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Emergy Analysis of the Resource Use in Greenhouse Crop Production and of the Resource Basis of the Swedish Economy

Charlotte Lagerberg

Swedish University of Agricultural Sciences

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Akademisk avhandling som för vinnande av agronomie doktorsexamen kommer att offentligen försvaras i aulan, Alnarpsgården, SLU, Alnarp, fredagen den 1 oktober, kl. 10.00.

Opponent: Professor Sergio Ulgiati, Department of Chemistry, University of Siena, Siena, Italy.

Abstract
During the past decades there has been an increasing concern about degradation of environmental systems. This has lead to an increased interest in environmental accounting methods providing decision support on issues regarding sustainability and effects of human activities. In the long run, crop production systems must be environmentally and socially adapted as well as productive. This thesis uses emergy analysis to adress issues of resource flows, environmental stress and sustainability of conventional and organic tomato production systems. An analysis of the Swedish economy was also performed. Since this larger economic system provides purchased inputs for the crop producing nurseries, this analysis on the national level is necessary to visualise resource flows of the subsystems. Trends concerning use of resources, trade, environmental loading and sustainability between 1988 and 1996 were addressed. It is concluded that the sustainability of the Swedish economy will be enhanced by decreasing the dependency on imported non-renewable resources. A similar conclusion is drawn on the company level. By replacing fossil fuels for heating of greenhouses with a more renewable locally produced fuel, such as wood powder from logging residues, the sustainability of tomato production systems can be improved. Raising the yield was found to be an important factor for enhanced efficiency in resource use of the studied organic tomato production systems. The replacement of fuels was shown to be more important than the fertilizer strategy in directing the tomato production systems towards sustainability.

Key words: energy, environmental load, fuel, organic, sustainability, tomato, wood powder

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Errata

to Lagerberg, C. (1999). Emergy analysis of the resource use in greenhouse crop production and of the resource basis of the Swedish economy. Doctoral thesis. Acta Universitatis Agriculturae Sueciae. Agraria no. 191, Swedish University of Agricultural Sciences, Alnarp.

p.12, 3rd paragraph, line 6: hierarchy

p.14, 3rd paragraph, line 7: ...inputs to a process, ...

p. 14, 5th paragraph, line 2: population centres like farms converge resources (products) to villages....

p. 18, 1st paragraph, line 7: ...appropriate when ~~not~~ there is no access....

p. 21, 4th paragraph, line, last line: ...; Marcettini, 1996). should be ....; Bastianoni and Marchettini, 1996).

paper II, p. 4, 1st paragraph, 1st line: ..denotes the available energy...

paper II, p. 9, 2nd paragraph, line 1: ...of exported goods ~~and services~~...

paper II, p. 10, 1st paragraph, line 1: ...(Table 1, note 13)...

paper II, p. 10, Table 2, footnote *** ....calculated in proportion to ILR for trade partners...

paper II, p. 11, Table 3, same as Table 2 footnote ***

paper II, p. 21, 3rd paragraph, line 2: about two or less indicates....

paper II, p. 21, 3rd paragraph, line 9: resource yield ratio~~n~~ near unity...

paper IV, p. 1, abstract, line 4: ...fertilizer, were compared to....

paper IV, p. 1, abstract, line 8: .... were shown to utilize....

paper IV, p. 2, 4th paragraph, line 8: ...during the earlier ~~and later~~ part~~s~~ of the year.

paper IV, p. 6, 5th paragraph, line1: The tomato production system a) was......

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To my darling Fredrik Fogelberg
and my dear parents
Connie Lagerberg and Karl-Erik Lagerberg

It is much easier to be critical than correct
Benjamin Disraeli

In memory of Märta Lagerberg
and Bruno Persson

The problems that exist in the world today cannot be solved with the level of thinking that created them
Albert Einstein

Abstract

Lagerberg, C. 1999. *Emergy analysis of the resource use in greenhouse crop production and of the resource basis of the Swedish economy.* Doctoral dissertation. ISSN 1401-6249, ISBN 91-576-5742-4.

During the past decades there has been an increasing concern about degradation of environmental systems. This has lead to an increased interest in environmental accounting methods providing decision support on issues regarding sustainability and effects of human activities. In the long run, crop production systems must be environmentally and socially adapted as well as productive. This thesis uses emergy analysis to adress issues of resource flows, environmental stress and sustainability of conventional and organic tomato production systems. An analysis of the Swedish economy was also performed. Since this larger economic system provides purchased inputs for the crop producing nurseries, this analysis on the national level is necessary to visualise resource flows of the subsystems. Trends concerning use of resources, trade, environmental loading and sustainability between 1988 and 1996 were addressed. It is concluded that the sustainability of the Swedish economy will be enhanced by decreasing the dependency on imported non-renewable resources. A similar conclusion is drawn on the company level. By replacing fossil fuels for heating of greenhouses with a more renewable locally produced fuel, such as wood powder from logging residues, the sustainability of tomato production systems can be improved. Raising the yield was found to be an important factor for enhanced efficiency in resource use of the studied organic tomato production systems. The replacement of fuels was shown to be more important than the fertilizer strategy in directing the tomato production systems towards sustainability.

Additional key words: energy, environmental load, fuel, organic, sustainability, tomato, wood powder

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Contents

Appendix

Papers I-IV

This thesis is based on the following papers, which are referred to by their Roman numerals.

I. Ohlander, L. Lagerberg, C. & Gertsson, U. (1999). Visions for ecologically sound agricultural systems. *Journal of Sustainable Agriculture* **14**(1), 73-79.

II. Lagerberg, C. Doherty, S. J. & Nilsson, P. O. Evaluation of the resource efficiency and sustainability of the Swedish economy using emergy based indices. *Manuscript.*

III. Lagerberg, C. & Brown, M. T. (1999). Improving agricultural sustainability: the case of Swedish greenhouse tomatoes. *Journal of Cleaner Production* **7**. *In press.*

IV. Lagerberg, C. Gertsson, U. Larsen, R. & Gäredal, L. Emergy evaluation of five greenhouse tomato production systems. *Manuscript.*

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Introduction

Long-term sustainability is the key to the future of humanity. Recognizing that the welfare of human economies is closely linked to the status of environmental systems, the issues of sustainability have reached the political agenda during the past decades. Several general criteria for sustainability have been proposed (e.g. World Commission on Environment and Development, 1987; Robèrt, 1994) which may be useful for overall guidance in the development of detailed tools of investigation. Environmental systems function as sources for resources driving our economic systems and sinks recycling and upgrading byproducts from society, on different scales of time and space. Costanza et al. (1997) estimated the economic value of biospheric services, directly and indirectly contributing to human welfare, to about USD 33 trillion (x 10^{12}) annually. Vitousek et al. (1986) estimated that nearly 40 percent of the net primary production of terrestrial ecosystems is used directly and indirectly for human activities.

For long-term sustainability, accurate decisions must be made about resource management and about the systems supporting our economies. Decision support tools for evaluating strategies, defining goals and monitoring progress are thus required. The concept of "Energy Return On Investment" (EROI) (Hall et al., 1986), i.e. the output/input ratio or net energy balance (e.g. Scrase et al., 1993), is a widely used indicator for addressing the feasibility of an energy generating process. The output/input energy ratio has been used extensively as an indicator of efficiency in investigations of agricultural products (Pimentel and Pimentel, 1979; Stanhill, 1980; Reist and Gysi, 1990; Jolliet, 1990; Franzluebbers and Francis, 1995). In this type of value system, resources are only assigned value in accordance with the direct and indirect fuel inputs associated with their production. Inputs not associated with fuel inputs are assigned no value. Targeting agricultural systems to higher output/input ratios may not be feasible, considering that agricultural food production systems are not designed to produce fuels for boilers. By aiming at high output/input ratios for food, products rich in fat and requiring postagricultural processing are benefited whereas products rich in water and ready-to-eat products are miscredited. Fluck (1992a) suggests that the quantity of agricultural product per unit of energy input be used instead of output energy per unit input energy. Measuring accumulated direct and indirect fuel energy inputs have been adopted and incorporated into other tools, e.g. Life Cycle Assessment (LCA) (Lindfors et al., 1995).

