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Emergy evaluation of food production in urban residential landscapes

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Abstract. To transform cities from heterotrophic into sustainable ecosystems many authors have called for increased food production, including home gardening, in urban areas. We conducted an emergy analysis of four model backyard landscape plots—a conventional ornamental landscape, an intensive organic garden, an edible landscape, and a forest garden—to assess the yield and sustainability of these systems. Data were collected during the 2001 growing season and extrapolated to make a five year projection. In the 2001 season, all plots had low Emergy Yield Ratios (EYR) of between 0.0003 and 0.17 and extremely low Emergy Sustainability Indices (SI). In the five year projection, all plots still had low EYRs of between 0.0008 and 0.33 and very low SIs. These low indices are due primarily to the high levels of economic inputs required for the installation and maintenance of these plots in an urban context. Analyses performed on larger systems (households, neighborhoods and cities) containing productive landscapes such as those studied here may produce different results. Installing food-producing landscapes in urban areas without altering the networks by which such landscapes are supplied, however, may not substantially alter the heterotrophic nature of cities.

Keywords: edible landscaping, urban food production, sustainability, emergy

Introduction

Cities are highly heterotrophic ecosystems (Collins *et al.*, 2000). Odum (2001) has gone so far as to call cities parasites of natural ecosystems. The extent of cities' dependence on outside energy and resources has been quantified by means such as ecological footprint analysis (Wackernagel and Rees, 1996; Rees, 1997) and Emergy analysis (Odum, 1996).

Alternative sustainable cities have been imagined which couple the heterotrophic urban ecosystem to the autotrophic agroecosystem (Barrett *et al.*, 1998). Local food production is an invariable component of sustainable cities as imagined and implemented over the last century (Howard, 1898; Stren *et al.*, 1992; United Nations Development Program, 1996; Altieri, 1999; Beatley, 2000; Corbett and Corbett, 2000). A pilot study in Vancouver by Levenston *et al.* (2001) estimated that 32% of the land area in a 3.4 acre residential city block was suitable for growing edible crops.

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Intensive organic gardening is widely promoted as a method for producing food on residential lots (Jeavons, 1995; Gussow, 2001; Ecology Action, 2002). Edible landscaping, which integrates food-producing plants into ornamental plantings and conventional designs, is also put forward as a productive landscaping alternative (Creasy, 1982; Kourik, 1986; Hagy, 1990; MacCubbin, 1998). Forest gardens, which attempt to imitate natural ecosystems in their structure and function while producing useful products for people, offer an ecological approach to residential food production (Hart, 1996; Whitefield, 2000; Hemenway, 2001).

The objective of this study was to compare the yield and inputs and to evaluate the sustainability of an intensive organic garden, an edible landscape, and a forest garden, as well as those of a conventional ornamental landscape established for purposes of comparison. We used Emergy analysis for our evaluation.

Emergy analysis

Emergy analysis provides a means of evaluating all inputs and outputs of a system in common units (solar energy). For this study it offered several advantages over alternative means of environmental accounting. Strictly economic analyses fail to capture the value of ecosystem services (Costanza *et al.*, 1997). Ecological accounting models which assign economic values to ecosystem services often depend on surrogate values including estimated replacement costs and willingness to pay (Costanza *et al.*, 1997; Edwards and Abivardi, 1997). Emergy analysis offers a more direct means of quantifying the inputs and outputs of the systems in question (Bardi and Brown, 2000). While ecological footprint analysis (Wackernagel and Rees, 1996) depicts spatially the resource consumption of productive processes, it does not clearly reflect the value of system yields, nor does it allow for comparisons of levels of environmental and economic inputs. Emergy analysis has been used previously to evaluate the energy flows and sustainability of countries (Huang and Odum, 1991; Ulgiati *et al.*, 1994; Brown and McClanahan, 1996; Ulgiati and Brown, 1998), agricultural production systems (Ulgiati *et al.*, 1994; Comar, 2000; Johannson *et al.*, 2000) and engineering projects (Brown and McClanahan, 1996; Prado-Jatar and Brown, 1997; Martin, 2002). In contrast, the term "exergy", or absolute energy efficiency, denotes the measure of the quality of energy; as energy is used in any process, it loses quality and decreases in exergy (Wall, 1993). In the simplest terms, then, emergy can be viewed as the measure of inputs to a system or product, and exergy is the measure of output in terms of energy dissipated.

The central concept of Emergy analysis is that a given resource embodies not only its available energy, but also the available energy used in its production (Odum, 1996; Brown and Herendeen, 1996). Wood, for instance, can be burned to produce a certain amount of energy (measured in Joules), but to produce that wood requires inputs of sun, rain, soil and, sometimes, management. Definitions of key terms in Emergy analysis are given below (Brown and McClanahan, 1996; Martin, 2002).

Emergy: An expression in one type of energy (solar energy) of all the available energy used directly or indirectly in the production of a product or service.

Transformity: A ratio obtained by dividing the total Emergy used in a process by the energy yielded by that process. Transformities (expressed as the Emergy per unit energy) are used to convert different energies to Emergy of the same type (solar Emergy).

Solar emjoule (sej): The units of solar energy previously used to create a product. Emergy analysis proceeds by multiplying the available energy of an item by its transformity to express the amount of solar energy necessary to create that item. In short, Energy (J) $*$ Transformity (sej/J) = Emergy (sej), where J = Joules and sej = solar emjoules

From a series of these calculations organized in an Emergy analysis table, indices can be calculated to represent the net yield of a particular system, the relative contribution of renewable resources, and the overall sustainability of a system. Following the maximum Emergy principle (Odum, 1996; Brown and Herendeen, 1996), more sustainable systems are those that use a small amount of economic inputs efficiently to capture natural energy and create products of greater Emergy value.

Methods

We established four contiguous 6 × 9 m landscape plots at The Ohio State University's Waterman Farm in Columbus, Ohio in the spring of 2001. One plot was a conventional ornamental landscape with a large area of turf, shade tree, shrubs, flowering vines, and a perennial border (figure 1). Another was an intensive organic garden with a large area of double-dug annual beds, rows of berry bushes, a fruit tree and a compost bin (figure 2). The third was an edible landscape, which was laid out exactly the same as the conventional ornamental landscape, but in which mostly edible species were substituted for the ornamental

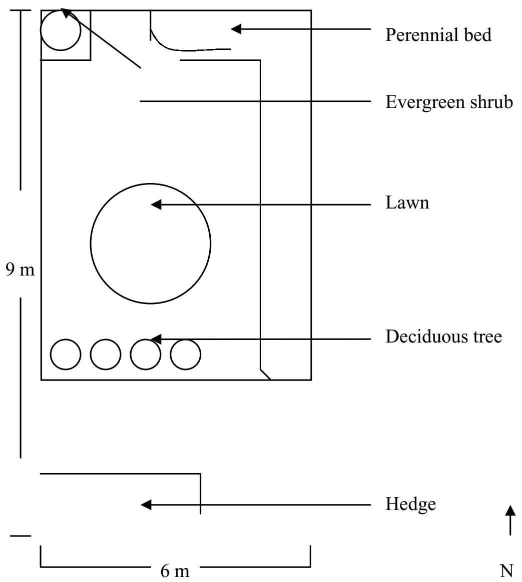

Figure 1. Schematic plan of the conventional ornamental landscape installed at The Ohio State University's Waterman Farm, Spring, 2001.

