.2 Amp x 24 hr/day x 121 day/yr = 6.61 kWh/r x 3.6E+06 J/kWh x 0.10 (use for sheep) = 2.38E+07 J. **(8)** ***Wood posts***: energy contribution of posts = 5 posts x 13630 g/post x 3.6 kcal/g x 4186 J/kcal = 1.03E+09 J. Yearly contribution = 1.03E+09 J x 0.067 (15 year depreciation rate, as decimal) = 6.85E+07 J. **(9)** ***Ironwood posts***: 4 posts x 966 g, wood/post = 3,864 g, total. Yearly contribution = 3,864 g x 0.067 (15 year depreciation rate) = 2.58E+02 g, wood. **(10)** ***Electric wire***: 648 ft x 11.4 g/ft = 7,387 g, galv. steel. Yearly contribution = 7,387 g x 0.067 (15 year depreciation rate) = 4.92E+02 g, galv. steel. **(11)** ***Insulators, ceramic***: 8 insulators x 106 g/insulator = 848 g, ceramic. Yearly contribution = 848 g x 0.067 (15 year depreciation rate) = 57 g, ceramic. **(12)** ***Grocery store culls***: 120 buckets x 20 lb/bucket x 0.45 kg/lb x 0.095% dry matter = 1.03E+05 g, culls (DM, based on average of oranges, pepper, cabbage, tomatoes, data from USDA, 2002) transformity for culls average of tomatoes, peppers, cabbage and oranges (from Brandt-Williams, 2001) **(13)** ***Soy meal***: 2.2 lb/day x 120 days x 453.6 g/lb x 14180 J/g = 1.70E+09 J. **SERVICES and LABOR (S): (14)** ***Labor***: total person-hours for management = 60 hours. Energy contribution of labor = (60 person-hours x 3500 kcal/day x 4186 J/kcal) / 8 person-hours/day = 1.10E+08 J. **(15*)*** ***Services***: purchased services for pigs (slaughter fees, fencing infrastructure) = $245.83 USD. (**16)** ***Pork production***: energy in meat = 450 lbs (hanging weight) x 453.6 g/lb x 1.573 kJ/g (based on USDA, 2002) x 1000 J/kJ = 3.21E+08 J.

Vegetable Production

The vegetables produced on the farm are cultivated using the bio-intensive method, based on the techniques developed by Jeavons (1995). The beds outlined are all double-dug and raised 4-6 inches above the soil surface to facilitate drainage and to improve aeration and root penetration. All labor is done by hand and purchased fertility is kept to a minimum. The analysis shows that the small area used by the garden and the high degree of labor involved lower the sustainability of the garden in emergy terms. However, other factors influence the garden's design such as securing a source of fresh food year-round, and maintaining a high crop diversity. The garden is not intended, nor designed, to yield net emergy. Figure 11 is an energy systems diagram of vegetable production and table 8 is a corresponding emergy evaluation table.

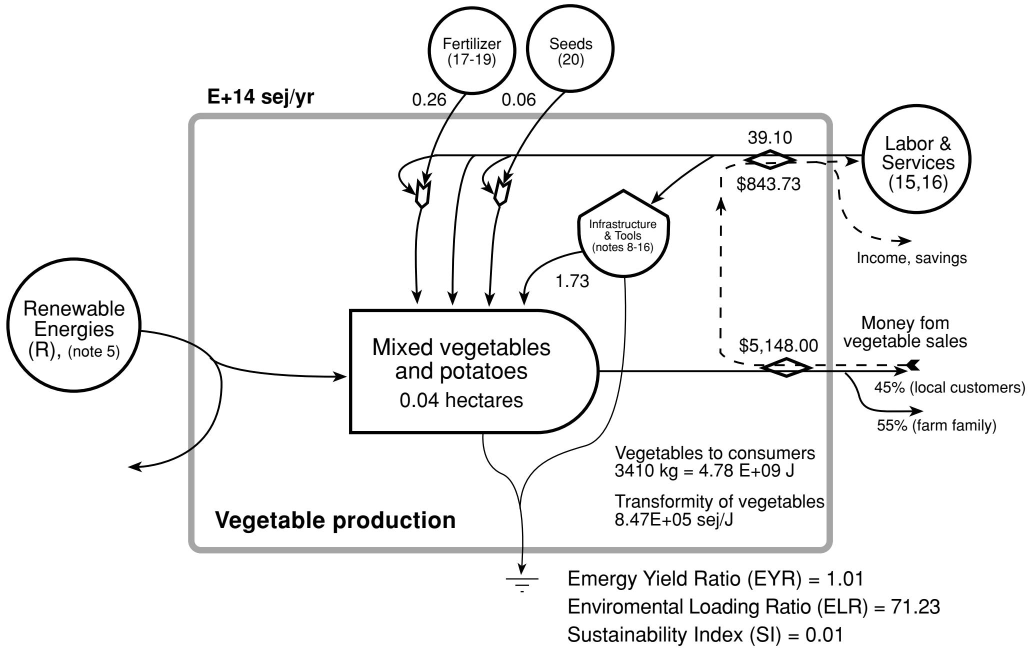


Figure 11. Energy systems diagram of vegetable production.

Table 8. Emergy evaluation of vegetable production.

Note	Item, unit	Data (units/yr)	Transformity* (sej/unit)	EMERGY (E14 sej/yr)	EmDollars (1993 USD)
RENEWABLE RESOURCES (R)					
1	Sun, J	1.86E+12	1 [a]	0.02	$1.36
2	Wind, J	2.79E+06	1.50E+03 [a]	0.00	$0.00
3	Rain, evapotranspiration, J	9.85E+08	1.82E+04 [a]	0.18	$13.08
4	Rain, geopotential, J	1.38E+06	2.79E+04 [a]	0.00	$0.03
5	Groundwater, J	1.41E+09	4.10E+04 [d]	0.58	$42.17
6	Earth cycle, J	3.68E+08	2.90E+04 [a]	0.11	$7.80
	Largest renewable input (groundwater)			**0.58**	**$42.17**
PURCHASED INPUTS (P)					
8	Wood posts (fencing), J	1.78E+08	3.49E+04 [I]	0.06	$4.53
9	Iron posts (fencing), g	6.27E+03	3.20E+09 [d]	0.20	$14.65
10	Welded wire, galvanized steel (fencing), g	1.27E+04	3.20E+09 [d]	0.41	$29.74
11	Plastic glazing (greenhouse), g	6.73E+03	3.80E+08 [d]	0.03	$1.87
12	Wood (greenhouse), J	4.58E+08	3.49E+04 [I]	0.16	$11.67
13	Wood, (garden beds), J	1.37E+08	3.49E+04 [I]	0.05	$3.49
14	Plastic (potting supplies), g	1.52E+03	3.80E+08 [d]	0.01	$0.42
15	Tools, wood, J	3.32E+08	3.49E+04 [I]	0.12	$8.45
16	Tools, steel, g	2.20E+04	3.20E+09 [d]	0.70	$51.39
17	Potash, g K	7.13E+02	1.10E+09 [a]	0.01	$0.57
18	Phosphate, g P	1.08E+03	1.78E+10 [a]	0.19	$13.99
19	Nitrogen, g N	1.64E+03	3.80E+09 [a]	0.06	$4.56
20	Seeds, J	1.81E+08	3.48E+04 [d]	0.06	$4.60

Table 8 continued.

SERVICES and LABOR (S)					
21	Labor, J	1.08E+09	2.56E+06 [g]	27.66	$2,019.06
22	Services, USD	$834.73	1.37E+12 [c]	11.44	$834.73
	Sum of purchased inputs			**41.15**	**$3,003.72**
PRODUCTION, J					
23	**Vegetable production, J**	**4.78E+09**			