Several methods and tools have been invented for analysing resource use and its consequences, e.g. Material Intensity Per Unit Service (MIPS) and "Ecological Rucksack" (Tischner and Schmidt-Bleek, 1993; Schmidt-Bleek, 1996; Schmidt-Bleek, 1997), Ecological Footprint (Wackernagel and Rees 1996; Folke et al. 1997; Wackernagel et al., 1997), Exergy analysis (Wall, 1987; Mc Govern, 1990) and Life Cycle Assessment. Sets of indicators have also been proposed (Azar et al., 1996; Bockstaller et al., 1997), but a method of appropriate weighting among indicators has yet to be developed. Andersson et al. (1998) proposed a way of incorporating four socio-ecological principles (Holmberg et al., 1996) into the LCA framework. Mattsson and Cederberg (1999) suggested indicators for land use to be included in the LCA methodology.

Assigning adequate value to human labour is as yet an unresolved matter in the above methods. Fluck (1992b) points out the difficult decision of how to allocate energy to labour. In energy analysis, human labour is usually either ignored, because of its low energy content, or reported in the form of "hours of man power". Systems using different amounts of materials or energies cannot be compared unless the materials and energies used are of the same kind.

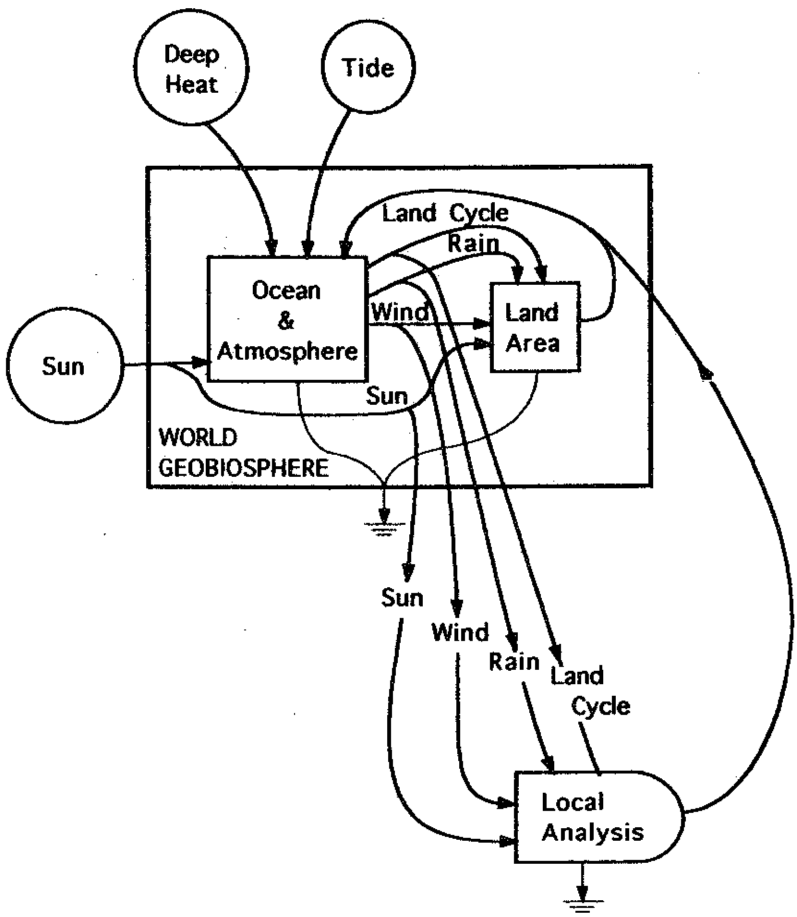


Figure 1. Emergy flows from the biosphere support the functioning of local systems. Modified from Odum (1996). Printed with the courtesy of John Wiley & Sons, Inc.

Obviously, items with the same contents of available energy may not share the same resource basis, i.e. the resources that went into making a product are not reflected by its energy content. Comparing systems with energy as the tracer for resource use thus requires that the different energies are weighted into one common type of energy, such as the solar energy equivalents used in emergy analysis (Odum, 1996).

The emergy analysis assigns values to natural resources as well as to materials, fuels and human services. These values are ultimately derived from the work of environmental systems, supplied via economic systems. It assigns intrinsic values to resources lacking direct market values and to resources not associated with fuel use. Items receive values in accordance with how much of the earth´s total driving force is required to run the analyzed subsystem. Figure 1 emphasizes the global perspective of the emergy analysis, showing the direct environmental inputs supporting a local area. Other materials, fuels and human labour are environmental resources fed through the economic system. The human economic system is regarded as a part of the larger environmental system and must contribute to the systems sustaining it, in order to remain a useful component.

Objectives

The objective of this thesis was to analyse resource flows, environmental loading and sustainability of crop production systems, using emergy analysis as the tool. The emergy analysis was chosen as the tool because of its ability to evaluate systems embracing different kinds of inputs within one value system.

The chosen systems were two greenhouse tomato production systems, a conventional Swedish system and an experimental organic Swedish production system. Tomato was chosen since it is an important horticultural crop. The conventional production systems are very intensive with respect to high inputs of non-renewable resources and high outputs. The production takes place in heated greenhouses. The effect of replacing the fossil fuel for heating with a fuel to a larger extent based on renewable resources was studied, as well as an alternative strategy for nutrient supply. The analysis was performed at company level, i.e. the economic units of tomato-producing companies were studied.

Subsystems cannot be fully analysed without knowledge of the resource flows of the economy in which they work. Therefore a full emergy analysis of the Swedish economy was performed, investigating the use of resources, trade, environmental loading, and sustainability.

General aspects on sustainability of agricultural systems are also discussed.

Emergy Analysis

The emergy analysis concept originates from the extensive works of Dr H.T. Odum and his colleagues at the University of Florida in Gainesville, USA (Odum, 1971; Odum, 1975; Odum and Odum, 1976; Odum et al., 1987; Odum, 1987; Odum, 1988a; Hall, 1995; Odum, 1996). The method has its roots in fundamental principles of systems ecology and self-organization of environmental systems of which the human systems are a part (Odum, 1988b; Beyers and Odum, 1993; Odum,1994). During the past decade the method has gained wider interest internationally and researchers from several countries have made further contributions within the field. Emergy analysis may be used for decision making on national level (Odum and Odum, 1983; Odum and Arding, 1991; Huang and Odum, 1991; Ulgiati et al., 1994) as well as regional (Odum et al., 1987a; Brown et al., 1991; Shengfang and Odum, 1994; Brown et al., 1995; Brown and McClanahan, 1996; Sohn et al., 1996; Prado-Jatar and Brown, 1997; Odum et al., 1998) and process levels (Pillet, 1991; Ulgiati et al., 1993; Bastianoni et al., 1994; Doherty, 1995).

Emergy, hierarchy and transformity

Emergy is defined as the accumulated resources used to produce a merchandise, service, or fuel, available in its present form, expressed in a common type of energy, solar Joules. To indicate that we are dealing with emergy, the unit is called solar emjoules (sej). Sometimes emergy is referred to as "energy memory" (Scienceman, 1987). While the energy content, in Joules, represents the energy still available in the product, the emergy, expressed in emjoules, represents the memory of the energy used in making the product. Emergy analysis accounts for direct environmental resources (e.g. solar insolation) as well as indirect environmental resources, i.e. materials, fuels and human labour supplied via economic markets.