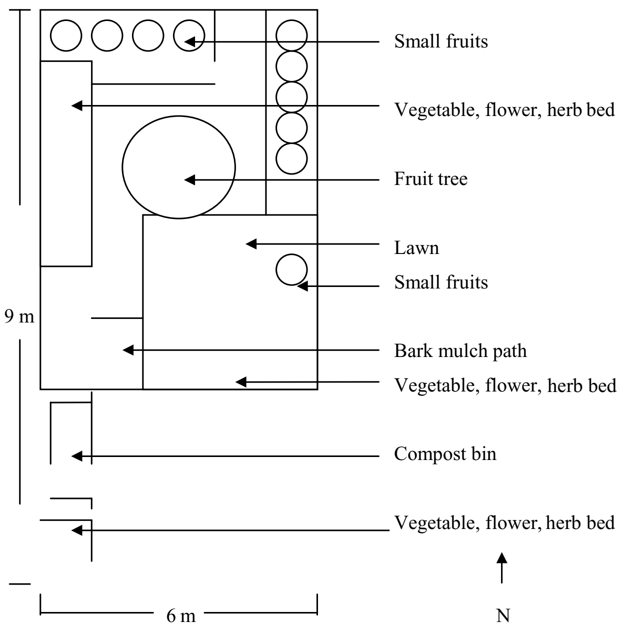

Figure 2. Schematic plan of the intensive organic garden installed at The Ohio State University's Waterman Farm, Spring, 2001.

plants used in the first plot. The edible landscape also included a compost bin (figure 3). The final plot was a forest garden with woody plants, vegetables, perennial edible greens, herbs and flowers planted through a thick leaf mulch (figure 4). Plant lists and sources for all plots are given in Appendix B. All plots were managed organically, with the exception of a single late-season application of combined fertilizer and herbicide to the three plots containing lawn.

Constructing the emergy analysis table

Work on the plots began April 13, 2001 and data was collected through October 20, 2001. Data collected included the amount of labor necessary for the installation and maintenance of the plots, the quantity and/or cost of all inputs to the plots (e.g., water, compost, plant materials, tools and supplies), the yield of vegetables, small fruits and cut flowers in each plot, andthe amount of waste removed from each plot.

Emergy analysis began with the construction of a system diagram for the landscape plots (figure 5). The system diagram organizes the relationships between the various components and the flows of energy and resources between them. Important inputs to the plots include sunlight, rain, wind, and materials and services fed back from the economy. Significant interactions within the plots include the cycling of nutrients through plants, consumers and compost/mulch systems, the management of all components through the interaction of materials and services, and the yields of various crops through harvest.

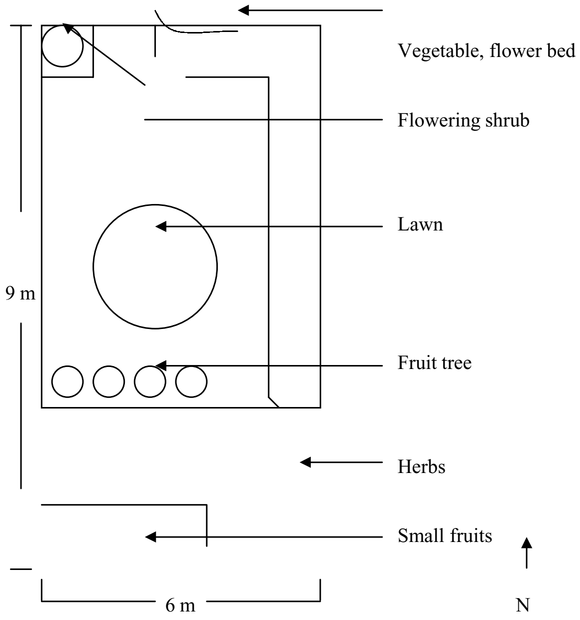

Figure 3. Schematic plan of the edible landscape installed at The Ohio State University's Waterman Farm, Spring, 2001.

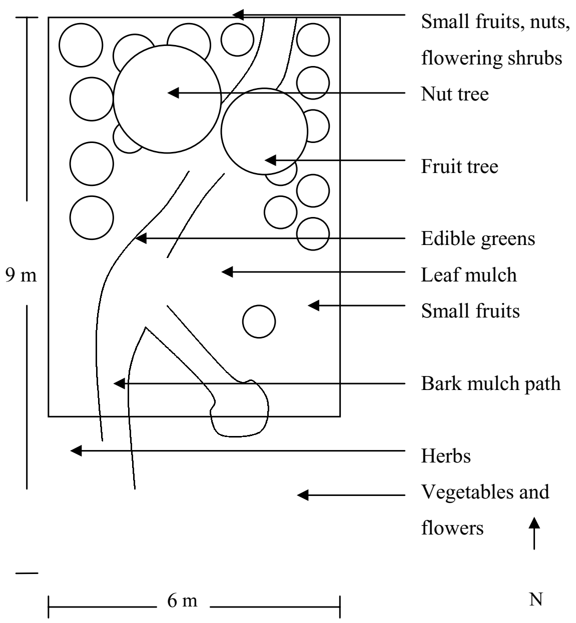

Figure 4. Schematic plan of the forest garden installed at The Ohio State University's Waterman Farm, Spring, 2001.