RENEWABLE RESOURCES (R): (notes 1-4) based on identical calculations as for the farm analysis substituting 3.68E+02 m^2 as the land area. **(5)** ***Groundwater**:* 75300 gal./yr x .00379 m^3/gal x 1E6 g/m^3 x 4.94 J/g = 1.41E+09 **(6)** ***Earth cycle***: based on identical calculations as for hay using 3.68E+02 m^2 as the land area. **PURCHASED INPUTS (P): (8)** ***Wood posts***: energy contribution of posts = 13 posts x 13,630 g/post x 3.6 kcal/g x 4186 J/kcal = 2.67E+09 J. Yearly contribution = 2.67E+09 J x 0.067 (15 year depreciation rate, as decimal) = 1.78E+08 J. **(9)** ***Iron posts***: 23 posts x 4090 g, iron/post = 94,070 g, total. Yearly contribution = 94,070 g x 0.067 (15 year depreciation rate) = 6.27E+03 g, iron. **(10)** ***Welded wire***: 368 ft x 519 g/ft = 109,992 g, galv. steel. Yearly contribution = 109,992 g x 0.067 (15 year depreciation rate) = 1.27E+04 g, galv. steel. **(11)** ***Plastic glazing***: 500 ft^2 x 202 g/ ft^2 = 101,000 g, plastic. Yearly contribution = 101,000 g x 0.067 (15 year depreciation rate) = 6.73E+03 g, plastic. **(12)** ***Wood (greenhouse)***: 0.95 m^3 x 480000 g/m^3 (Tsoumis, 1991) = 456,000 g x 3.6 kcal/g x 4186 J/kcal. Yearly contribution = 456,000 g x 0.067 (15 year depreciation rate) = 4.58E+08 J. **(13)** ***Wood (garden beds)***: 90,909 g x 3.6 kcal/g x 4186 J/kcal = 1,369,963,636 J. Yearly contribution = 1,369,963,636 g x 0.1 (10 year depreciation rate) = 1.37E+08 J. **(14)** ***Plastic (potting supplies)***: 50 lbs x 453.6 g/lb = 22,727 g. Yearly contribution = 22,727 g x 0.067 (15 year depreciation rate) = 1,515,15 g. **(15)** ***Tools, wood***: 220,000 g x 3.6 kcal/g x 4186 J/kcal = 3,315,312,000 J. Yearly contribution = 3,315,312,000 g x 0.1 (10 year depreciation rate) = 3.32E+08 J. **(16)** ***Tools, steel***: 220,000 g x 0.1 (10 year depreciation rate) = 2.20E+04 g. **(17)** ***Potash***: 7.57 kg, fish emulsion x 0.01 (% K, as decimal) + 9.1 kg, greensand x 0.07 (% K, as decimal) x 1000 g/kg = 712.7 g, K. **(18)** ***Phosphate***: 7.57 kg, fish emulsion x 0.01 (% P, as decimal) + 9.1 kg, bonemeal x 0.11 (% P, as decimal) x 1000 g/kg = 1,076.7 g, P. **(19)** ***Nitrogen***: 11.36 kg, bloodmeal x 0.11 (% N, as decimal) + 9.1 kg, bonemeal x 0.01 (% N, as decimal) + 7.57 kg, fish emulsion x 0.04 (% N, as decimal) x 1000 g/kg = 1,643.4 g, N. **(20)** ***Seeds***: 25 lbs., seeds x 0.88 (% DM, as decimal x 453.6 g/lb x 4.337 kcal/g x 4186 J/kcal = 181,169,202.61 J. **SERVICES and LABOR (S): (21)** ***Labor***: total person-hours for management = 182.5 hours. Energy contribution of labor = (590 person-hours x 3500 kcal/day x 4186 J/kcal) / 8 person-hours/day = 1.08E+09 J. **(22*)*** ***Services***: purchased services for vegetables (seeds, tools, ammendments, etc.) + yearly contribution of services for infrastructure (fencing, lumber, etc.) = $834.73 USD. **(23)** ***Vegetable production***: energy in vegetables = 3.09E+06 g x 0.29 kcal/g (from average of lettuce, broccoli, cauliflower, squash, carrots, kale, cabbage, from USDA, 2002) x 4186 J/kcal = 3.75E+09 J. Energy in potatoes = 3.18E+05 g x 0.77 kcal/g x 4186 J/kcal = 1.02E+09 J. Total production = 4.78E+09 J

Barley Production

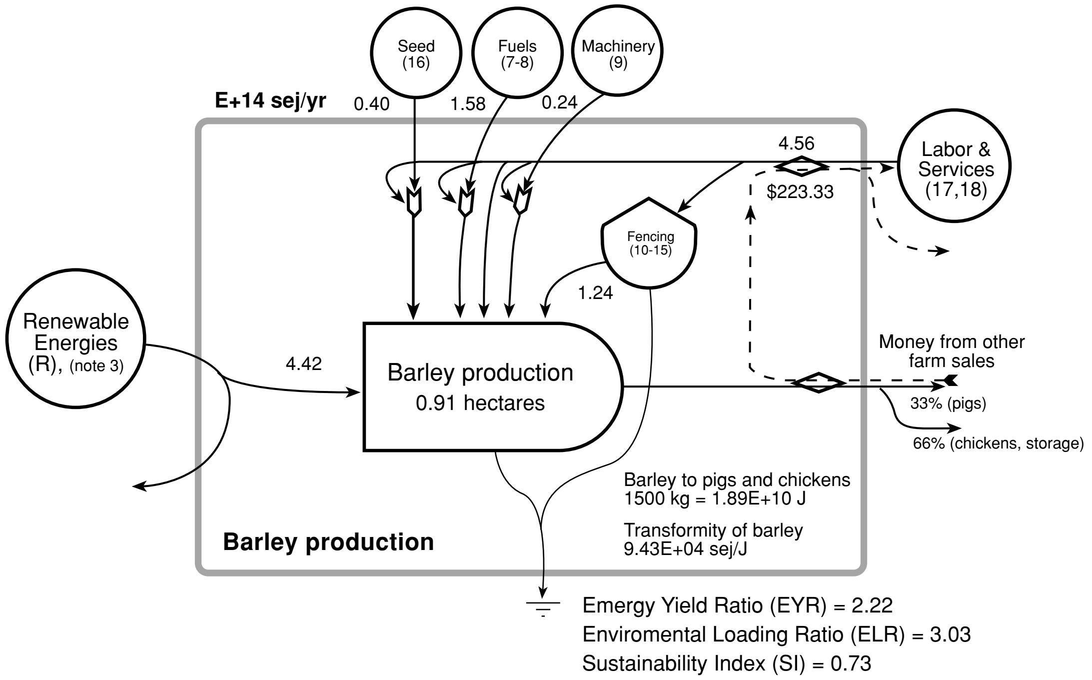


Figure 12. Energy systems diagram of barley production.

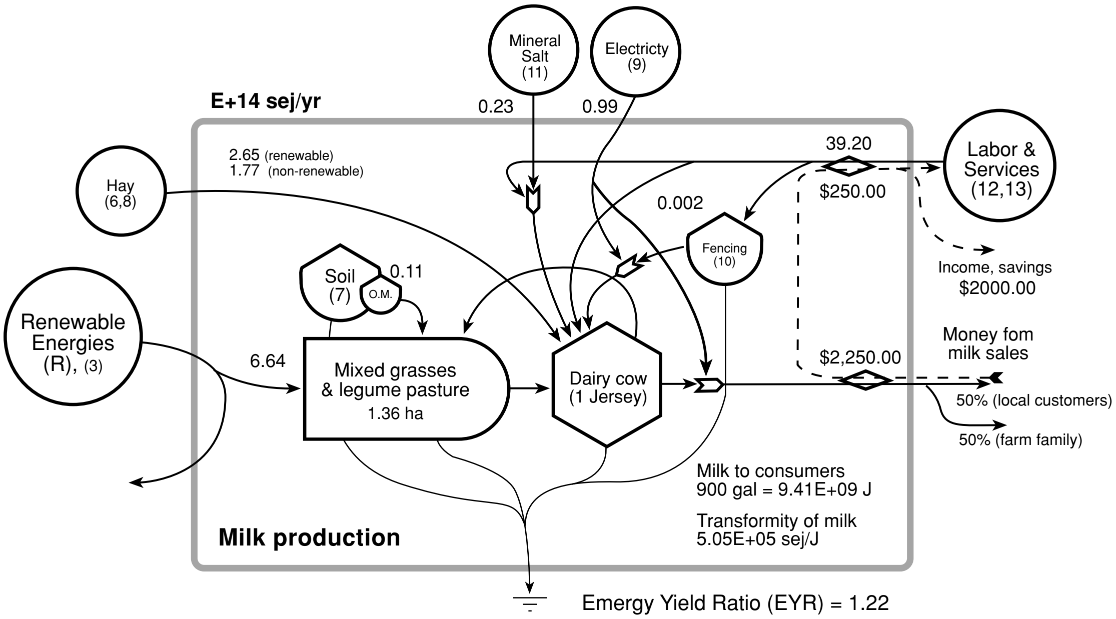
Barley is the grain crop produced on the farm and is grown for the purpose of providing feed for chickens and pigs, and to provide straw for the animal stalls during winter. The grain was planted by hand and tilled-in using a rotovator. The harvest was hired out to a local farmer, registered as a purchased service. Figure 12 is an energy systems diagram of barley production and table 9 is the corresponding table.

Table 9. Emergy evaluation of barley production.