All processes are driven by energy transformations. During the course of transformation, according to the Second Law of Thermodynamics, some available energy is lost. All systems, whether large or small, are organized in webs of energy transformations, resembling trophic levels, where the complexity of the structures increase with each transformation step. Figure 2 shows an example of an energy transformation *hierachy*. Reading the figure from left to right, in each transformation step (dashed vertical lines) some available energy is degraded and lost while energy of lower complexity is transformed into a smaller quantity of energy of higher complexity. Many Joules of one kind converge to fewer Joules of the next level, as shown by Figure 2d. The heat sinks designate that some available energy is lost during the process of transformation. The energy required

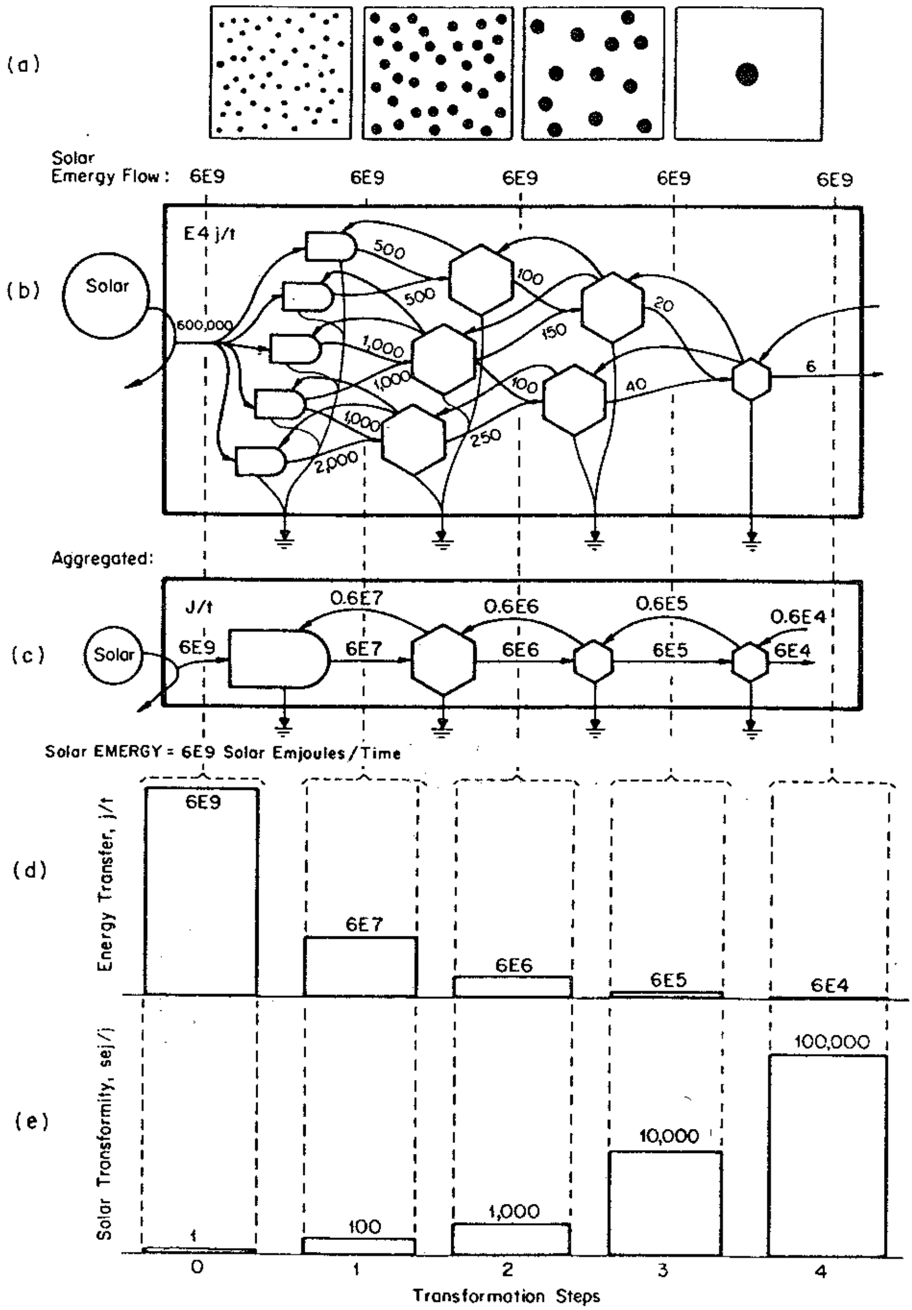


Figure 2. Energy transformation hierarchy. (a) Spatial view of units and their territories. (b) Energy network with transformations and feedbacks. (c) Aggregation of energy networks into an energy chain. (d) Energy flows for the levels in the energy hierarchy. (e) Transformities. From Odum (1996). Printed with the courtesy of John Wiley & Sons, Inc.

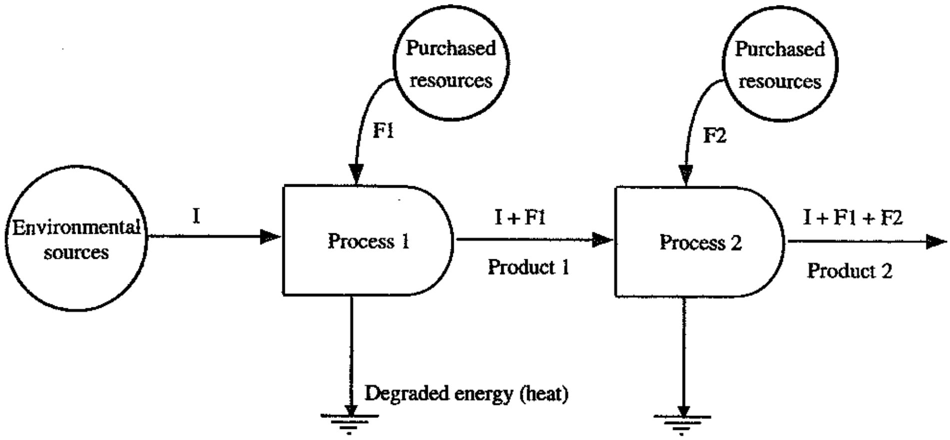
to sustain a process, expressed in a common type of energy (sej), increases with each transformation step. This leads to the key concept of *transformity*. Another way of expressing it is that the transformity is the emergy divided by the energy content of the product. Its unit is thus sej/J. The transformity reflects the level of complexity and the position of the product in the global hierarchy of energy webs. It is regarded as a measure of energy quality in emergy analysis. It is thus a different measure that must not be confused with the physical energy quality measured by availability to do work (exergy). The transformity will increase with each transformation step (Figure 2e).

Emergy is a measure of energy convergence over time and space. Small things (e.g. forget-me-nots), with a rapid turnover and having small territories of influence, have small transformities while larger things (e.g. oak trees), having longer turnover times and larger support areas, have larger transformities (Figure 2a). Doherty (1995) found higher transformities to be coupled to longer replacement times in forestry systems. The feedbacks from higher levels shown in Figure 2b and c are imperative in order to sustain the web. By feeding back some higher transformity energy down the chain (from right to left in Figure 2) the higher transformity level controls lower transformity flows and amplifies the flows of useful energy supporting its existence. The higher the transformity of an item, the greater the environmental work required to produce it and the greater the potential impact on its surroundings (Odum, 1996; Brown and Ulgiati, 1997).

The emergy of an item is the energy content of the item multiplied by its transformity. For calculation purposes it is sometimes convenient to express transformities in emergy per unit flow (e.g. sej/kg glass), but in its strict sense it is by definition always expressed per unit available energy (sej/J). Transformities are usually available from other studies (e.g. Brown and Arding, 1991; Haukoos, 1994; Odum, 1996). Figure 3 shows how transformities are calculated by summing all the inputs to process, direct environmental inputs as well as purchased inputs, expressed in emergy (sej), and then dividing this total emergy by the energy content of the product of the process. This was how the transformity of aluminium in the appendix of Paper III and the transformity of organic tomatoes in Table 1 (item 43) of Paper IV were estimated.

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

Systems including people are also organized in energy hierarchies, where population centres like villages converge resources (products) to villages converging further towards towns and cities (Odum, 1996).



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

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

Figure 3. Calculation of transformities. From Lagerberg (1999). Printed with the courtesy of International Society for Horticultural Science.

The global emergy budget

The baseline for emergy analysis is the energy budget of the earth, from which all transformities are ultimately derived. Three independent sources interact to run the processes of the global geobiosphere, i.e. solar insolation, tidal energy and deep heat energy from inside the earth (Figure 4). Data on solar energy, tidal energy and the energy from earth heat are used to estimate the average emergy of wind, water and earth flows. The total emergy of the geobiosphere is 9.44E24 sej/year (Figure 4; Odum, 1996). From energies and turnover times, transformities of further components of the earth energy hierarchy were calculated.