Table 1. Emergy evaluation of four landscape plots (conventional ornamental landscape, intensive organic garden, edible landscape, forest garden) at The Ohio State University's Waterman Farm, Columbus, Ohio based on data from the 2001 growing season

	Data						Solar emergy (sej)			
Item	Conventional ornamental landscape	Intensive organic garden	Edible landscape	Forest garden	Units	Sej/unit	Conventional ornamental landscape	Intensive organic garden	Edible landscape	Forest garden
Renewable resources (*R*)										
Sunlight	1.90E+11	1.90E+11	1.90E+11	1.90E+11	J	1	1.90E+11	1.90E+11	1.90E+11	1.90E+11
Rain-chemical	1.70E+08	1.70E+08	1.70E+08	1.70E+08	J	1.82E+04	3.09E+12	3.09E+12	3.09E+12	3.09E+12
Wind	1.38E+07	1.38E+07	1.38E+07	1.38E+07	J	1.50E+03	2.07E+10	2.07E+10	2.07E+10	2.07E+10
Total (*R*)							3.09E+12	3.09E+12	3.09E+12	3.09E+12
Non-renewable resources (*N*)										
Soil	3.10E+06	7.70E+06	7.70E+06	3.10E+06	J	7.40E+04	2.29E+11	5.70E+11	5.70E+11	2.29E+11
Total (*N*)							2.29E+11	5.70E+11	5.70E+11	2.29E+11
Total (*I*)							3.32E+12	3.66E+12	3.66E+12	3.32E+12
Materials (*M*)										
Plant materials	629	255	230	702	$	1.25E+12	7.86E+14	3.19E+14	2.88E+14	8.78E+14
Seed	9.10E+06	1.60E+07	9.60E+06	4.50E+06	J	6.60E+04	6.01E+11	1.06E+12	6.34E+11	2.97E+11
Compost	57	110	57	104	$	1.25E+12	7.13E+13	1.38E+14	7.13E+13	1.30E+14
Manure	2.8	81	52	88	$	1.25E+12	3.50E+12	1.01E+14	6.50E+13	1.10E+14
Leaves	0	0	0	4.40E+09	J	2.40E+04	0	0	0	1.06E+14
Branches	0	0	0	3200	g	3.49E+04	0	0	0	1.12E+08
Newspaper	0	0	0	1.20E+05	g	3.90E+09	0	0	0	4.68E+14
Bark Mulch	6.80E+09	8.50E+09	3.70E+09	4.30E+09	J	3.49E+04	2.37E+14	2.97E+14	1.29E+14	1.50E+14
Straw	7.60E+07	5.00E+07	7.60E+07	0	J	1.04E+05	7.90E+12	5.20E+12	7.90E+12	0
Water	5530	4712	4929	1784	gallons	8.50E+09	4.70E+13	4.01E+13	4.19E+13	1.52E+13
Pesticides	0	51	51	51	g	1.50E+10	0	7.65E+11	7.65E+11	7.65E+11

Fertilizers	0.545	0.273	0.545	0	kg	3.80E+12	2.07E+12	1.04E+12	2.07E+12	0
Fuel	7.20E+06	4.60E+06	5.10E+06	0	J	6.60E+04	4.75E+11	3.04E+11	3.37E+11	0
Lumber	0.50	144	104.00	2.00	$	1.25E+12	6.25E+11	1.80E+14	1.30E+14	2.50E+12
Steel	0	1280	613	53	g	1.80E+09	0	2.30E+12	1.10E+12	9.54E+10
Gravel	0	6804	6804	6804	g	1.00E+09	0	6.80E+12	6.80E+12	6.80E+12
Tools and machinery	318	370	352	181	$	1.25E+12	3.98E+14	4.63E+14	4.40E+14	2.26E+14
Other supplies (purchased)	16	42	39	50	$	1.25E+12	2.00E+13	5.25E+13	4.88E+13	6.25E+13
Total (*M*)							1.57E+15	1.61E+15	1.23E+15	2.16E+15
Services (*S*)										
Labor	39	107	72	93	hours	4.70E+12	1.83E+14	5.03E+14	3.38E+14	4.37E+14
Waste collection, processing	5.51E+04	3.28E+04	4.42E+04	1.26E+04	g	3.26E+07	1.80E+12	1.07E+12	1.44E+12	4.11E+11
Total (*S*)							1.85E+14	5.04E+14	3.40E+14	4.38E+14
Total (*F*)							1.76E+15	2.11E+15	1.57E+15	2.59E+15
Yield										
Vegetables	0	1.10E+09	5.20E+08	8.30E+08	J	3.28E+05	0	3.61E+14	1.71E+14	2.72E+14
Small fruit	0	4.40E+05	4.60E+05	1.20E+06	J	3.41E+05	0	1.50E+11	1.57E+11	4.09E+11
Tree fruit	0	0.00E+00	0.00E+00	0.00E+00	J	2.87E+05	0	0	0	0
Nuts	0	0.00E+00	0.00E+00	0.00E+00	J	8.43E+05	0	0	0	0
Cut flowers	2.10E+06	8.60E+05	0	1.30E+07	J	2.37E+05	4.98E+11	2.04E+11	0	3.08E+12
Total (*Y*)							4.98E+11	3.61E+14	1.71E+14	2.76E+14

Data are presented in exponential notation so that 2.8E + 10 $= 2.8 \times 10^{10}$. Calculations and references for transformities are given in Appendix C. Categories on far left (I, F, Y) are from aggregated system diagram (figure 6) and were used in the calculation of emergy indices (Table 2).

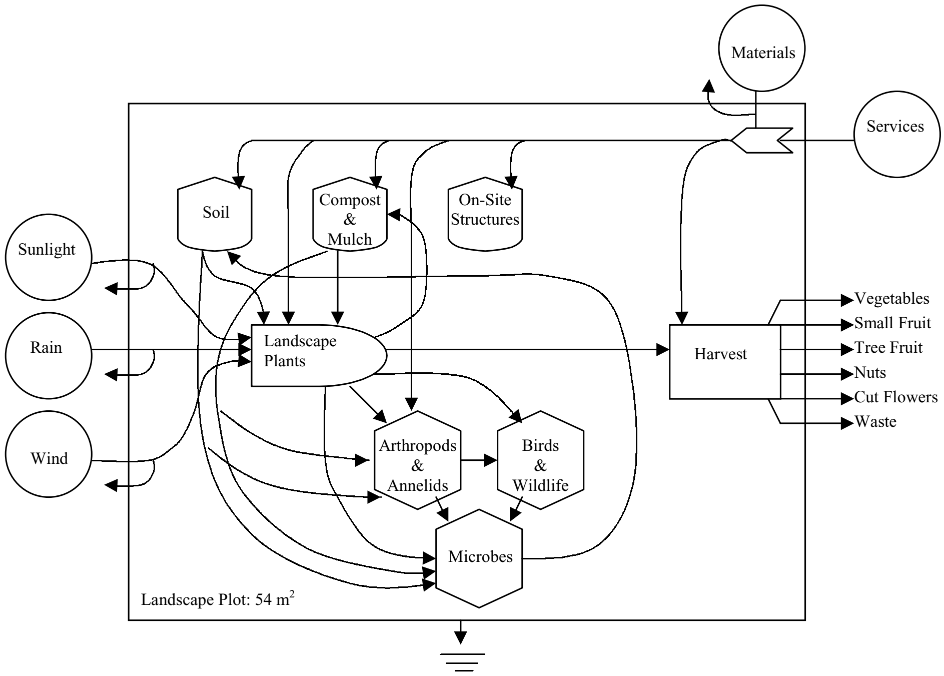

Figure 5. Energy system diagram of a landscape plot. Inputs and outputs from the system determined the row headings in the Emergy analysis tables (Tables 1 and 3). Diagram by Joseph Phillips.