Note	Item, unit	Data (units/yr)	Transformity* (sej/unit)	EMERGY (E14 sej/yr)	EmDollars (1993 USD)
RENEWABLE RESOURCES (R)					
1	Sun, J	4.59E+13	1[a]	0.46	$33.48
2	Wind, J	9.64E+07	1.50E+03[a]	0.00	$0.11
3	Rain, evapotranspiration, J	2.43E+10	1.82E+04[a]	4.42	$322.88
4	Rain, geopotential, J	3.40E+07	2.79E+04[a]	0.01	$0.69
5	Earth cycle, J	9.09E+09	2.90E+04[a]	2.64	$192.44
	Largest of the renewable inputs (rain)			**4.42**	$322.88
NONRENEWABLE STORAGES (N)					
6	Net topsoil loss, J	7.27E+09	7.38E+04[a]	5.37	$391.70
	Sum of free inputs			**9.79**	**$714.58**
PURCHASED INPUTS (P)					
7	Diesel, J	2.32E+09	6.60E+04[a]	1.53	$111.86
8	Lubricants, J	7.74E+07	6.60E+04[a]	0.05	$3.73
9	Machinery, g	5.83E+03	4.10E+09[h]	0.24	$17.46
10	Wood posts (fencing), J	5.07E+08	3.49E+04[I]	0.18	$12.91
11	Iron posts (fencing), g	2.10E+04	3.20E+09[d]	0.67	$49.04
12	Barb wire, galvinized steel (fencing), g	1.11E+04	3.20E+09[d]	0.35	$25.90
13	Electric wire, galvinized steel (fencing), g	1.06E+03	3.20E+09[d]	0.03	$2.47
14	Insulators, ceramic (fencing), g	5.65E+01	2.00E+09[a]	0.00	$0.08
15	Insulators, plastic (fencing), g	3.04E+01	3.80E+08[d]	0.00	$0.01
16	Seed, J	1.14E+09	3.48E+04[d]	0.40	$29.07
SERVICES and LABOR (S)					
17	Labor, J	5.86E+07	2.56E+06[g]	1.50	$109.59
18	Services, USD	$223.33	1.37E+12[c]	3.06	$223.33
	Sum of purchased inputs			**8.02**	**$585.44**
PRODUCTION, J					
19	**Barley production, J**	**1.89E+10**			

RENEWABLE RESOURCES (R): (notes 1-5) renewable resource data based on identical calculations as for the farm analysis substituting 9.09E+03 m^2 as the land area. **NONRENEWABLE STORAGES (N): (6)** ***Net topsoil loss***: based on erosion rates calculated with the Revised Universal Soil Loss Equation (RUSLE) (erosion rate = R*K*LS*C*P), using estimates from (Brady & Weil, 2000, pp.482-88). Erosion rate calculated as 40*17.02 (factor R) * 0.063 (factor K) * 0.75 (factor LS) * 0.022 (factor C) * 1.0 (factor P) * 1000000 g/Mg = 7,076,916 g/ha/yr. Net loss of topsoil = 7,076,916 g/ha/yr * 0.91 ha (farmed area) = 1.01E+06 g/yr. Loss of organic matter = 1.01E+06 g (topsoil loss) x 0.05% (organic matter) = 6.43E+06 g, organic matter/yr. Energy loss = 6.43E+06 g, (org. matter) x 5.4 kcal/g (Odum, 1996) x 4186 [J/kcal] = 7.27E+09 J/yr. **PURCHASED INPUTS (P): (7)** ***Diesel***: estimated 60 liters used to till and plant. Energy content = 60 l x 3.87E+07 J/l (U.S. Department of Energy, 2000) = 2.32E+09 J. **(8)** ***Lubricants***: estimated 2 liters used. Energy content = 2 l x 3.87E+07 J/l (U.S. Department of Energy, 2000) = 7.74E+07 J. **(9)** ***Machinery***: Tractor, John Deere 770 (20 hp) = 8.75E+02 kg steel x 0.10 (use factor, portion used for haymaking) = 87.5 kg, steel x 0.0667 (15 year depreciation rate) = 5,833.33 g. **(10)** ***Wood posts***: energy contribution of posts = 37 posts x 13630 g/post x 3.6 kcal/g x 4186 J/kcal = 7,599,749,976 J. Yearly contribution = 7,599,749,976 J x 0.067 (15 year depreciation rate, as decimal) = 5.06E+08 J. **(11)** ***Iron posts***: 77 posts x 4090 g/post = 314,930 g, total. Yearly contribution = 314,930 g x 0.067 (15 year depreciation rate) = 2.10E+04 g, iron. **(12)** ***Barbed wire***: 4,210 ft x 39.5 g/ft = 166,295 g, galvanized steel. Yearly contribution = 166,295 g x 0.067 (15 year depreciation rate) = 1.11E+04 g, galvanized steel. **(13)** ***Electric wire***: 1390 ft x 11.4 g/ft = 15,846 g, galv. steel. Yearly contribution = 15,846 g x 0.067 (15 year depreciation rate) = 1.06E+03 g, galv. steel. **(14)** ***Insulators, ceramic***: 8 insulators x 106 g/insulator = 848 g, ceramic. Yearly contribution = 848 g x 0.067 (15 year depreciation rate) = 57 g, ceramic. **(15)** ***Plastic***: 24 insulators x 19 g/insulator = 456 g. Yearly contribution = 456 g x 0.067 (15 year depreciation rate) = 30 g, plastic. **(16)** ***Seed***: 9.09E+04 g x 0.85% DM x 1.48E+04 J/g = 1.14E+09 J. **SERVICES and LABOR (S): (17)** ***Labor***: total person-hours for management = 32 hours. Energy contribution of labor = (32 person-hours x 3500 kcal/day x 4186 J/kcal) / 8 person-hours/day = 5.86E+07 J. **(18*) Services***: purchased services for harvest and implement rental, machinery depreciation = $223.33 USD. (**19)** ***Barley***: energy in barley = 1,500,000 g x 0.85 %DM x 1.48E+04 J/g = 1.89E+10 J.

Milk Production



Emergy Yield Ratio (EYR) = 1.22
Enviromental Loading Ratio (ELR) = 4.58
Sustainability Index (SI) = 0.27

Figure 13. Energy systems diagram of milk production.

The farm has one milk cow that is milked twice a day, everyday. The cow is free to forage on approximately 1.36 ha of mixed grass and legume pasture and is fed hay during the late summer and winter. The primary emergy inputs come from human labor, as the milking is done by hand. Figure 12 is an energy systems diagram of milk production and table 10 is the corresponding table.

Table 10. Emergy evaluation of milk production.

Note	Item, unit	Data (units/yr)	Transformity[ref.] (sej/unit)	EMERGY (E14 sej/yr)	EmDollars (1993 USD)
RENEWABLE RESOURCES (R)					
1	Sun, J	6.88E+13	1 [a]	0.69	$50.22
2	Wind, J	1.45E+08	1.50E+03 [a]	0.00	$0.16
3	Rain, evapotranspiration, J	3.65E+10	1.82E+04 [a]	6.64	$484.32
4	Rain, geopotential, J	5.09E+07	2.79E+04 [a]	0.01	$1.04
5	Earth Cycle, J	1.36E+10	2.90E+04 [a]	3.95	$288.65
6	Hay, J (renewable emergy)	1.06E+10	2.49E+04 [g]	2.65	$193.29
	Sum of renewable inputs (rain) + hay			**9.28**	$677.62
NONRENEWABLE STORAGES (N)					
7	Net Topsoil Loss	1.49E+08	7.38E+04 [a]	0.11	$8.01
	Sum of free inputs			**9.39**	**$685.63**
PURCHASED INPUTS (P)					
8	Hay, J (purchased emergy)	7.09E+09	2.49E+04 [g]	1.77	$128.86
9	Electricity, J	6.19E+08	1.60E+05 [a]	0.99	$72.33
10	Plastic (fencing), g	4.55E+02	3.80E+08 [d]	0.00	$0.13
11	Mineral salt blocks, g	4.50E+04	1.00E+09 [a]	0.45	$32.85
SERVICES and LABOR (S)					
12	Labor, J	1.40E+09	2.56E+06 [g]	35.77	$2,611.30
13	Services, $/yr	2.50E+02	1.37E+12 [c]	3.43	$250.00
	Sum of purchased inputs			**42.41**	**$3,095.46**
PRODUCTION, J					
14	**Milk, J**	**9.41E+09**			

RENEWABLE RESOURCES (R): (notes 1-5) renewable resource data based on identical calculations as for the farm analysis substituting 1.36E+04 m^2 as the land area. **(6)** ***Hay (renewable portion)****:* 5% of hay yield is fed to the dairy cow, and 60% of hay emergy is renewable = 3.55E+11 J x 0.05 x 0.60 = 1.06E+10 J **NONRENEWABLE STORAGES (N): (7)** ***Net topsoil loss***: based on identical calculations as for cattle using 1.36E+04 m^2 as the land area. **PURCHASED INPUTS (P): (8)** ***Hay (non-renewable portion)****:* 20% of hay yield is fed to sheep, and 40% of hay emergy is non-renewable (purchased) = 3.55E+11 J x 0.20 x 0.4 = 2.84E+10 J **(9)** ***Electricity***: energy use based on stove burner (for bottle prep) = 1 kW x .5 hrs/day x 300 x 3.6E6 J/kWh = 5.40E+08 J. Electric fencing = energy use based on Gallagher M1500 fence charger = 120V x 0.2 Amp x 24 hr/day x 365 day/yr = 220.24 kWh/r * 3.6E+06 J/kWh * .10 (use factor %, as decimal) = 6.19E+08 J**.** Total energy used = **(10)** ***Plastic***: 2 electro-tape fences x 3410 g/each = 6,820 g. Yearly contribution = 6,820 g x 0.067 (15 year depreciation rate) = 4.55E+02 g, plastic. **(11)** ***Mineral salt blocks***,g: 2 blocks x 50 lb/block x 0.45 kg/lb = 45 kg x 1000 g/kg = 45,000 g, minerals. **SERVICES and LABOR (S): (12)** ***Labor***: total person-hours for management = 762.5 hours. Energy contribution of labor = (762.5 person-hours x 3500 kcal/day x 4186 J/kcal) / 8 person-hours/day = 1.40E+09 J. **(13*****) Services***: purchased services for dairy cow (bottles, filters, soap) = $250.00 USD. **(14)** ***Milk production***: energy in milk = 1000 gallons x 2615.7 kJ/qt x 4 qt/gal x 1000 kJ/J = 9.41E+09 J.