Using these transformities, the environmental emergy supporting local areas is calculated (Figure 1). If direct environmental flows are coproducts of the same source, only the largest emergy flow is used, since this flow accounts for the emergy of coproduct flows as well. For instance, in the case of Swedish greenhouse tomatoes (Paper III, Table 1) only the rain component was used. For more information on emergy of global processes, calculations of basic transformities and the emergy budget of the biosphere, see Odum (1996) and Brown and Ulgiati (1999).

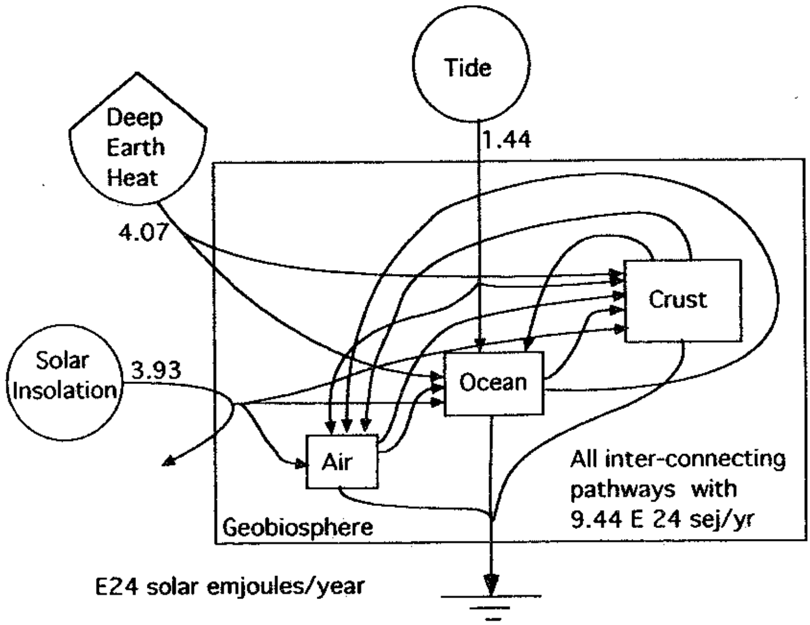


Figure 4. Independent sources driving the processes of the geobiosphere. Pathways within the system share the same baseline emergy of 9.44×10^{24} sej/year. From Odum (1996). Printed with the courtesy of John Wiley & Sons, Inc.

Evaluating systems involving the human economy

Figure 5 shows an overview of the human economic system incorporated in the global system and dependent on the environmental processes serving as sources and sinks for resources entering and leaving the economic system. Dashed lines represent monetary flows, which always flow in the opposite direction to resource flows. Money is paid to people in accordance with the amount of human labour required for processing and handling of natural resources. In general, money can thus be regarded as a symbol of accumulated human labour associated with the merchandise being traded in the economic system. This approach provides the emergy analysis with the means to assign emergy value to human labour, i.e. to evaluate human labour within the same value system as purely environmental services supporting the system in question.

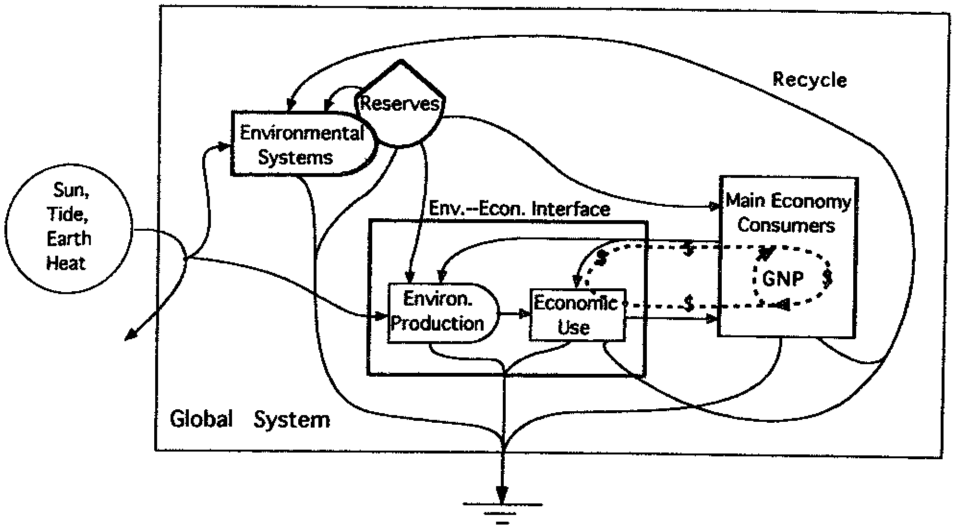


Figure 5. The global system with the embedded human economic system dependent on environmental services. From Odum (1996). Printed with the courtesy of John Wiley & Sons, Inc.

An emergy to currency ratio is produced by calculating the annual emergy budget of the national economy of which the subsystem is a part, i.e. accounting for direct environmental inputs as well as mined resources and imported inputs required to support the economy, and dividing it by the total monetary flow being supported by the resources, i.e. the gross domestic product (GDP). This ratio, expressed in sej/currency (Paper II, Table 4, line 19) reflects the average resources required to circulate a unit of currency in the economy. It may be regarded as a resource shadow carried by the currency and is dependent on the lifestyle of the nation, i.e. the kinds of resources and services we require to lead our lives.

In the subsystem, the macroeconomic resource shadow supporting the direct and indirect labour used in the system is arrived at by multiplying the price (e.g. USD or Euro) of the direct labour and input merchandise (materials and fuels) by the emergy to currency ratio (e.g. sej/USD or sej/Euro) for the economy in which the analysed subsystem works. In this way, we produce an accumulated measure of the resources required in support of the human services (labour) from raw material to purchased product.

From this it follows that purchased inputs have two components contributing to their emergy value, i.e. the emergy associated with the accumulated natural resources used in producing the input and the emergy supporting the human services required for handling in the economy.

Services to subsystems may suffer from imperfections of market pricing, but even so the price will still reflect the average resources shadow required to circulate the money in the economy, i.e. the work that this money generates in the economy. Another way of assigning emergy value to direct human labour includes dividing the total resource use of the national economy with e.g. the total working hours of the nation and multiplying this emergy/working hour by the hours worked in the subsystem. This may be appropriate when not there is no access to monetary flows of the system under analysis.

Emergy indices

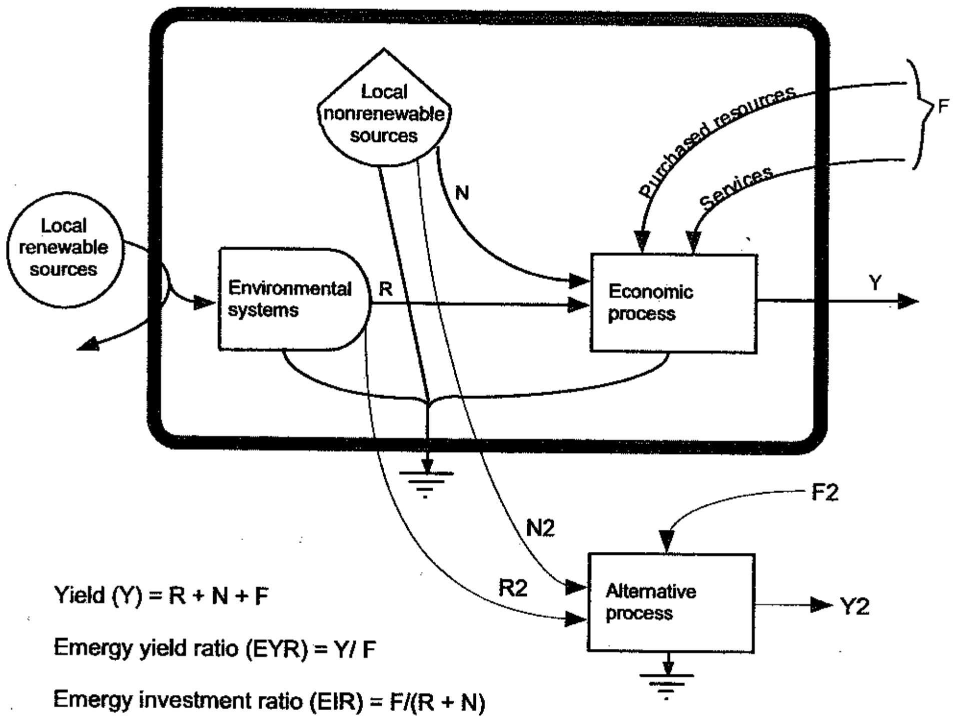
In order to evaluate for instance a production system and alternative productions, one defines the flows of inputs supporting the production, by setting up a table where the raw data (unit flows) are multiplied by their transformity. Thus the emergy contribution of each input to the functioning of the system is accounted for.