The Emergy analysis table (figures 2.6) was constructed directly from the system diagram. Inflows and outflows that cross the system boundaries appear as items in the table. The amount of each item that flows into or out of the system is first quantified in raw units (joules, US dollars, grams, gallons). Multiplying these raw units by their respective transformities calculates the solar Emergy of each item. Transformity values were found in the Emergy literature and are cited in Appendix C. Where necessary, conversions were made between the units in which we collected the data and the units of the transformity (e.g. grams to Joules). The calculations for all conversions are shown in Appendix C. Following other Emergy analyses (Brown and Herendeen, 1996; Prado-Jatar and Brown, 1997; Martin, 2002), previously calculated Emergy/dollar ratios (Ortega *et al.*, 2000) were used in conjunction with dollar values to calculate solar emjoules. This procedure was followed for plant materials, compost, manure, lumber, tools and machinery, and other supplies. If the plant materials, for instance, had grown naturally in the vicinity and had been simply transplanted into the plots, using dollar values would overestimate their Emergy. Since, however, the plant materials used were grown in nurseries in a processed medium, intensively managed over a period of weeks or years, transported to retail outlets and then purchased, using dollar values provides a reasonable approximation of the Emergy they contain. The same logic applies to other purchased inputs. The transformity for dollars is based on the ratio of the total solar Emergy use in a country for a year and the Gross National Product (in dollars) for that year (Odum, 1996).

Renewable resources

Solar energy is based on average daily total global horizontal solar radiation for Columbus for the months of April–October from 1961–1990 (National Solar Radiation Data Base, 2002). Rain energy is based on measurements collected at the Ohio Agricultural Research and Development Center's Columbus weather station (Ohio Agricultural Research and Development Corporation, 2002) and at a nearby greenhouse (unpublished data) during the 2001 season. Wind energy is estimated from July figures for Flint, Michigan given in Odum (1996). Because the inputs of sun, wind and rain are all dependent on the global climate cycle, only the largest of these inputs, rain, is counted in the total renewable environmental inputs. This avoids double-counting and overestimating the renewable environmental contribution (Odum, 1996).

Non-renewable resources

Following other Emergy analyses (Ulgiati *et al*., 1994; Comar, 2000; Johannson *et al*., 2000), soil is treated as a non-renewable resource whose contribution is measured by the energy of organic matter contained in the soil lost to erosion. Soil loss is estimated based on an average figure for the region (Ohio State University Extension, 1995), multiplied by a multiplier for each plot. The multiplier for each plot was determined by calculating the percentage of land area in each plot that was not permanently vegetated or mulched times the percentage of a year that that soil was exposed. The percent organic matter of the soil was determined through soil tests prior to installation of the landscapes.

Materials

For purposes of the analysis, these plots were treated as if they were the backyards of single-family houses in Columbus. Purchase prices and quantities of inputs in the 2001 season were recorded by the authors as they installed and maintained the landscape plots. Plant materials included balled and burlapped, containerized and bare root trees and shrubs, containerized perennials up to 1 gallon size, and cell packs of annual vegetable and flower transplants. Seeds were used for grass, cover crops, and a few vegetables and flowers. Compost was incorporated into planting beds and used for planting in the forest garden. Manure was incorporated into planting beds except in the conventional ornamental landscape, scattered on lawns, and used to make manure teas for fertilization. Leaves and newspaper were used in the forest garden for the construction of a sheet mulch. Branches served in the forest garden as tomato supports. Bark mulch was used around shrubs, in the conventional ornamental landscape's perennial bed, and to cover paths in the organic garden and the forest garden. Straw was used to protect grass seed and seedlings during the establishment of lawns. The water input is considered to be drinking water purchased from the municipal supply system. Pesticides used were Safer® insecticidal soap, Dipel® dry flowable biological insecticide (Bt), and Bonide® rotenone-pyrethrin spray. The synthetic fertilizer used was Ace Premium Weed and Feed (N-P-K: 29-3-4). Fuel was gasoline used for mowing lawns. Lumber was used in compost bins, a trellis for blackberries in the intensive organic garden, and garden stakes. Steel included hardware used in the compost bins and trellis. Gravel was used in water-filled basins included for insect attraction in the three food-producing plots. Tools, machinery and supplies were considered purchased at full price in the minimum quantity necessary if used at all in the construction or maintenance of these plots. These items include a shovel, a rake, a turning fork, a hand trowel, a knife, a lawnmower, a pump sprayer, a plastic basin, a five gallon plastic bucket, jute twine, bird nets, plastic bags, Johnny's fava/broad bean/vetch inoculant, and Hinder® deer and rabbit repellant.

Services

Labor was calculated in person-hours. Waste collection and processing was included as a service to account for the energy inputs necessary to remove wastes from gardens in a municipal context. Wastes included containers and cell packs included with plant materials, packaging associated with other purchased inputs, and yard waste that was not recycled through composting or mulching. The positive Emergy of these wastes was not counted as a yield of the systems as, in the municipal context, these materials would largely go to a landfill.

Yield

All materials harvested from the plots for use were weighed at the time of harvest. Yields are broken down into vegetables (including herbs), small fruit (blackberries), tree fruit, nuts, and cut flowers. Tree fruits, nut crops (hazelnuts), and two additional small fruit crops (jostaberries and grapes) did not yield in the 2001 season.

Calculation of system indices

Four Emergy indices were calculated to compare the inputs and outputs of the four systems and to evaluate their sustainability. Calculation of the indices began with the construction of an aggregated systems diagram (figure 6). Items were grouped into the following categories: renewable inputs (R), non-renewable inputs (N), material inputs (M), services (S), and yield (Y). These categories were further grouped to create indigenous inputs ($I = R + N$) and economic inputs ($F = M + S$). Indigenous inputs (I) can be thought of as the free environmental resources available in the landscape plots. Economic inputs (F [which stands for feedback]) consist of high-value resources returned from the human economy to these systems. From these groups the following indices can be calculated (Ulgiati *et al.*, 1994; Brown and McClanahan, 1996; Martin, 2002):

Emergy Yield Ratio (EYR) = Y/F
Emergy Investment Ratio (EIR) = F/I
Environmental Loading Ratio (ELR) = $[F + N]/R$
Emergy Sustainability Index (SI) = EYR/ELR

The *Emergy Yield Ratio* (EYR) is a ratio of the Emergy of the yield of a system to the Emergy of the materials and services fed back into that system from the larger economy. An EYR of greater than 1.0 indicates that the system in question is making a positive