Egg Production

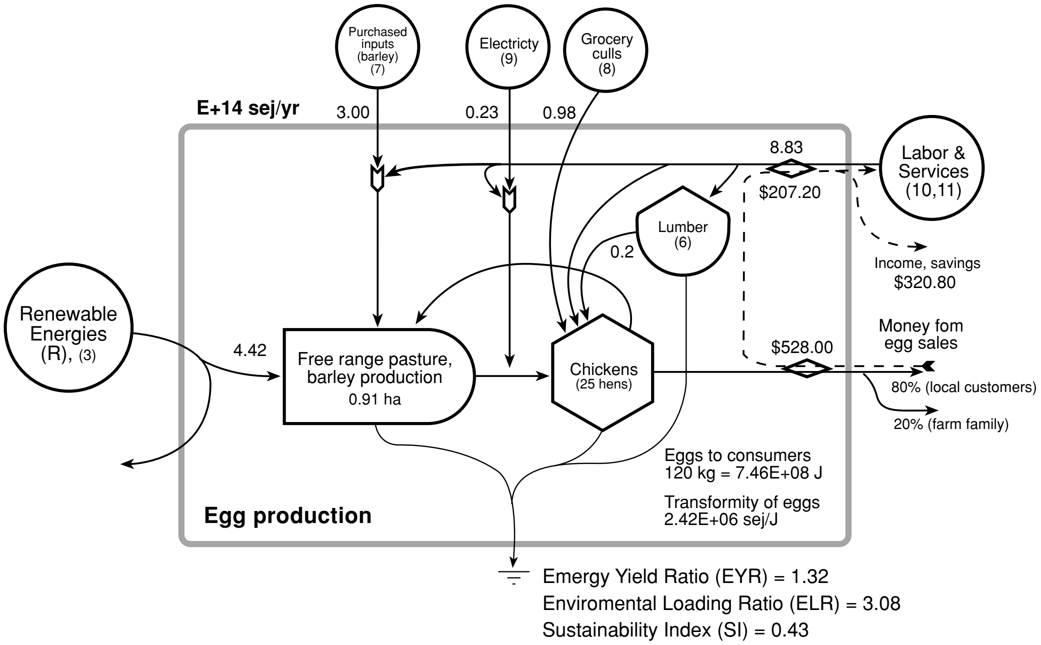


Figure 14. Energy systems diagram of egg production.

Egg production is based on 25 laying hens that are allowed to range freely around the farm. The estimated range area is 0.91 ha. Figure 13 is an energy systems diagram of egg production and table 11 is the correspoding table.

Table 11. Emergy evaluation of egg production.

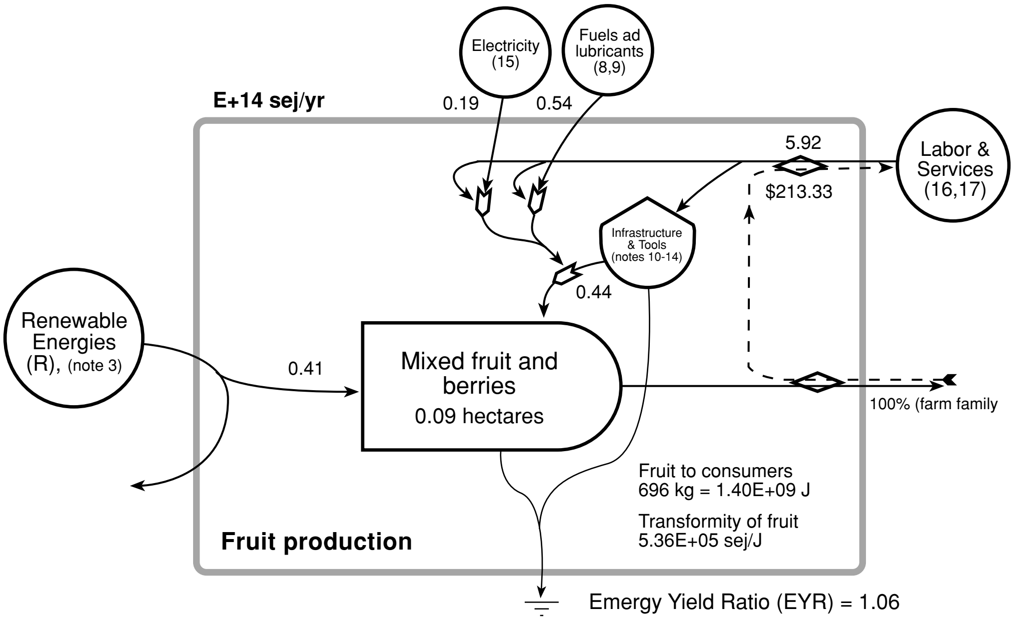
Note	Item, unit	Data (units/yr)	Transformity[ref.] (sej/unit)	EMERGY (E14 sej/yr)	EmDollars (1993 USD)
RENEWABLE RESOURCES (R)					
1	Sun, J	4.59E+13	1[a]	0.46	$33.48
2	Wind, J	6.89E+07	1.50E+03[a]	0.00	$0.08
3	Rain, evapotranspiration, J	2.43E+10	1.82E+04[a]	4.42	$322.89
4	Rain, geopotential, J	3.40E+07	2.79E+04[a]	0.01	$0.69
5	Earth Cycle, J	9.09E+09	2.90E+04[a]	2.64	$192.44
	Largest renewable input (rain)			**4.42**	**$322.89**
PURCHASED INPUTS (P)					
6	Lumber, J	5.79E+08	3.49E+04[I]	0.20	$14.74
7	Grocery store culls , g	1.56E+04	6.31E+09[b]	0.98	$71.87
8	Barley (purchased inputs), J	3.26E+09	9.22E+04[g]	3.00	$219.21
9	Electricity, J	3.90E+08	1.60E+05[a]	0.62	$45.54

Table 11 continued.

SERVICES and LABOR (S)					
10	Labor, J	2.34E+08	2.56E+06 [g]	5.99	$437.50
11	Services, $/yr	2.07E+02	1.37E+12 [c]	2.84	$207.20
	Sum of purchased inputs			**13.65**	**$996.06**
PRODUCTION, J					
12	**Egg production, J**	**7.46E+08**			
13	**Stew hens production, J**	**8.81E+08**			

RENEWABLE RESOURCES (R): (notes 1-5) renewable resource data based on identical calculations as for the farm analysis substituting 9.09E+03 m^2 as the land area. **PURCHASED INPUTS (P): (6)** ***Lumber****:* energy in lumber = 1.2 m^2 x 4.80E+05 g/m^3 (Tsoumis, 1991) x 576,000 g x 3.6 kcal/g x 4186 J/kcal x 0.67 (depreciation rate, as decimal) = 5.79E+08 J **(7)** ***Grocery store culls***: 365 buckets x 1 lb/bucket x 0.45 kg/lb x 0.095% dry matter = 1.56E+04 g, culls (DM, based on average of oranges, pepper, cabbage, tomatoes, data from USDA, 2002) **(8)** ***Barley (purchased imputs)***: 1.89E+10 J x 0.23 (%, as decimal of barley production) x 0.75 (% of barley production that is purchased) = 3.26E+09 J. **(9)** ***Electricty***: 4.32 kWh/yr (light bulb) x 3.6E6 J/kWh + 1 kWh/stove burner x 2 hrs/wk x 52 wks/yr x 3.6E6 = 3.90E+08 J. **SERVICES and LABOR (S): (10)** ***Labor***: total person-hours for management = 127.75 hours. Energy contribution of labor = (127.75 person-hours x 3500 kcal/day x 4186 J/kcal) / 8 person-hours/day = 2.34E+08 J. **(11*)*** ***Services***: yearly expenditures, $126.00 + infrastructure costs, $81.20 = $207.20 USD. **(12, 13)** ***Egg production***: energy in eggs = 1.20E+05 g x 6.23 kJ/g x 1000 kJ/J = 7.46E+08 J. Energy in stew hens = 8.16E+04 g x 10.8 kj/g x 1000 J/kJ = 8.81E+08 J.

Fruit and Berry Production



Emergy Yield Ratio (EYR) = 1.06
Enviromental Loading Ratio (ELR) = 16.64
Sustainability Index (SI) = 0.06

Figure 15. Energy systems diagram of fruit and berry production.