Once inputs are weighted into the common type of energy, resulting in emergy, and summed to arrive at the total emergy support required to drive the analysed system in question, flows of different kinds can be compared. Figure 6 shows the calculation of some selected indices which may be used to analyse the performance of the system further.

The emergy yield (Y) is defined as the sum of all emergy inputs to the process in question. The higher the emergy yield, the more resources went into making the product(s) of the process or system. The emergy yield ratio (EYR) is the yield divided by the emergy of purchased inputs. This index indicates the dependency of non-local (purchased) inputs and the ability to make use of local resources. In the case of fuels, the EYR indicates whether the output of the process is capable of competing as a primary energy source for the economy. The higher the EYR, the higher the return on invested emergy. If the EYR is less than 1, the output of the system does not deliver a positive net contribution to the economy. In the case of national economies which do not have a yield to a larger economy, the EYR is more of an index of total emergy use divided by the imported emergy. Sometimes the EYR has been termed net yield ratio (NYR).

The emergy investment ratio (EIR) is calculated by dividing the flow of purchased emergy by the local free renewable and non-renewable emergy received from the environment. The EIR indicates whether the production is using the inputs from the economy efficiently, regardless of whether they are renewable or not, compared with alternative processes. If the process draws less inputs from the economy and relatively more free resources from the local environment than competing processes, the EIR is less than that of competitors. The price of products from this process will be lower than for products of competing processes. Similarly, if the process draws more inputs from the economy per unit of free inputs from the local environment, the process may be less competitive and product prices may be higher. For national economies, the EIR indicates whether the economy is an efficient user of imports in exploiting indigenous environmental resources.

The environmental loading ratio (ELR) is defined as the sum of the emergy of local non-renewable emergy, purchased emergy and services divided by the local renewable emergy, i.e. developed divided by renewable flows. A large ELR suggests high environmental stress by the process and is usually indicative of highly technological systems running on large amounts of non-renewable flows.



Yield (Y) = R + N + F

Emergy yield ratio (EYR) = Y/ F

Emergy investment ratio (EIR) = F/(R + N)

Environmental loading ratio (ELR) = (F + N)/R

Sustainability index (SI) = EYR/ELR

Figure 6. Calculation of emergy indices. From Lagerberg (1999). Printed with the courtesy of International Society for Horticultural Science.

The emergy sustainability index (ESI or SI) is an aggregated measure of yield and environmental loading. It is derived by dividing the EYR by the ELR. A higher ESI indicates higher sustainability. Large external inputs of emergy may be sustainable if matched by large amounts of local renewable emergy use. The ESI is discussed thoroughly by Brown and Ulgiati (1997). Ulgiati and Brown (1998) simulates the behaviour of the EYR, ELR and ESI in relation to the ratios of locally renewable and locally non-renewable resource-use to the amount of purchased emergy associated with resources and services. Brown and Ulgiati (1998) propose a procedure for calculating the support area required to balance the function of a system. Ulgiati et al. (1995) propose that inputs and costs necessary to clean up and repair damage caused by the use of an item be placed within the system boundary, thus defining a second expanded emergy yield ratio called end use emergy yield ratio (EUEYR). From this would follow a set of new indices (and transformities) involving the end use emergy and giving perspective on future environmental impact.

The papers

Tomato for fresh consumption was chosen for the study for several reasons. Tomato is an important commercial crop internationally, both for fresh consumption and for processing. In Sweden, tomato production is only for fresh consumption and the crop is a major greenhouse crop. There is much international trade in tomatoes. Sweden, being about 25 % self-sufficient on an annual basis, imports significant amounts of tomatoes from Spain, Holland and Denmark. The Swedish domestic production of tomatoes takes place in high yielding greenhouse systems demanding large amounts of inputs. Based on energy of accumulated fuel consumption and greenhouse gas emissions, it has sometimes been debated whether we should be producing tomatoes in Sweden and in such complex heated greenhouse systems (Carlsson-Kanyama, 1998). For these reasons it is an interesting task to use the emergy analysis to shed further light on the issues of resource use and sustainability of these intensive production systems. This requires that the economy of Sweden, which is the larger economic system in which the tomato production systems work, be analysed. The emergy to currency ratio arrived at in Paper II is used to assign emergy values to direct and indirect human services in Papers III and IV, thus carrying information on the resource shadows of embodied human services.

Paper I

Paper 1 describes and emphasizes some basic features of agricultural systems and sustainability. Nature must be seen as a dynamic system where subsystems constantly reorganize in a pulsing pattern, during which the system may shift and species not contributing to the whole may be excluded. Agricultural systems are connected to the surrounding systems by the input of energy, materials, services and information. They are open subsystems in the overall larger natural ecosystems, which are self-regulated via subsystem feedback and larger scale control mechanisms. In agriculture, people take over the responsibility not only of regulating the system according to their needs but also of supporting the system which serves them and of which they are a part. This system of the human economy is included in the larger natural ecosystems which are continuously reorganized. The products of a system must be useful for that system, either directly within the system, or by feedback through other surrounding systems. They must contribute to the structure supporting it, otherwise the system will not be competitive but will be excluded in favour of competing systems.

Paper II

Paper II presents emergy analyses of the Swedish economy for 1988 and 1996. Data on direct environmental support, such as rainfall and wind action on land and territorial waters, as well as annual statistics on industrial production and trade, were used to quantify the flows of emergy, i.e. weighted resources, supporting the economy.

Expressed in emergy, imports as well as exports, increased, showing that the economy was more dependent on international trade in 1996 than in 1988. The total emergy yield of the economy increased less than the environmental loading ratio and the renewable resources used were less in comparison with non-renewable resource use. These three components of the SI interacted to result in a less sustainable economy in 1996 than in 1988. The Swedish economy was shown to benefit from exporting more upgraded goods and less raw materials.

Papers III and IV

Papers III and IV describe the emergy analyses of a conventional Swedish tomato production system and an organic experimental system respectively. Both tomato crops were grown in heated greenhouses, located in the South of Sweden which is the major tomato-producing region. The conventional system was heated with oil and propane (for carbon dioxide supply and heating) while the organic system was heated with oil, assuming that the substrate would release enough carbon dioxide to ensure that this would not be limiting for growth. The organic crop was grown in restricted beds with a substrate containing soil, straw, manure and peat and was fertilized with red clover mulch during the growing season. A portion of the substrate components was regarded as renewable. The conventional crop was grown in a soilless system with rockwool substrate. The studies were performed at company level, while studies of agricultural systems have been performed by others at field level (Ulgiati et al., 1993; Marchettini, 1996).

The organic system was an experimental low-yielding system, less economically optimized than the conventional system. This was extended by prolonging the production period to a more reasonable one and by raising the harvest level, while adjusting the inputs accordingly. Both systems were modified and analysed as regards an alternative fuel source, i.e. the oil was replaced by domestically-produced wood powder from logging residues.

The tomato production systems were shown to be highly dependent on non-renewable and purchased resources fed back from society. Direct environmental inputs contributed far less than 1 % of the total emergy driving the systems. The importance of direct and indirect human labour was also emphasised.