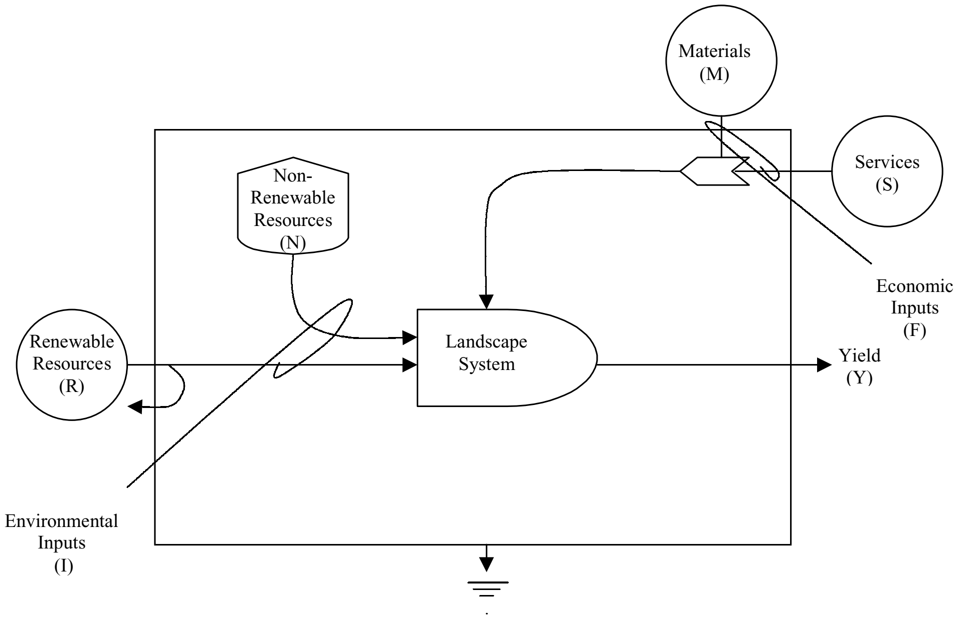

Figure 6. Aggregated system diagram of a landscape plot where environmental (I) and economic (F) resources are used by the landscape system to create yield (Y). These aggregated categories form the basis of the Emergy indices (Tables 2 and 4). Diagram by Joseph Phillips.

contribution to the economy. An EYR of less than 1.0 indicates that the system is absorbing resources of higher Emergy value than the products it creates.

The *Emergy Investment Ratio* (EIR) is the ratio between the amount of inputs that are derived from the human economy and the amount that are freely available on site. Systems with lower EIRs are more efficient in exploiting indigenous resources and require fewer economic inputs.

The *Environmental Loading Ratio* (ELR) is similar to EIR, but it aggregates non-renewable resources with economic inputs rather than with renewable resources available on site. Thus the ELR indicates the impact a system has on the environment relative to the amount of renewable Emergy it uses.

The *Emergy Sustainability Index* (SI) is a ratio of the Emergy Yield Ratio to the Environmental Loading Ratio. The SI indicates whether the yield of the system is favorable compared to the stresses imposed upon the environment. The calculations used for the Emergy indices are shown in Table 2.

Five year projection

A projection was made through five growing seasons (a total of 4½ years) based on the 2001 data (Table 3). The calculations used for this projection are detailed in Appendix B.

Solar energy was calculated using average daily total global horizontal solar radiation for all months in Columbus from 1961–1990 (National Solar Radiation Data Base, 2002).

Table 2. Emergy indices for four landscape plots (conventional ornamental landscape, intensive organic garden, edible landscape, forest garden) at The Ohio State University's Waterman Farm, Columbus, Ohio based on data from the 2001 growing season

		Result			
	Calculation	Conventional landscape	Intensive organic garden	Edible landscape	Forest garden
Category totals					
Renewable resources (R)	From figure 2.6	3.09E+12	3.09E+12	3.09E+12	3.09E+12
Non-renewable resources (N)	From figure 2.6	2.29E+11	5.70E+11	5.70E+11	2.29E+11
Environmental inputs (I)	$R + N$	3.32E+12	3.66E+12	3.66E+12	3.32E+12
Materials (M)	From figure 2.6	1.57E+15	1.61E+15	1.23E+15	2.16E+15
Services (S)	From figure 2.6	1.85E+14	5.04E+14	3.40E+14	4.38E+14
Economic inputs (F)	$M + S$	1.76E+15	2.11E+15	1.57E+15	2.59E+15
Yield (Y)	From figure 2.6	4.98E+11	3.61E+14	1.71E+14	2.76E+14
Indices					
Emergy yield ratio (EYR)	Y/F	2.83E−04	0.17	0.11	0.11
Emergy investment ratio (EIR)	F/I	529	576	429	780
Environmental loading ratio (ELR)	$(F + N)/R$	569	682	509	838
Emergy sustainability index (SI)	EYR/ELR	4.97E−07	2.51E−04	2.13E−04	1.27E−04

Data are presented in exponential notation so that $2.8\text{E}+10 = 2.8 \times 10^{10}$. Indices calculated using category totals from Table 1.

Rain energy was calculated using an average yearly precipitation figure based on data from the Ohio Agricultural Research and Development Center's Columbus weather station from 1986–2001 (Ohio Agricultural Research and Development Center, 2002). Wind energy was calculated using the same data from Odum (1996), but including January figures. Again, rain energy was the greatest of the renewable environmental inputs. Soil loss was calculated by the same procedure as for the 2001 growing season.

Inputs necessary only for installation were not counted again. For all data recorded in dollar values a 9% discount rate was applied for future years (Martin, 2002). All annuals (except for 10% which were assumed to re-seed in the forest garden) and 10% of herbaceous perennials were projected to be replaced each subsequent season. All seed except for grass seed was counted again each subsequent season. Compost was assumed to be created on site in sufficient quantities to provide for future needs. Manure was anticipated for three manure teas and three lawn fertilizations. The same quantity of leaves used to renew the sheet mulch in the forest garden at the end of the 2001 season was counted for each subsequent season. It was projected that branches would have to be replaced every other year. We assumed 25% replacement of bark mulch annually to account for decomposition. Water, pesticides, and fertilizer were counted in the same amounts every year. Fuel use was projected to increase by 50% due to early season mowing that was not needed in 2001 while the lawns established. It was assumed that stakes would have to be replaced every other year. No further inputs of steel, gravel, and tools and machinery were projected. Most supplies purchased in 2001

Table 3. Emergy evaluation of four landscape plots (conventional ornamental landscape, intensive organic garden, edible landscape, forest garden) at The Ohio State University's Waterman Farm, Columbus, Ohio based on a five year projection