The fruits and berries grown on the farm are grown for home consumption only. The orchard contains apple, plum and cherry trees as well as blueberries, strawberries and currents. Some vegetables are also grown in the orchard, but their total quantities are small compared to the main vegetable garden and thus only fruit and berries where accounted for in this evaluation. The grass in the orchard is mowed a few times during the summer months and this accounts for the fuel and machinery used in the fruit production. Otherwise, all other labor is done by hand. Figure 14 is an energy systems diagram of fruit production and table 12 is the corresponding table.

Table 12. Emergy evaluation of fruit and berry production.

Note	Item, unit	Data (units/yr)	Transformity[ref.] (sej/unit)	EMERGY (E14 sej/yr)	EmDollars (1993 USD)
RENEWABLE RESOURCES (R)					
1	Sun, J	4.30E+12	1[a]	0.04	$3.14
2	Wind, J	9.03E+06	1.50E+03[a]	0.00	$0.01
3	Rain, evapotranspiration, J	2.28E+09	1.82E+04[a]	0.41	$30.26
4	Rain, geopotential, J	3.18E+06	2.79E+04[a]	0.00	$0.06
5	Earth Cycle, J	8.52E+08	2.90E+04[a]	0.25	$18.04
6	Groundwater	4.68E+08	4.10E+04[d]	0.19	$14.00
	Sum of largest renewable inputs (rain)			**0.41**	**$30.26**
PURCHASED INPUTS (P)					
7	Machinery, g steel	3.00E+03	4.10E+09[h]	0.12	$8.98
8	Lubricants, J	3.87E+07	6.60E+04[a]	0.03	$1.86
9	Gasoline, J	7.74E+08	6.60E+04[a]	0.51	$37.29
10	Wood posts (fencing), J	6.30E+08	3.49E+04[I]	0.22	$16.05
11	Electric wire, galvanized steel (fencing), g	2.63E+03	3.20E+09[d]	0.08	$6.14
12	Insulators, ceramic (fencing), g	2.54E+02	1.00E+09[a]	0.00	$0.19
13	Plastic (fencing), g	2.57E+02	3.80E+08[d]	0.00	$0.07
14	Plastic (hoses), g	2.06E+03	3.80E+08[d]	0.01	$0.57
15	Electricity, J	1.19E+08	1.60E+05[a]	0.19	$13.89
SERVICES and LABOR (S)					
16	Labor, J	1.17E+08	2.56E+06[g]	3.00	$219.18
17	Services, $/yr	2.13E+02	1.37E+12[c]	2.92	$213.33
	Sum of purchased inputs			**5.93**	**$517.54**
CROP YIELD (Y1)					
18	**Fruit and Berries**	**1.40E+09**			

RENEWABLE RESOURCES (R): (notes 1-4) renewable resource data based on identical calculations as for hay production using 8.52E+02 m^2 as the land area. **(5)** ***Earth cycle***: based on identical calculations as for hay using 8.52E+02 m^2 as the land area. **(6)** ***Groundwater**:* 25000 gal./yr x .00379 m^3/gal x 1E6 g/m^3 x 4.94 J/g = 4.68E+08 J. **PURCHASED INPUTS (P): (7)** ***Machinery***: lawn mower = 30,000 g/steel. Yearly contribution = 30,000 g/steel x 0.1 (deprec. rate, as decimal) = 3.00E+03 g. Yearly contribution = 2.67E+09 J x 0.067 (15 year depreciation rate, as decimal) = 1.78E+08 J. **(8)** ***Lubricants***: estimated 1 liter used. Energy content = 1 liter x 3.87E+07 J/l (U.S. Department of Energy, 2000) = 3.87E+07 J. **(9)** ***Gasoline***: estimated 20 liters used. Energy content = 20 l x 3.87E+07 J/l (U.S. Department of Energy, 2000) = 7.74E+08 J. **(10)** ***Wood posts***: energy contribution of posts = 46 posts x 13630 g/post x 3.6 kcal/g x 4186 J/kcal = 9,448,337,808 J. Yearly contribution = 16,226,493,192 J x 0.067 (15 year depreciation rate, as decimal) = 6.30E+08 J. **(11)** ***Electric wire***: 3456 ft x 11.4 g/ft = 39,398 g, galv. steel. Yearly contribution = 39,398 g x 0.067 (15 year depreciation rate) = 2.63E+03 g, galv. steel. **(12)** ***Insulators, ceramic***: 36 insulators x 106 g/insulator = 3,816 g, ceramic. Yearly contribution = 3,816 g x 0.067 (15 year depreciation rate) = 2.54E+02 g, ceramic. **(13)** ***Plastic, insulators***: 203 insulators x 19 g/insulator = 3,857 g. Yearly contribution = 3,857 g x 0.067 (15 year depreciation rate) = 2.57E+02g, plastic. **(14)** ***Plastic, hoses***: 2 hoses x 9000 g/each = 18,000 g. Yearly contribution = 18,000 g x 0.067 (15 year depreciation rate) = 2.06E+03 g, plastic. **(15)** ***Electricity***: energy use based on Gallagher M1500 fence charger = 120V x 0.2 Amp x 24 hr/day x 365 day/yr = 220.24 kWh/r * 3.6E+06 J/kWh = 7.93E+08 J x 0.15 (portion used for orchard, given as decimal) = 1.19E+08 J. **SERVICES and LABOR (S): (16)** ***Labor***: total person-hours for management = 64 hours (watering, mowing, pruning, harvest). Energy contribution of labor = (64 person-hours x 3500 kcal/day x 4186 J/kcal) / 8 person-hours/day = 1.17E+08 J. **(17*****) Services***: purchased services for fuel + yearly contribution of services for infrastructure (fencing, lumber, etc.) = $213.33 USD. **(18)** ***Fruit and berry production***: energy in fruit and berries = 430,920 g apples, 113,400 g plums, 11,340 g cherries, 13,608 g grapes, 9,072 g peaches, 22,680 g melons, 22,680 g strawberries, 22,680 g currants, 4,536 g blueberries, 22,680 g raspberries, 22,680 g blackberries. 696,276 g x 2.01 kJ/g (from apples, plums, strawberries) = 1.40E+09 J.

Emergy-Based Ratios and Indices

In order to compare the results of the emergy evaluations of the farm and its subsystems, a number of emergy-based indices were calculated. The indicators reveal that those management areas that are highly dependent on purchased inputs and human labor and are spatially less extensive relative to the amount of feedback emergy receive the lowest sustainability ratings when compared to the areas of the farm that are spatially extensive and receive a larger portion of their total emergy requirements from the local

Table 13. Summary of emergy flows and emergy indices for the S&S Homestead Farm and subsystems.

Summary of emergy flows **All Quantities (E14 sej), unless otherwise noted**

Name of flow	**Farm**	**Hay (separate)**	**Cattle (w/hay)**	**Sheep (w/hay)**	**Grain**	**Eggs**	**Chickens**	**Dairy**	**Pork**	**Fruit**	**Vegetables**
Local renewable sources (R)	121.65	50.87	93.73	19.44	4.42	4.42	4.42	9.28	1.66	0.41	0.58
Local non-renewable sources (N)	2.01	0.84	0.95	0.15	5.37	0.00	0.00	0.11	0.00	0.00	0.00
Purchased resources (P)	65.96	14.43	39.67	14.17	3.06	4.81	4.81	3.21	12.19	0.97	2.05
Services and Labor (S)	318.23	22.13	47.12	13.32	4.56	8.83	8.83	39.20	6.18	5.93	39.12
Feedback from economy (F)	384.19	36.56	86.78	27.48	7.62	13.65	13.65	42.41	18.37	6.90	41.17
Emergy Yield (Y)	507.85	88.27	181.46	47.07	17.41	18.07	18.07	51.80	20.04	7.31	41.75
Emdollar value of Emergy Yield (Y)	$37,069	$6,443	$13,245	$3,436	$1,271	$1,319	$1,319	$3,781	$1,463	$533.91	$3,047
Money received (in actual $)	$18,473	$0	$8,221	$1,071	$0	$528	$0	$2,600	$905	$0.00	$5,148
Difference	$18,596	n/a	$5,024	$2,365	n/a	$791	$791	$791	$558	n/a	-$2,101
Name of Index, expression											
Emergy Yield (Y) = (R+N+F), sej/yr	5.08E+16	8.83E+15	1.81E+16	4.71E+15	1.74E+15	1.81E+15	1.81E+15	5.18E+15	2.00E+15	7.31E+14	4.17E+15
Emergy Investment Ratio (EIR) = (P+S)/(N+R)	3.20	0.71	0.92	1.40	0.78	3.08	3.08	4.51	11.04	17.10	71.27
Nonrenewable/Renewable (N+P)/R	0.56	0.30	0.43	0.74	1.91	1.09	1.09	0.36	7.33	2.35	3.56
Empower Density, sej/ha/yr	2.03E+15	8.44E+14	1.54E+15	2.59E+15	1.92E+15	1.99E+15	1.99E+15	3.80E+15	5.86E+15	8.59E+15	8.55E+16
Transformity (sej/j) = (N+R+P+S)/energy of (Y)	7.78E+05	1.46E+04	7.66E+05	9.11E+05	9.22E+04	2.42E+06	2.05E+06	5.50E+05	6.24E+06	5.36E+05	8.74E+05
Transformity per g (sej/g), (N+R+P+S)/mass of (Y)	-	2.49E+04	6.46E+09	1.44E+10	1.16E+09	1.51E+10	2.21E+10	1.40E+09	9.82E+09	1.08E+09	1.22E+09
Emergy Yield Ratio (EYR) = Y/F	1.32	2.41	2.09	1.71	2.28	1.32	1.32	1.22	1.09	1.06	1.01
Enviromental Loading Ratio (ELR) = (P+N+S)/R	3.17	0.74	0.94	1.42	2.94	3.08	3.08	4.58	11.04	16.64	71.27
Sustainability Index (SI) = EYR/ELR	0.42	3.28	2.23	1.21	0.78	0.43	0.43	0.27	0.10	0.06	0.01
Emergy Footprint Ratio (EFR) = (P+N+S+R)/R	4.28	1.74	1.94	2.42	3.94	4.08	4.08	5.58	12.04	17.64	72.27
Direct Area Demand, ha	25.00	10.45	11.82	1.82	0.91	0.91	0.91	1.36	0.34	0.09	0.05
Indirect Area Demand, ha	82.06	7.69	11.06	2.58	2.67	2.80	2.80	6.25	3.78	1.42	3.48
Portion local, renewable	0.24	58%	52%	41%	25%	24%	24%	18%	8%	6%	1%
Portion imported, non-renewable	0.76	42%	48%	59%	75%	76%	76%	82%	92%	94%	99%