Discussion

Time is an important factor in sustainability. Productivity is important on any time scale, while sustainability in a very short perspective becomes less relevant. In the longer time perspective, the agricultural system must not only be stable in the sense that the coefficient of variation in yield is small, but it must also be resilient, i.e. be able to recover its functions after a disaster. In the long run, all agricultural systems must be environmentally adapted, productive and produce suitable products in a socially acceptable way. That is, in additon to the fact that the yield of the systems must match the environmental stress caused, the systems must also be socially sound. This is in accordance with the definition of the emergy sustainability index, being a function of output (yield) and environmental stress. However, the social perspective is not incorporated into the framework of emergy analysis.

Simulations of the behaviour of the sustainability index (SI) and the environmental loading ratio (ELR) in relation to locally available renewable and non-renewable inputs (Ulgiati and Brown, 1998) supports the conclusions of Paper II. Long-term sustainability of the Swedish economy would be enhanced by supporting the use of locally renewable emergy flows, e.g. replacement of imported fossil fuels with domestic renewable fuels. Reduction of fuel and electricity use would reduce imports and total resources use would then decrease. Consequently, the renewable fraction of the total resource use would increase and the sustainability would increase. The ratio of imports to local resources would decrease, indicating a more efficient overall resource use. The decrease in environmental loading, combined with the increase in the emergy yield ratio, would most likely increase the sustainability of the economy.

The decreasing SI of the Swedish economy reported in Paper II has also been found for Taiwan (Brown and Ulgiati, 1997) and Italy (Ulgiati and Brown, 1998). These declining levels of sustainability indicate increasing dependency of non-renewable and imported energy and materials. This would seem to confirm the statement of Brown and Ulgiati (1997) that "In essence, the ESI is inversely proportional to 'economic development status'.". The trend of declining emergy to currency ratio of Sweden is in accordance with trends found for Taiwan and the world (Huang and Odum, 1991; Odum, 1996).

A similar conclusion as regards increasing the sustainability was drawn at the national level and crop producing company level, i.e. decreasing the dependency on imported non-renewable resources would be beneficial to sustainability. By replacing the fossil fuel heating of greenhouses with a more renewable locally produced fuel, such as wood powder from low input logging residue, the sustainability of tomato production systems can be enhanced.

The organic system (Paper IV) was based more on renewable resources, although it was just as dependent on purchased inputs as the conventional system (Paper III). For processes delivering the same output (tomatoes), that with the lower transformity is more efficient. Raising the yield was found to be an important factor in lowering the transformities of the organic tomatoes, which were higher than those of the conventional system in both the oil heated and wood powder heated alternatives. The wood powder fuel gave systems with less overall resource use, reflected by lower transformities, as well as a higher degree of sustainability. The systems involving the wood derived fuel were also shown to require more domestic human labour, which may be of interest to policy makers on the larger regional or national level. However, the wood powder was a more expensive fuel and was thus shown to be ecologically advantageous at company, regional and national levels, but economically disadvantageous at company level. The decrease in profits when converting to wood powder heating makes increasing the yield of the organic system even more important. The tradeoff was shown to be greater for replacing the fuel with a more renewable one than replacing the fertilizer with one derived from more renewable resources. Thus, the replacement of fuels is more important than the fertilizer strategy in directing the systems towards sustainability.

It has been difficult to compare the findings of Papers III and IV with other studies on agricultural products. This is because no emergy analyses have been performed on greenhouse crops or at the company level. Furthermore, no emergy studies on Swedish crops are available and previous studies on foreign crops (Ulgiati et al., 1994) were usually published with transformities given in sej/J including services. Comparing ready-to-eat tomatoes with products requiring post-harvest processing was not regarded as a terribly interesting issue either. One may also discuss whether tomatoes are an essential part of life. One must remember that tomatoes and other vegetables in general contain healthy substances, such as antioxidants. If they are to be regarded as a luxury rather than as life-supporting, then it might be more feasible to compare luxury products to each other, regardless of whether they are food, jewelry, cigarettes, cars or computers etc. Similarly, products considered to be imperative for sustaining life may be compared to each other. There are not enough emergy analyses available to perform this comparison. However, one recent emergy analysis on field-grown tomatoes in Florida was available (Brandt-Williams and Odum, 1999). Despite the high yields of Swedish tomato production systems (Papers III and IV), the transformity was larger than for Florida tomatoes. For those greenhouse systems where the oil was substituted for wood powder, the ELRs and SIs were lower and higher respectively, indicating a better environmental performance for Swedish tomatoes.

When analyzing sustainability in agricultural systems we need to expand the system boundary to include specific production inputs that otherwise would not have belonged to the system. By definition, all purchased inputs crossing the border of the system are considered non-renewable. This is not feasible when answering questions about how the use of a relatively local resource, e.g. the manure considered to be supplied from a neighbouring farm to the organic tomato production (Paper IV), affects the performance of the system. Locally, we may have competition for a resource but semilocally or regionally a resource may be abundant and renewable. For instance, the boundary was expanded around wood powder production in Paper III. The same was true for the production of substrate components, considered to contribute to semilocal renewable emergy in the tomato study in Paper IV. Purchased straw, manure, clover mulch and wood powder (Papers III and IV) were not regarded as 100 % non-renewable since this was considered to obstruct the analysis. Some of these inputs were purchased from nearby farms and were derived, in their turn, from a portion of locally renewable resources.

If the emergy analysis is to be used as a tool for addressing regional issues of resource use, which would open interesting perspectives to policy makers, there is a need for a second window of analysis, to show how the smaller window is affected by the larger surroundings. This was indicated by Odum (1996). The production of inputs within the larger window just covers the resource requirement of the system in the main focus and the spatial concentration of emergy (empower density) and other indices may be calculated having the smaller system in strict focus.

Expanding boundaries on the semilocal scale would be facilitated by presenting future transformities declaring the portions of different kinds of resources contributing to the transformity. For example, when calculating the transformity for straw in Paper IV, 39 percent of the transformity was derived from resources local to the farm producing the straw and thus semilocal to the tomato production. Ulgiati et al. (1994) and Bastianoni and Marchettini (1996) give percentages of different resource categories, but give little information on where the boundaries for those calculations were drawn. Future emergy analyses would benefit from transformities given declaring the percentages of emergy derived from each type (local renewable, local non-renewable and purchased resources and services). One must then take care to describe the boundary used for determining the allocation into these subgroups.

Emergy analysis has a great potential for providing perspectives which cannot be seen by other methods. If the analyses in this thesis had been performed with energy analysis, the significance of human labour for running the systems would have been lost. Since the resource use is not reflected by the energy contents of accumulated fuel use, the perspective of the resource history and hierarchy would also have been lost. Resources would only be given value in accordance with how many Joules of fuel had been used in manufacturing. In fact the only information generated would have been on fuel use and heat content, regardless of any qualities of the fuels other than Joule contents.

Most methods concerned with material use and economic interface (e.g. MIPS, ecological footprints, LCA and different energy analyses) would benefit from the procedure of weighting resources provided by emergy analysis. Emergy analysis in return lacks the perspective on specific environmental problems, i.e. effect categories identified from the human viewpoint, provided by the LCA. The end use emergy ratios proposed by Ulgiati et al. (1995), however, in essence mean expanding the boundary to include clean-up processes (based on current knowledge) in the system being analysed. This would include more future environmental impact in e.g. transformities. Toxic substances are probably underestimated by emergy analysis. One way of supplying information on toxic substances is the red-flagging of pesticides. Cederberg and Mattson (1998) based red-flagging on traits which were considered to be highly undesirable, e.g. long persistence in soil.

When communicating the results of an emergy analysis to extensionists and expert groups with the ultimate aim of reaching politicians and consumers, it is suggested that the transformity in sej/J be supplemented with sej/kg product. There is an urgent need for compilations of databases of transformity calculations, to make transformities easily available and to enhance the transparency. More transformities specific for Swedish conditions need to be calculated. Future development would benefit from analysing systems with several tools for analysing aspects of sustainability. Baumann and Cowell (1998) provide a framework for comparing methods which may facilitate such a comparison.