		Data						Solar Emergy (sej)			
Note	Item	Conventional ornamental landscape	Intensive organic garden	Edible landscape	Forest garden	Units	Sej/unit	Conventional ornamental landscape	Intensive organic garden	Edible landscape	Forest garden
I	Renewable resources (*R*)										
	1 Sunlight	1.27E+12	1.27E+12	1.27E+12	1.27E+12	J	1	1.27E+12	1.27E+12	1.27E+12	1.27E+12
	2 Rain—chemical	1.25E+09	1.25E+09	1.25E+09	1.25E+09	J	1.82E+04	2.28E+13	2.28E+13	2.28E+13	2.28E+13
	3 Wind	7.30E+08	7.30E+08	7.30E+08	7.30E+08	J	1.50E+03	1.10E+12	1.10E+12	1.10E+12	1.10E+12
	Total (*R*)							2.28E+13	2.28E+13	2.28E+13	2.28E+13
	Non-renewable resources (*N*)										
	4 Soil	4.60E+06	4.10E+07	4.10E+07	6.10E+06	J	7.40E+04	3.40E+11	3.03E+12	3.03E+12	4.51E+11
	Total (*N*)							3.40E+11	3.03E+12	3.03E+12	4.51E+11
	Total (*I*)							2.31E+13	2.58E+13	2.58E+13	2.33E+13
F	Materials (*M*)										
	5 Plant materials	713	611	366	1279	$	1.25E+12	8.91E+14	7.64E+14	4.58E+14	1.60E+15
	6 Seed	9.10E+06	6.00E+07	1.20E+07	2.30E+07	J	6.60E+04	6.01E+11	3.96E+12	7.92E+11	1.52E+12
	7 Compost	57	110	57	104	$	1.25E+12	7.13E+13	1.38E+14	7.13E+13	1.30E+14
	8 Manure	16	110	87	114	$	1.25E+12	2.00E+13	1.38E+14	1.09E+14	1.43E+14
	9 Leaves	0	0	0	7.30E+09	J	2.40E+04	0	0	0	1.75E+14
	10 Branches	0	0	0	9600	g	3.49E+04	0	0	0	3.35E+08
	11 Newspaper	0	0	0	1.20E+05	g	3.90E+09	0	0	0	4.68E+14
	12 Bark Mulch	1.40E+10	1.70E+10	7.40E+09	8.60E+09	J	3.49E+04	4.89E+14	5.93E+14	2.58E+14	3.00E+14
	13 Straw	7.60E+07	5.00E+07	7.60E+07	0	J	1.04E+05	7.90E+12	5.20E+12	7.90E+12	0
	14 Water	2.77E+04	2.36E+04	2.46E+04	8.92E+03	gallons	8.50E+09	2.35E+14	2.01E+14	2.09E+14	7.58E+13
	15 Pesticides	0	255	255	255	g	1.50E+10	0	3.83E+12	3.83E+12	3.83E+12

(*Continued on next page*.)

Table 3. (*Continued*).

Note	Item	Data: Conventional ornamental landscape	Data: Intensive organic garden	Data: Edible landscape	Data: Forest garden	Units	Sej/unit	Solar Emergy (sej): Conventional ornamental landscape	Solar Emergy (sej): Intensive organic garden	Solar Emergy (sej): Edible landscape	Solar Emergy (sej): Forest garden
	16 Fertilizers	2.73	1.37	2.73	0	kg	3.80E+12	1.04E+13	5.21E+12	1.04E+13	0
	17 Fuel	5.10E+07	3.20E+07	3.60E+07	0	J	6.60E+04	3.37E+12	2.11E+12	2.38E+12	0
	18 Lumber	1.00	147	108.00	5.00	$	1.25E+12	1.25E+12	1.84E+14	1.35E+14	6.25E+12
	19 Steel	0	1280	613	53	g	1.80E+09	0	2.30E+12	1.10E+12	9.54E+10
	20 Gravel	0	6804	6804	6804	g	1.00E+09	0	6.80E+12	6.80E+12	6.80E+12
	21 Tools and machinery	318	370	352	181	$	1.25E+12	3.98E+14	4.63E+14	4.40E+14	2.26E+14
	22 Other supplies (purchased)	21	56	52	66	$	1.25E+12	2.63E+13	7.00E+13	6.50E+13	8.25E+13
	Total (M)							2.15E+15	2.58E+15	1.78E+15	3.22E+15
	Services (S)										
	23 Labor	99	467	292	385	hours	4.70E+12	4.65E+14	2.19E+15	1.37E+15	1.81E+15
	24 Waste collection, processing	2.50E+05	4.00E+04	5.10E+04	2.20E+04	g	3.26E+07	8.15E+12	1.30E+12	1.66E+12	7.17E+11
	Total (S)							4.73E+14	2.20E+15	1.37E+15	1.81E+15
	Total (F)							2.63E+15	4.77E+15	3.15E+15	5.03E+15
Y	Yield										
	25 Vegetables	0	5.50E+09	2.60E+09	4.20E+09	J	3.28E+05	0	1.80E+15	8.53E+14	1.38E+15
	26 Small fruit	0	6.80E+06	3.50E+07	3.90E+07	J	3.41E+05	0	2.32E+12	1.19E+13	1.33E+13
	27 Tree fruit	0	1.50E+07	1.50E+07	1.50E+07	J	2.87E+05	0	4.31E+12	4.31E+12	4.31E+12
	28 Nuts	0	0.00E+00	0.00E+00	6.80E+06	J	8.43E+05	0	0	0	5.73E+12
	29 Cut flowers	1.10E+07	4.30E+06	0	6.50E+07	J	2.37E+05	2.61E+12	1.02E+12	0	1.54E+13
	Total (Y)							2.61E+12	1.81E+15	8.69E+14	1.42E+15

Calculations and references for transformities are given in Appendix C. Data are presented in exponential notation so that $2.8\text{E} + 10 = 2.8 \times 10^{10}$. Categories on far left (I, F, Y) are from aggregated system diagram (figure 6) and were used in the calculation of Emergy indices (Table 4).