environment. Table 13 is a summary table of the emergy flows and emergy-based indices for the farm and its subsystems. The farm as a whole is listed first, after which the subsystems are listed in decreasing order of their respective Sustainability Index (SI) value.

Emergy Yield Ratios (EYR) for the S&S Homestead Farm

As stated in the materials and methods section and illustrated in figure 4, the Emergy Yield Ratio (EYR) is the ratio of the emergy of the output (Y), divided by the emergy of those inputs (F) to the process that are fed back to the system from outside. Figure 15 is a graph of the Emergy Yield Ratio of the farm and its subsystems or management areas. It indicates that those managements areas of the farm that have a large renewable component in comparison to the economic and labor inputs they require are the subsystems that have the highest EYR.

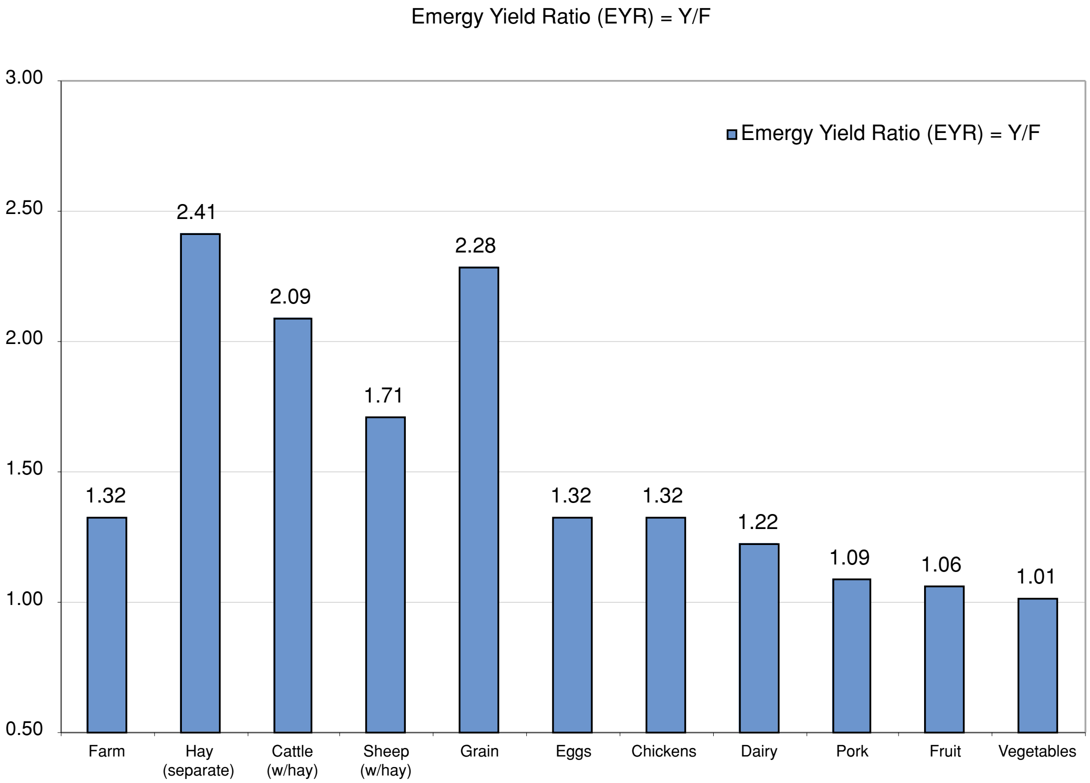


Figure 16. Graph of the EYR ratio for the S&S Homestead Farm and subsystems.

The EYR indicates those subsystems that are driving, or powering a given system. In the case of the S&S Homestead Farm, it is clear that the grass-fed livestock systems, and the hay and grain fields are the systems that provide the most yield to the farm organism. This should be taken into consideration when management questions arise regarding these areas. If the maximum power principle is correct, then it would behoove the stewards of this farm to make sure that these large and important subsystems receive feedback, in the form of nutrients and land care, that is commensurate with the relative importance of these systems to overall health of the farm as both and ecological and economic entity.

Environmental Load Ratios (ELR) for the S&S Homestead Farm

The Environmental Load Ratio (ELR) is the ratio of purchased (F) and indigenous non-renewable emergy (N) to free environmental emergy (R). It is an indicator of the amount stress that a production process places on the local environment, measured against a backdrop of natural undisturbed ecosystems. If a given agricultural system requires large amounts of purchased emergy and draws down the nonrenewable storages that form the productive base of the system (such as soil organic matter), then the system will register high a ELR. In the case of the S&S Homestead Farm, none of the management areas are diminishing the soil resources to any great extent, so any high ELR values that are registered are based on high purchased (F) emergy inputs in comparison to the renewable inputs (R). The only except is the grain which registered comparatively higher uses of nonrenewable storages or (N) values, as estimated with RUSLE equation (see table 9, figure 12). Figure 17 is a graph of the ELR for the farm and subsystems.

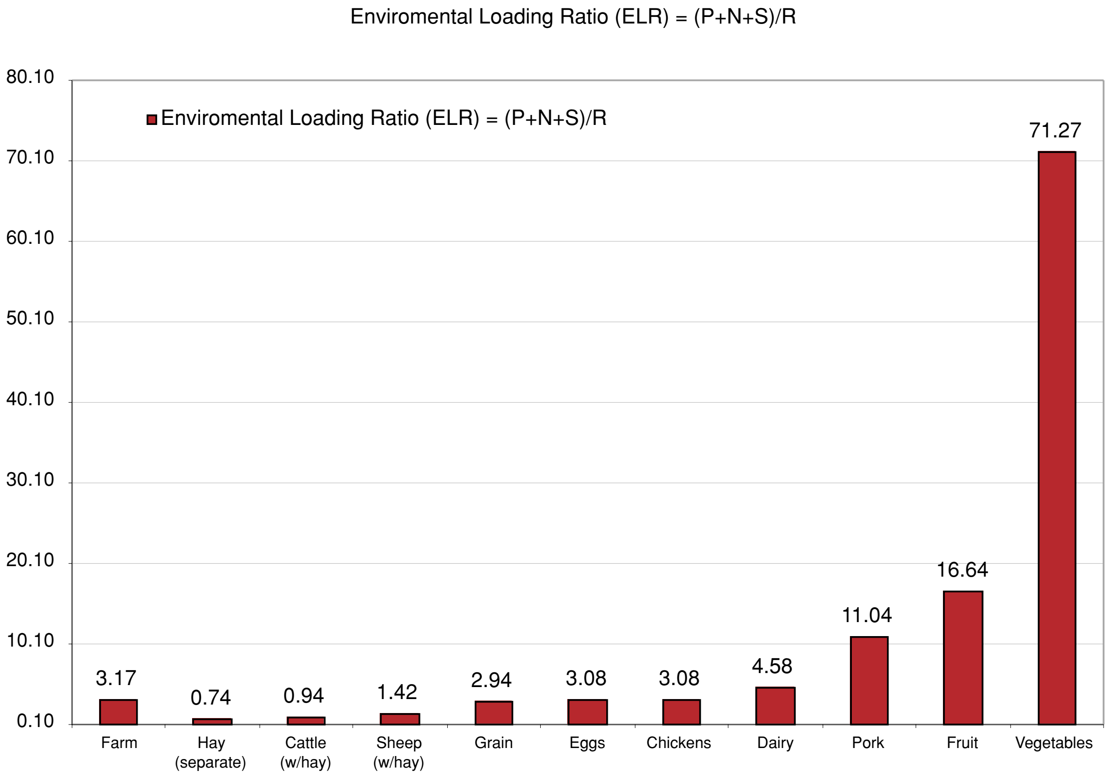


Figure 17. Graph of the ELR ratio for the S&S Homestead Farm and subsystems.