References

Andersson, K. Høgaas Eide, M. Lundqvist, U. and Mattsson, B. (1998). The feasibility of including sutainability in LCA methodology. *Journal of Cleaner Production* **6**(3-4), 289-298.

Azar, C. Holmberg, J. and Lindgren, K. (1996). Socio-ecological indicators for sustainability. *Ecological Economics* **18**, 89-112.

Bastianoni, S. and Marchettini, N. (1996). Ethanol production from biomass: analysis of process efficiency and sustainability. *Biomass and Bioenergy* **11**(5), 411-418.

Bastianoni, S. Brown, M. T. Marchettini, N. and Ulgiati, S. (1994). Assessing energy quality, process efficiency and environmental loading in biofuels production from biomass. In: Chartier, Ph. Beenackers, A. A. C. M. and Grassi, G. (Eds.). *European Biomass Conference 8. Biomass for energy, environment, agriculture and industry,* 2300-2312.

Baumann, H. and Cowell, S. (1998). An evaluative framework for environmental management approaches. In: Baumann, H. Life cycle assessment and decision making — theories and practices. *AFR report no 183*, Department of Technical Environmental Planning, Chalmers University of Technology, Gothenburg, Sweden.

Beyers, R. J. and Odum, H.T. (1993). *Ecological Microcosms.* Springer-Verlag, New York.

Bockstaller, C. Girardin, P. and van der Werf, H. M. G. (1997). Use of agro-ecological indicators for the evaluation of farming systems. *European Journal of Agronomy* **7**, 261-270.

Brandt-Williams, S. and Odum, H. T. (1999). Procedure for agricultural emergy* evaluation. In: Ortega, E. Safonor, P. and Comar, V. (Eds.). (1999). *Introduction to ecological engineering with emergy analysis of Brazilian case studies.* (in press).

Brown, M. T. and Arding, J. (1991). Transformities. *Working paper.* Center for Wetlands, University of Florida, Gainesville, USA.

Brown, M. T. and McClanahan, T. R. (1996). EMergy analysis perspectives of Thailand and Mekong river dam proposals. *Ecological Modelling* **91**, 105-130.

Brown, M. T. Tennenbaum, S. and Odum, H. T. (1991). Emergy analysis and policy persepctives for the Sea of Cortez, Mexico. *CFW Publication # 88-04. Research studies conducted under contract no. 571945612 to the Cousteau Society.* Center for Wetlands, University of Florida, Gainesville, Florida.

Brown, M. T. and Ulgiati, S. (1997). Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. *Ecological Engineering* **9**, 51-69.

Brown, M. T. and Ulgiati, S. (1998). Emergy evaluation of the environment: quantitative perspectives on ecological footprints. In: Ulgiati, S. Brown, M.T. Giampietro, M. Herendeen, R. A. and Mayumi, K. (Eds.). *Advances in energy studies. Energy flows in ecology and economy.* Musis Publisher, Roma, Italy, 223-240.

Brown, M. T. and Ulgiati, S. (1999). Emergy evaluation of natural capital and biosphere services. *Ambio.* (in press)

Brown, M. T. Odum, H. T. McGrane, G. Woithe, R. D. Lopez, S. and Bastianoni, S. (1995). Emergy evaluation of energy policies for Florida. *Report to the Florida Energy Office.* Center for Environmental Policy, Department of Environmental Engineering Sciences, University of Florida, Gainesville, USA.

Carlsson-Kanyama, A. (1998). Food consumption patterns and their influence on climate change. Greenhouse gas emissions in the life-cycle of tomatoes and carrots consumed in Sweden. *Ambio* **27(7)**, 528-534.

Cederberg, C. and Mattsson, B. (1999). Life cycle assessment of milk production – a comparison of conventional and organic farming. In: Cederberg, C. Environmental aspects of nutrient flows in agriculture with a case study of milk. Licentiate thesis. *Report 1999:6*. Göteborg University, Department of Applied Environmental Science, paper II.

Costanza, R. d'Arge, R. de Groots, R. Farber, S. Grasso, M. Hannon, B. Limburg, K. Naeem, S. O'neil, R. V. Paruelo, J. Raskin, R. G. Sutton, P. and van den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature* **387**, 253-260.

Doherty, S. J. (1995). Emergy evaluations of and limits to forest production. *Dissertation. Department of Environmental Engineering Sciences, University of Florida, Gainesville, USA.*

Fluck, R. (1992a). Energy analysis for agricultural systems. In: Fluck, R. (Ed.). *Energy in farm production. Energy in world agriculture vol. 6*. Elsevier, Amsterdam, 45-52.

Fluck, R. (1992b). Energy human labor. In: Fluck, R. (Ed.). *Energy in farm production. Energy in world agriculture vol. 6*. Elsevier, Amsterdam, 31-37.

Folke, C. Jansson, Å, Larsson, J. and Costanza, R. (1997). Ecosystem appropriation by cities. *Ambio* **26** (3), 167-172.

Franzluebbers, A. J. and Francis, C. A. (1995). Energy output:input ratio of maize and sorghum management in Eastern Nebraska. *Agriculture, Ecosystems and Environment* **53**, 271-278.

Hall, C. A. S. (Ed.). (1995). *Maximum power. The ideas and applications of H. T. Odum*. University Press of Colorado, Niwot, Colorado, USA.

Hall, C. A. S. Cleveland, C. J. and Kaufmann, R. (1986). *Energy and resource quality. The ecology of the economic process*. John Wiley & Sons, New York.

Haukoos, D. S. (1994). *An Emergy analysis of various construction materials. ENV 6905*. Department of Environmental Engineering Sciences, University of Florida, Gainesville, USA.

Holmberg, J. Robèrt, K.-H. and Eriksson, H.-E. (1996). Socio-ecological principles for a sustainable society: scientific background and Swedish experience. In: Costanza. R. Olman, S. and Martinez-Alier, J. (Eds.). *Getting down to earth: practical imlications for ecological economics*. Island Press, Washington.

Huang, S.-L. and Odum, H. T. (1991). Ecology and economy: emergy synthesis and public policy in Taiwan. *Journal of Environmental Management* **32**, 313-333.

Jolliet, O. (1990). Bilan écologique de la production de tomates en serre. *Revue Suisse Vitic, Arboric. Hortic.* **25** (4), 261-267.

Lagerberg, C. (1999). Evaluation of resource flows of tomato production systems under glass according to the method of emergy analysis. Proceedings of the XXVth International Horticultural Congress, Brussels, Belgium, 1998. *Acta Horticulturae*. (in press)

Lindfors, L.-G. Christiansen, K. Hoffman, L. Virtanen, Y. Juntilla, V. Hanssen, O.-J. Rønning, A. Ekvall, T. and Finnveden, G. (1995). Nordic guidelines on life-cycle assessment. *Nord 1995:20*. The Nordic Council of Ministers.

Mc Govern, J. A. (1990). Exergy analysis – a different perspective on energy. Part 1: the concept of exergy. *Proc. Instn. Mech. Engrs* **204**, 253-262.

Mattsson, B. and Cederberg, C. (1999). Agricultural land use in life cycle assessment (LCA): case study of vegetable oil crops. In: Cederberg, C. Environmental aspects of nutrient flows in agriculture with an LCA case study of milk. *Report 1999:6*, Department of Applied Environmental Science, Göteborg, Sweden, paper III.

Odum, H. T. (1971). *Environment, power and society*. Wiley-Interscience.

Odum, H. T. (1975). Energy quality and carrying capacity of the earth. *Tropical Ecology* **16**, 1-8.

Odum, H. T. (1987). Living with complexity. In: *The Craaford Prize in the Biosciences. Craaford Lectures*. The Royal Swedish Academy of Sciences, 19-85.

Odum, H. T. (1988a). Energy, environment and public policy. A guide to the analysis of systems. *UNEP Regional Seas Reports and Studies No. 95*. Oceans and Coastal Areas Programme Activity Centre, United Nations Environmnet Programme, P.O. Box 30552, Nairobi, Kenya.