Table 4. Emergy indices for four landscape plots (conventional ornamental landscape, intensive organic garden, edible landscape, forest garden) at The Ohio State University's Waterman Farm, Columbus, Ohio based on a five year projection

		Result			
	Calculation	Conventional landscape	Intensive organic garden	Edible landscape	Forest garden
Category totals					
Renewable resources (R)	From figure 2.9	2.28E+13	2.28E+13	2.28E+13	2.28E+13
Non-renewable resources (N)	From figure 2.9	3.40E+11	3.03E+12	3.03E+12	4.51E+11
Environmental inputs (I)	$R + N$	2.31E+13	2.58E+13	2.58E+13	2.33E+13
Materials (M)	From figure 2.9	2.15E+15	2.58E+15	1.78E+15	3.22E+15
Services (S)	From figure 2.9	4.73E+14	2.20E+15	1.37E+15	1.81E+15
Economic inputs (F)	$M + S$	2.63E+15	4.77E+15	3.15E+15	5.03E+15
Yield (Y)	From figure 2.9	2.61E+12	1.81E+15	8.69E+14	1.42E+15
Indices					
Emergy yield ratio (EYR)	Y/F	9.92E−04	0.38	0.28	0.28
Emergy investment ratio (EIR)	F/I	114	185	122	216
Environmental loading ratio (ELR)	$(F + N)/R$	115	210	138	221
Emergy sustainability index (SI)	EYR/ELR	8.61E−06	1.81E−03	1.99E−03	1.28E−03

Data are presented in exponential notation so that 2.8E + 10 = 2.8×10^{10}. Indices calculated using category totals from Table 3.

could continue to be used for multiple seasons. We assumed a 10% re-purchase rate. We eliminated from labor projections all work that only needed to be done the first season (e.g., building compost bins), calculated a weekly average for subsequent years, and added two average weeks to the total to account for early season maintenance. Waste collection was based on the assumption that the same quantities of organic waste and plastic waste from cell packs would be discarded each season and that stakes would be thrown away as they were replaced.

The yield of vegetables was assumed to be identical each season. Small fruit yields included additions of jostaberries the second season and grapes in seasons four and five. Tree fruit yields also began in years four and five. Projected yields of fruits not harvested in 2001 were based on average U.S. yields (Jeavons, 1995). Cut flowers were counted at the same levels each season. Emergy indices were calculated as for the 2001 season (Table 4).

Results

The renewable environmental inputs were equal for all plots (Table 1). Rain was the renewable input with the greatest value (3.09×10^{12} sej), as is frequently the case in Emergy analyses of agricultural systems (Comar, 2000; Johannson *et al.*, 2000). Soil loss was greater in the intensive organic garden and the edible landscape due to the exposed soil in the planting beds. Non-renewable inputs, however, represent only 7–16% of the total environmental contribution.

Plants themselves were the greatest of the material inputs in the conventional ornamental landscape and the forest garden. In the intensive organic garden and the edible landscape plant materials were the second greatest inputs after tools and machinery. Other purchased inputs (compost, manure, lumber and other supplies) also made substantial contributions to the materials total. The Emergy input from manure and compost was nearly twice as much in the intensive organic garden and the forest garden as in the other landscapes. Due to the construction of compost bins and a trellis, the intensive organic garden and the edible landscape had much larger Emergy inputs in the form of lumber than the other landscapes. Water too was a significant input. The input of water to the forest garden was 1/3–1/2 of that to the other landscapes. Due to the mostly organic management of the plots and the extensive use of manual labor, items that are normally high contributors in agricultural systems (fertilizer, pesticide, fuel) were less significant in these landscapes. Sources of organic matter (including bark mulch, leaves, and newspaper) made a greater contribution to the totals in the plots where they were used. Despite differences of two or more orders of magnitude in individual material input items, the total material inputs for each plot were all in the same order of magnitude. The edible landscape had the lowest Emergy of material inputs at 1.23×10^{15} sej, and the forest garden the highest at 2.16×10^{15} sej. Labor was a very important input as well. In the intensive organic garden it was the greatest economic input of all. Compared to labor, waste collection and processing made only a minor Emergy contribution. The sum of economic inputs from the economy in all plots was three orders of magnitude greater than the sum of environmental inputs.

The total yield of all plots was largely determined by its yield of vegetables. The total yield of the conventional ornamental landscape was low, as this plot was not designed to have productive value. The total yield of the intensive organic garden was greatest at 3.61×10^{14} sej. The forest garden had a total yield of 2.76×10^{14} sej. The edible landscape had a total yield of 1.71×10^{14} sej. The total yield of every plot was less than the total economic inputs into that plot.

The Emergy Yield Ratio (EYR) was greatest in the intensive organic garden at 0.17, but still far below 1.0 (Table 2). The edible landscape and forest garden both had EYRs of 0.11. Given the high amount of inputs used to establish these plots, we anticipated a low EYR in the first season. The Emergy Investment Ratio and Environmental Loading Ratio were also very high, highest in the forest garden and lowest in the edible landscape. The Emergy Sustainability Index too indicates that the plots were far from sustainability. Of the food-producing plots, the intensive organic garden had the greatest index (0.00025), due to its higher yield, and the forest garden the lowest (0.00013), due to its higher ELR.

Five year projection

Renewable environmental contributions increased in the five year projection, but were still two orders of magnitude less than the economic inputs from the first season (Table 3). Rain remained the largest environmental input at 2.28×10^{13} sej. The relative contribution of soil to the environmental inputs decreased over the five year projection, especially in the conventional ornamental landscape and the forest garden where vegetation and mulch keep the soil virtually fully covered.

The Emergy input from plant materials increased to the point that, proportionally, it was the greatest material input in all plots. One-time inputs from the 2001 season (e.g., compost, tools and machinery) still represented a substantial portion of the economic inputs total. Over five years bark mulch became one of the largest inputs. The edible landscape still had the lowest material inputs at 1.78×10^{15} sej and the forest garden the highest at 3.22×10^{15} sej. In all plots except the conventional ornamental landscape, labor became the greatest economic input of all. Waste collection and processing was still a relatively minor input.

Projected yields through five seasons were primarily determined by vegetable yields, even though the other small fruits, fruit trees and nuts began to yield in the later years of the projection. The intensive organic garden was projected to have the greatest yield at 1.81×10^{15} sej. The forest garden was projected to yield a total of 1.42×10^{15} sej over five seasons. The edible landscape was projected to yield 8.69×10^{14} sej. Even over five seasons, however, yields still have not surpassed inputs.

The EYR of all plots remained below 1.0 (Table 4). It was highest (0.38) for the intensive organic garden, and equal for the edible landscape and forest garden (0.28). The Emergy Investment ratio and Environmental Loading Ratios of the plots still remained very high. The edible landscape was projected to have the highest Emergy Sustainability Index at 0.002, and the intensive organic garden was close behind at 0.0018. These indices, however, remained very low.

Discussion

Emergy analysis shows the three productive landscapes used in this study to be far from sustainable. Compared with other food production systems on which Emergy analyses have been performed, the plots in this study had very low Emergy Yield Ratios. Ulgiati *et al.* (1994) report an overall EYR of 1.43 for Italian agriculture. Comar (2000) reports EYRs of 1.56 for a biodynamic farm, and 2.14 for a conventional farm in Brazil. Even after five years, the intensive organic garden, edible landscape and forest garden in this study are projected to have EYRs ranging from 0.28 to 0.38. The Emergy Sustainability Indexes of these plots are also extremely low, 0.0013–0.002, compared to 0.9 and 2.39 for the biodynamic and conventional production systems in Brazil (Comar, 2000). These low SIs indicate that the plots are consuming large amounts of economic and non-renewable resources relative to the extent that they harness renewable energies and yield high Emergy products.