The Sustainability Index (SI) for the S&S Homestead Farm

The Sustainability Index (SI) = EYR/ELR and is an aggregate measure of yield and sustainability that assumes that the objective function for sustainability is to obtain the highest yield ratio at the lowest environmental load. The SI is addressed by Ulgiati and Brown (1998, p. 33) in their paper: "When evaluating relationships between man-made processes and their environment, this index might be used in two ways: (a) to compare different processes yielding the same product. The higher the SI the larger the economic and ecological compatibility of the process in comparison with alternative for the same product; (b) to evaluate technical and technological innovation. A process could be modified by introducing new patterns or technologies, towards a larger yield per unit if environmental stress. This can be achieved by increasing the ability of the process to exploit locally renewable sources, or by decreasing the need of nonrenewable inputs from outside."

On the S&S Homestead Farm, the (SI) indicated that those areas of the farm that were had a small area in comparison to the amount of labor and purchased services required registered the lowest SI figures. Specifically pork, fruit and vegetable production, which are all intensively managed areas of the farm register low SI ratings. In the overall farm analysis the farm infrastructure is considered in its entirety and thus lowers the farm's Sustainability Index below what might be expected from the sum of the subsystem analyses. Figure 18 is a graph showing the SI ratings for the S&S Homestead Farm and its subsystems.

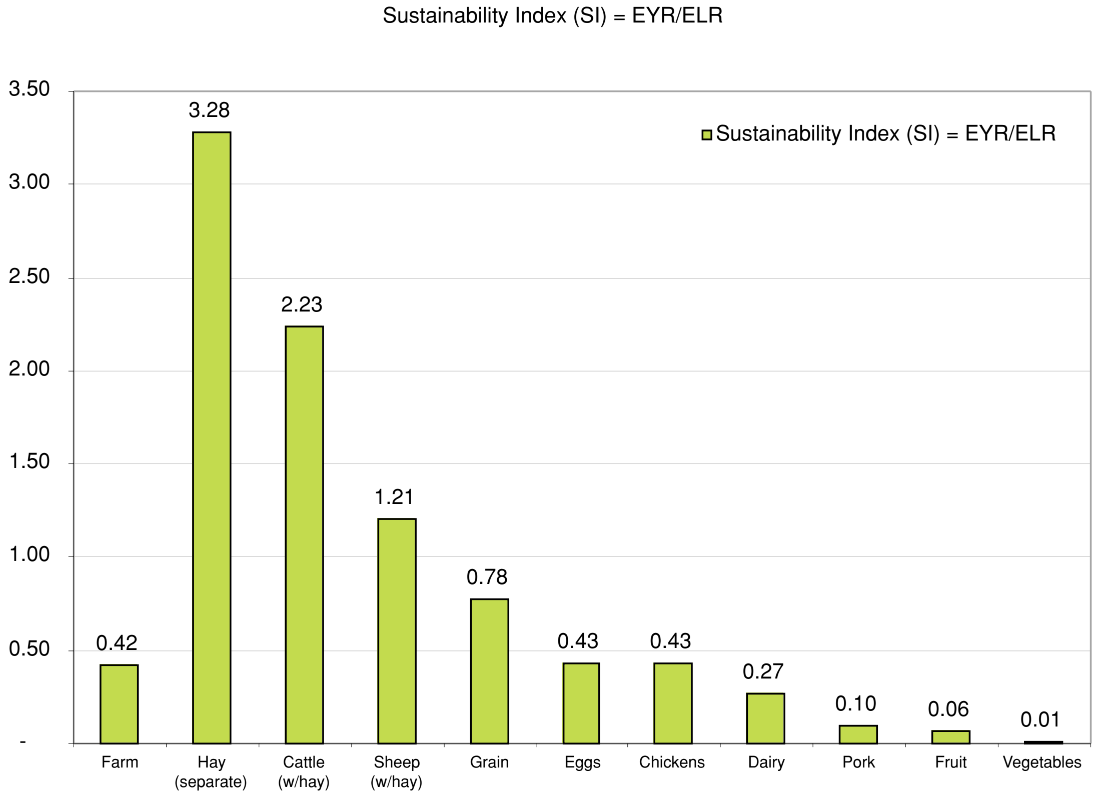


Figure 18. Graph of the Sustainability Index (SI) for the S&S Homestead Farm and subsystems.

Efficiency of Agricultural Production at the S&S Homestead

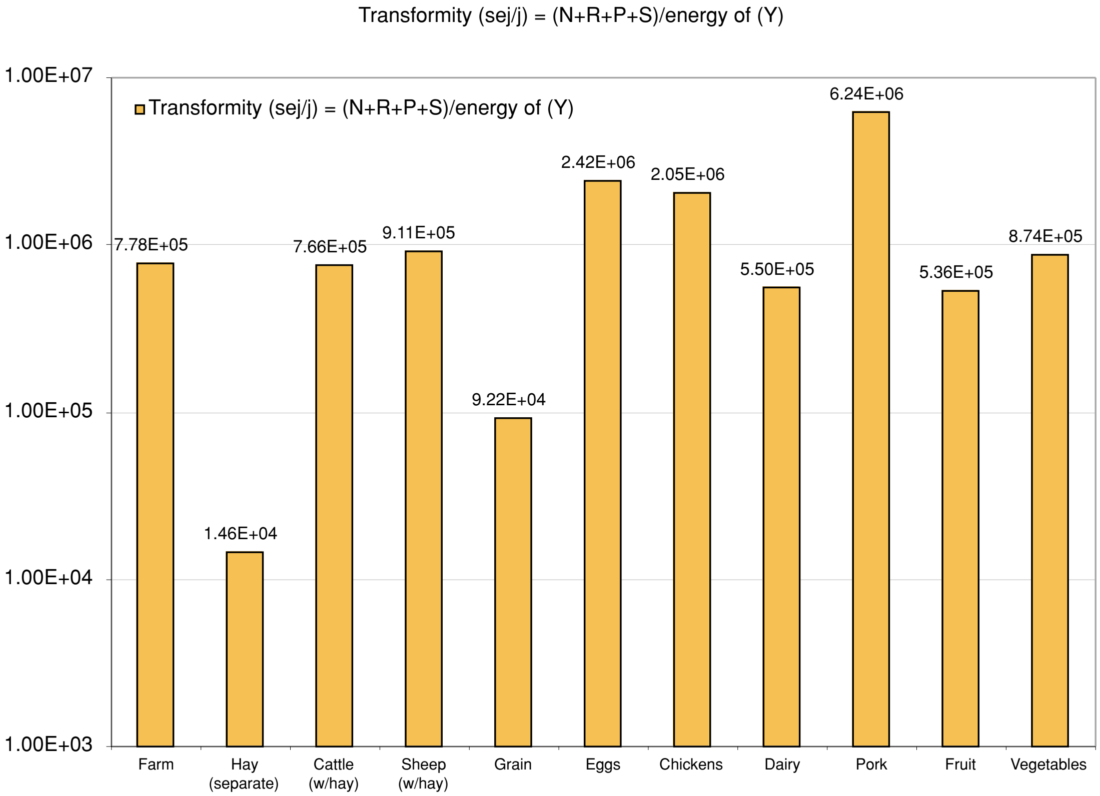


Figure 19. Graph of the transformities for the products of the S&S Homestead Farm and subsystems.

When the energy used up during production is divided by the energy remaining in the product one derives the transformity of that product, expressed as the ratio of solar emjoules per Joule (sej/J). On the S&S Homestead farm, the various management area differ widely with respect to the relatively efficiency at which a Joule of a given product can be produced. In nature, it has been observed that animals are usually of one to two orders of magnitude higher transformity than green plants. Since this pattern is a sustainable one, it provides a reference frame from which to decipher sustainable patterns in mixed agricultural systems. Specifically, it is instructive to note the relationship between the hay production and the cattle production at the S&S Homestead Farm, which are coupled systems, as well as the grain production and the pork production, also coupled systems. The transformity of the fodder, hay and grain, respectively, are between one an two orders of magnitude lower than the animals they feed. This only makes sense as a large quantity of relatively low quality energy (hay and grain) is required to produce smaller quantities of higher quality products (beef and pork). It is also interesting to note that the plant food products that humans enjoy register transformities that are essentially equal to meat products. If humans were listed on the graph, we would clearly be one to two orders of magnitude higher transformity than the meat, fruits and vegetables that feed us.