While the sustainability of the plots appears to increase with time, it is unlikely that projections beyond five years would produce EYRs and SIs equal to or greater than 1.0. Beyond five years certain initial inputs, such as lumber, tools and machinery, would need to be replaced, thereby increasing the economic inputs even as yields continued to increase. The fundamental issue is not the time frame of the analysis, but the Emergy Investment Ratios (EIR) (figures 2.8, 2.10), which are very high for all plots.

The principal reason for the high EIRs (and the low EYRs and SIs) are the high levels of economic inputs from the economy used in the establishment and maintenance of these plots. Items such as compost, lumber, tools and machinery that are purchased initially for use in the plots represent a considerable investment of Emergy into the systems. Even plant materials, the essential items in any landscape or garden, represent an enormous Emergy investment. Labor is a very significant input to all of the systems, particularly in the five year projections. These small-scale plots do not lend themselves to mechanical management and require hand labor for nearly every task.

Two of the items which represent a large Emergy input to the forest garden are perhaps over-valued. Leaves and newspaper collectively account for over a quarter of the Emergy invested in the forest garden. If the leaves and newspaper had to be produced and purchased, these figures would be accurate. These items, however, are freely available in most cities for the effort of collecting them. Eliminating leaves and newspaper from the analysis, however, would only bring the economic inputs of the forest garden in line with the inputs to the intensive organic garden and the edible landscape and would not dramatically alter its indices.

Despite large differences in individual items, all of the food-producing plots end up with total economic inputs in the same order of magnitude in both the 2001 season and the five year projections. This indicates that the different systems trade off certain inputs for others. The forest garden, for instance, uses no fuel, fertilizers or machinery for lawn care, but substitutes leaves and manure for its sheet mulch and more plant materials to take the place of grass.

To attempt to create more favorable EYRs, one approach would be to decrease inputs. Substitutions may be possible to reduce the level of certain inputs. Compost bins, for instance, could be constructed with less expensive (and Emergy-rich) lumber. Landscaping fabric could be used beneath bark mulch to reduce its replacement rate. This fabric in turn, though, would represent the input of a certain amount of Emergy. As with the trade-offs discussed above, substituting resources may not decrease the overall level of inputs. Another method of decreasing inputs is to produce more resources on site. Instead of importing such large quantities of compost initially, for instance, fertility could be built over time on site through the growth of compost crops. As this approach may negatively affect short-term yield, however, it could have less of an impact on EYRs than desired. Seed saving and on-site propagation would reduce plant material costs, but would require further investments of time.

The second approach to improving the EYRs of food-producing landscapes would be to increase their yields. Of all the items in the five year projection, yields are the most uncertain. As the systems develop and their management improves, yields may increase substantially. Biointensive gardeners report yields of up to 322 pounds from 100 square feet in one growing season (Ecology Action, 2002). These are yields 5.5 times greater than the yields of the intensive organic garden in this study. As few significant additions of external nutrients are projected, however, yields of our plots could potentially decline over time. Weather and pest and disease pressures also vary from season to season. Differences in productivity between plots could emerge more clearly in later seasons. Increasing yield through more intensive management, intercropping, and season extension with cold frames and cloches would likely require further inputs of plant materials, labor, and other supplies, which, as we have seen, are three of the greatest inputs to the plots already. In short, it is difficult to predict whether, on balance with inputs, yields of these plots can be increased sufficiently to produce EYRs of greater than 1.0.

It is possible that larger plots devoted to these systems would have EYRs and SIs closer to 1.0, as yields increased with area and the systems benefited from economies of scale. Whether increases within the confines of a typical urban or suburban lot, or the time budget of a typical family would be sufficient, however, is uncertain. A better approach in a larger residential lot might be to devote some of the area to the production of resources (e.g., rough lumber, leaves, composting materials) for use in the food-producing components of the system.

It is instructive to compare the three productive plots to the conventional ornamental landscape, which was designed to represent what is present in a typical midwestern back yard. The SI of the conventional ornamental landscape is three orders of magnitude lower than the SIs of the productive plots in the 2001 season and after the five year projection. In the 2001 season the conventional ornamental landscape consumed fewer resources than any plot save the edible landscape, and after five years it is projected to consume fewer resources than any of the others. The resources it did consume, however, are put to less productive use. As the conventional ornamental landscape was not designed to produce anything, it is expected that its EYR, and therefore its SI, would be extremely low. Emergy analysis does not value the other "products" of an ornamental landscape, including a relaxing environment, a desirable public image, or insect and wildlife habitat. These "products" may be found to some degree, however, in all of the landscapes included in this study. The aesthetic value or intrinsic "beauty" of constructed landscapes cannot be quantified in the same emergy terms as can physical products or outputs, such as fruit, flowers, or compost. Aesthetic value, though arguably real in terms of human comfort and well-being, is subjective in the extreme, and does not correspond to either the perceived or actual complexity and maintenance requirements of residential landscapes (Beck *et al.*, 2002).

This analysis defines the system borders as the borders of the individual plot. When so defined, the systems prove to be far from sustainable. The question remains of what effect food-producing landscapes would have on the larger systems of a household, a neighborhood and a city. At the household level, for instance, labor, one of the largest inputs, would not have to be imported, merely re-allocated, with multiple potential effects on sustainability. At the neighborhood level, leaves, newspaper and even bark mulch could be obtained from within the borders of the system, rather than having to be imported. At the city level, finished compost and plant materials could all be produced and cycled internally. At all of these levels, the food produced internally would reduce the need for food to be purchased and transported from elsewhere. Larger scale operations possible at the neighborhood or city level might also have different economies of scale. Our comparison with the conventional ornamental landscape suggests that putting productive landscapes on 32% of an residential city block, as Levenston *et al.* (2001) indicate is possible, would increase the EYR and SI of that system, but may not bring these indices up to 1.0.

Conclusion

We conducted an Emergy analysis of a model conventional urban residential landscape and three food-producing alternative landscapes. Our analysis indicates that urban residential landscapes consume a great quantity of resources and that even food-producing systems yield far less Emergy than they consume. Manufactured inputs such as lumber, tools and machinery account for part of the total inputs, but essential items such as plant materials and labor account for a large portion of the total. By themselves the productive plots evaluated in this study are not sustainable food production systems. To evaluate whether they would be sustainable in a larger household or city context will require further research. As long as such landscapes are primarily supplied through the Emergy-intensive economic system, however, Emergy Yield Ratios and Emergy Sustainability Indices are likely to remain low. Installing food-producing landscapes alone may not substantially alter the heterotrophic nature of cities.

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