Ecological (Emergy) Footprint of the S&S Homestead Farm

The Ecological Footprint (EF) is a popular concept and an accessible accounting tool used to quantify the amount of resources consumed by a human population within a given area (Wackernagel & Rees, 1996; Folke et al., 1997). With EF accounting, the resources consumed by a process or population are translated into an estimation of the amount of productive land needed to produce the resources in question. An emergy-based ecological footprint can also be calculated using data compiled for emergy analyses. After all resource flows to a system have been accounted for and translated into emergy values one can calculate an Emergy Footprint Ratio (EFR). This is derived by dividing the total emergy yielded by a system (Y) by the total renewable emergy flows (R) supporting that same system EFR = (R+N+F)/R. The resulting number indicates how many times larger a production system's support area receiving renewable emergy would have to be for it to meet its emergy requirements locally. Figure 19 depicts this concept graphically by calculating the footprints of the various management areas of the S&S Homestead Farm.

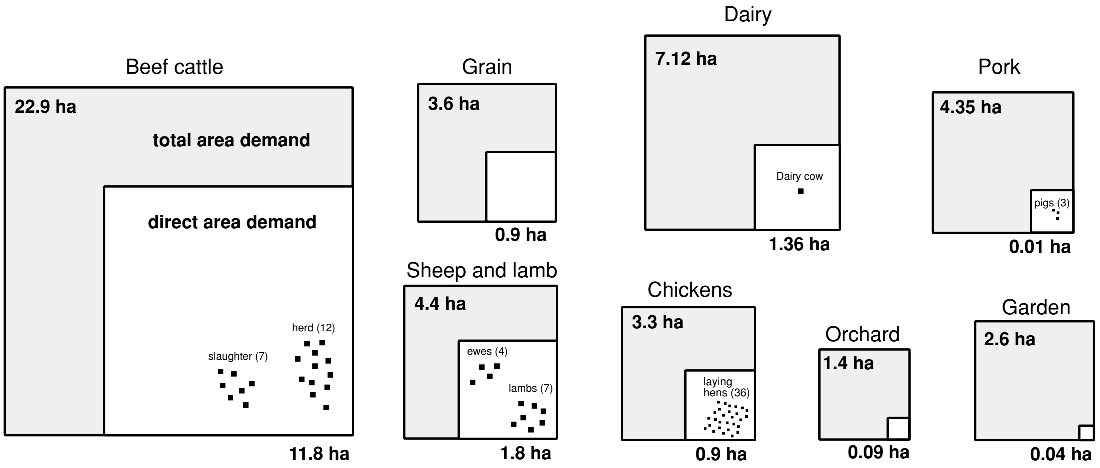


Figure 19. Illustration of the Emergy Footprint Ratio (EFR) for the subsystems of the S&S Homestead Farm.

Table 14 compares the output and sustainability of the S&S Homestead Farm with other system yielding similar products. It is offered to provide a context for the analysis, and to show how the farm compares with systems in different geographic spaces as well as other time eras.

Table 14. Comparison of emergy-based indices and ratios for food production at S&S Homestead Farm and similar products.

		Transformity	Emergy flow (sej/yr)				Emergy-based indices		
Reference	Product	(sej/J)	R	N	F	EYR	ELR	EFR	SI
(Brandt-Williams, 2001)	Cabbage (1 ha, Florida, 1992)	2.08E+05	1.63E+15	9.50E+14	6.71E+15	1.38	4.70	5.70	0.29
(Brandt-Williams, 2001)	Potatoes (1 ha, Florida, 1992)	1.49E+05	1.49E+15	9.50E+14	1.03E+16	1.24	7.52	8.52	0.16
(Lagerberg & Brown, 1999)	Greenhouse tomatoes (wood heated, Sweden)	5.36E+06	1.00E+17		1.41E+18	1.07	14.10	15.10	0.08
(Brandt-Williams, 2001)	Tomatoes (1 ha, Florida, 1992)	5.97E+05	1.56E+15	-	2.56E+16	1.06	16.40	17.40	0.06
This study	Vegetables (0.05 ha, S&S Homestead)	8.74E+05	5.78E+13	-	4.12E+15	1.01	71.27	72.27	0.01
(Brandt-Williams, 2001)	Dairy cow (1 ha, 1 cow, Florida, 1996)	1,21E+06	4.18E+15	9.50E+14	1.83E+16	1.28	4.61	5.61	0.28
This study	Dairy cow (1.36 ha, 1 cow, S&S Homestead)	5.50E+05	9.28E+14	1.10E+13	4.24E+15	1.22	4.58	5.58	0.27
This study	Beef (11.8 ha, 19 cattle, S&S Homestead)	7.66E+05	9.37E+15	9.50E+13	8.68E+15	2.09	0.94	1.94	2.23
(Brandt-Williams, 2001)	Beef (10 ha, 20 steers, Florida, 1992)	5.64E+05	2.98E+16	1.00E+14	4.23E+16	1.71	1.42	2.42	1.20
This study	Barley (1 ha, S&S Homestead)	9.22E+04	4.87E+14	5.90E+14	8.38E+14	2.28	2.94	3.94	0.78
(Brandt-Williams, 2001)	Oats (1 ha, Florida, 1992)	2.09E+05	1.56E+15	9.50E+14	3.17E+15	1.79	2.64	3.64	0.68
(Rydberg & Jansen, 2002)	Oats (1 ha, Sweden, 1927)	4.47E+04	2.84E+14	-	1.03E+15	1.27	3.64	4.64	0.35
(Ivarsson, J., 2000)	Barley (1 ha, Sunshine Farm, Kansas, 2000)	2.10E+05	3.45E+14	8.53E+14	2.81E+15	1.43	10.63	11.63	0.13
(Andresen, et al., 2000)	Pig production, ecological (0.41 ha, 3 pigs, Sweden)	4.80E+05	1.70E+14	-	1.32E+15	1.13	7.77	8.77	0.15
This study	Pig production (0.34 ha, 3 pigs, S&S Homestead)	6.24E+06	1.66E+14	-	1.84E+15	1.09	11.04	12.04	0.10
(Andresen, et al., 2000)	Pig production, conventional (0.186 ha, 3 pigs, Sweden)	5.80E+05	7.71E+13	-	1.72E+15	1.04	22.31	23.31	0.05
This study	Hay (1 ha, S&S Homestead)	2.49E+04	4.87E+14	8.04E+12	3.50E+14	2.41	0.74	1.74	3.28
(Rydberg & Jansen, 2002)	Hay (1 ha, Sweden, 1927)	1.36E+04	3.86E+14	-	3.83E+14	2.01	0.99	1.99	2.02
(Ivarsson, J, 2000)	Sunshine Farm, Land Institute (Kansas, 2000)	-	7.75E+15	1.73E+16	7.88E+16	1.32	12.40	13.40	0.11
This study	S&S Homstead Farm	7.78E+05	1.22E+16	2.01E+14	3.84E+16	1.32	3.17	4.17	0.42

Discussion and Conclusion

By characterizing a farming system in terms of its energy flow dynamics, including overall energy conversion efficiency and external resource dependency, we can gain an accurate picture of what a particular farming system requires to be maintained, the quality and quantity of its output, and its effects on the local environment. Using energy as measure, food production at the S&S Homestead is both efficient and relatively sustainable given the amount of work from both nature and the human economy required to produce its output. Meat production represents the bulk of the food produced on the farm, and the pasture-based beef and lamb production exhibit both good production efficiency (relatively low transformity) and low environmental load in comparison to other systems. Clearly, the management areas of the farm differ greatly in overall management intensity. When gauging sustainability using the emergy-based ratios it is important to understand that the EYR and ELR are ratios of local renewable and nonrenewable inputs to feedback from outside, so the number of variables is three, not just two. This means that a sustainable system is not only characterized by a low requirement of feedback, but also by a large renewable input in comparison with the feedback itself, which can also be large (Ulgiati & Brown, 1998). In the right circumstance, a large purchased input from outside the process can confer sustainability on a production process, so long as the purchased inputs are matched to a large amount of emergy from renewable sources (Ulgiati & Brown, 1998). The S&S Homestead Farm is a good example of a mixed, balanced farm, where some management areas are both spatially extensive and require low labor inputs, while others are more intensive, yielding smaller quantities of specific products that the farmers value for reasons other than their yield to other parts of the system.

In closing, while emergy analysis is one way to objectively assign non-market values to products, and has proved a useful tool for evaluating the S&S Homestead Farm, it cannot capture the intangible properties that are often key components of human value judgements regarding environmental decisions. In addition to the ubiquitous market valuation of goods and services - based on the neoclassical paradigm of willingness-to-pay as sole measure of value - spiritual values, cultural mores, ethics and aesthetic preference all inform the management practices of farmers and natural resource stewards and the societies that they support. As a scientific measure of value, emergy analysis seeks only to show, in objective terms, what has gone in to making a product and to what extent that product is compatible with its local environment. Emergy analysis, in this case, was used to monitor the performance of the S&S Homestead Farm in terms of how closely the farm resembles a natural system and how much the farm system relies on external resources for its operation. It does not presume to explain the reasoning behind why the farm is organized the way it is. It does show however, the end result of the reasoning behind the organization of the farm, and that this reasoning is sound, based on its performance in comparison to other systems yielding similar products.

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