Odum, H. T. (1988b). Self-Organization, Transformity, and Information. *Science* **242**, 1132-1139.

Odum, H. T. (1994). *Ecological and general systems. An introduction to systems ecology*. 2nd edition. Revised edition. University Press of Colorado, Niwot, USA.

Odum, H. T. (1996). *Environmental accounting. EMERGY and environmental decision making*. Wiley & Sons, Inc., New York.

Odum, H. T. and Odum, E. C. (1976). *Energy basis for man and nature*. McGraw-Hill Book Company, New York.

Odum, H. T. and Odum, E. C. (Eds.). (1983). Energy analysis overview of nations, with sections by Bosch, G. Braat, L. Dunn, W. Innes, G. de R. Richardson, J. R. Scienceman, D. M. Sendzimir, J. P. Smith, D. J. and Thomas, M. V. Working Paper WP-83-82. International Institute of Applied Systems Analysis, Laxenburg, Austria.

Odum, H. T. and Arding, J. E. (1991). Emergy analysis of shrimp mariculture in Equador. *Working Paper*. Department of Environmental Engineering Sciences and Center for Wetlands, University of Florida, Gainesville, USA.

Odum, H. T. Odum, E. C. and Blissett, M. (1987). Ecology and economy: "emergy" analysis and public policy in Texas. *Lyndon B. Johnson School of Public Affairs and Texas Department of Agriculture, Policy Research Project Report Number 78.* Board of Regents, The University of Texas, Austin

Odum, H. T. Odum, E. C. and Brown, M. T. (1998). *Environment and society in Florida.* Lewis Publishers, Boca Raton, USA.

Odum, H.T. Wang, F. C. Alexander, J. F. Gilliland, M. Miller, M. and Sendzimer, J. (1987b). Energy analysis of environmental value. *Center for Wetlands Publication # 78-17.* Center for Wetlands, Phelps Laboratory, University of Florida, Gainesville, Florida 32611, USA.

Pillet, G. (1991). Shadow pricing for natural resource goods and services, using the emergy method. In: Guvenen, O. Labys, W. C. and Lesourd, J.-B. (Eds.). *International commodity market models. Advances in methodology and applications.* Chapman and Hall.

Pimentel, D. and Pimentel, M. (1979). *Food, energy and society.* Edward Arnold, London

Prado-Jatar, M. A. and Brown, M. T. (1997). Interface ecosystems with an oil spill in a Venezuelan tropical savannah. *Ecological Engineering* **8**, 49-78.

Reist, A. and Gysi, C. (1990). Cultures hors sol: bilan écologique. *Revue suisse Vitic. Arboric. Hortic.* **22** (4), 223-235.

Robèrt, K.-H. (1994). Non-negotiable facts as a basis for decision-making. *Proceedings of the third Stockholm water symposium 10-14 August 1993. Integrated measures to overcome barriers to minimizing harmful fluxes from land to water.* GOTAB, Stockholm, 181-189.

Scienceman, D. M. (1987). Energy and emergy. In: Pillet, G. and Murota, T. (Eds.). *Environmental economics — the analysis of a major interface.* Rolland Leimgruber, Geneva, 257-276.

Shengfang, L. and Odum, H. T. (1994). Emergy evaluation of the environment and economy of Hong Kong. *Journal of Environmental Sciences* **6**(4), 432-439.

Schmidt-Bleek, F. (1996) Dematerialisation – from concept to practice. In: AFR, Naturvårdsverket. Dematerialisering – en strategi för uthållig utveckling. Seminarium 13 juni, 1996, Stockholm. *AFR-report 136*, 17-32.

Schmidt-Bleek, F. (1997). The ecological reform of the economy. In: Smith, P. and Tanner, A. *Dimensions of sustainability. Proceedings of the congress challenges of sustainable development, Amsterdam, 22-25 August 1996.* Nomos Verlagsgesellschaft, Baden-Baden, 69-80.

Scrase, J. I. Hall, D. O. and Stuckey, D. C. (1993). Bioethanol from grapes in the European community. *Biomass and Bioenergy* **5** (5), 347-358.

Sohn, Ji-Ho. Shin, Sung-Kyo. Cho, Eun-Il and Lee, Suk-Mo. (1996). EMERGY analysis of Korean fisheries. *Journal of Korean Fishery Society* **29**(5), 689-700. (English summary and tables).

Stanhill, G. (1980). The energy cost of protected cropping: a comparison of six systems of tomato production. *Journal of Agricultural Engineering Research* **25**, 145-154.

Tischner, U. and Schmidt-Bleek, F. (1993). Designing goods with MIPS. *Fresenius Environmental Bulletine* **2**, 479-484.

Ulgiati, S. and Brown, M. T. (1998). Monitoring patterns of sustainability in natural and man-made ecosystems. *Ecological Modelling* **108**, 23-36.

Ulgiati, S. Odum, H. T. and Bastianoni, S. (1993). Emergy analysis of Italian agricultural system. The role of energy quality and environmental inputs. In. Bonati, L. (Ed.). *International workshop on ecological physical chemistry 2, 1992, Milano. Trends in ecological physical chemistry*, 187-215.

Ulgiati, S. Odum, H. T. and Bastianoni, S. (1994). Emergy use, environmental loading and sustainability. An emergy analysis of Italy. *Ecological Modelling* **73**, 215-268.

Ulgiati, S. Brown, M. T. Bastianoni, S. and Marchettini, N. (1995). Emergy-based indices and ratios to evaluate the sustainable use of resources. *Ecological Engineering* **5**, 519-531.

Vitousek, P. M. Erlich, P. R. Erlich, A. H. and Matson, P. A. (1986). Human appropriation of the products of photosynthesis. *BioScience* **36**, 368-373.

Wackernagel, M. and Rees, W. (1996). *Our ecological footprint. Reducing human impact on the earth.* The New Catalyst Bioregional Series, New Society Publishers,Gabriola Island, BC, Canada.

Wackernagel, M. Onisto, L. Linares, A. C. Falfán, I. S. L. García, J. M. Guerro, A. I. S. and Guerro, G. S. (1997). *Ecological footprints of nations. How much nature do they use? How much nature do they have?* The Earth Council, Costa Rica.

Wall, G. (1987). Exergy conversion in the Swedish society. *Resources and Energy* **9**, 55-73.

World Commission on Environment and Development. (1987). *Our common future.* Oxford University Press.

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I

Visions for Ecologically Sound Agricultural Systems

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ABSTRACT. Agriculture of today may be defined as goal oriented manipulation of ecosystems for human gains. Future agricultural systems should be aimed at goal oriented, sustainable management of ecosystems for both human and ecosystem gains. Consequently, people take over the responsibility not only of regulating the system according to their needs, but also of supporting the system that serves them and of which they are a part. This agricultural human-regulated system is included in the larger natural ecosystems which are self-regulating through subsystem feedback and larger scale control mechanisms. The products of a system must be useful for that system, either directly within the system, or by feedback through other surrounding systems, otherwise the system will be degraded. *[Article copies available for a fee from The Haworth Document Delivery Service: 1-800-342-9678. E-mail address: getinfo@haworthpressinc.com]*

KEYWORDS. Sustainable agriculture

INTRODUCTION

The economy of nature and of humans is based on transformation and utilization of energy, some from the sun and some from fossil fuels and

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geothermal energy (Odum, 1983). Solar (and geothermal) energy drives the production of all ecosystem goods and services. Stored energy and material are the main driving forces of the processes of the industrial economy (Odum, 1983; Hall et al., 1986). Energy and matter are usually returned to the environment as wastes and heat having less value and usefulness.

Agricultural systems are open subsystems in the overall global ecosystem. These subsystems are connected with their surroundings by the input of energy, materials, services and information. Environmental work is the energetic base for the sum of activities at all levels. The system tends to respond to stimuli as a whole, even if the stimulus is only applied to one part of the system. This calls for a holistic system view when analysing and designing future agricultural systems.

To be able to support the increasing human population, production of food has to increase. Since the possibilities to clear new land seem to be limited, although opinions differ on this point, the only other option is to increase production on already cultivated land. In addition, there is a pressing need to improve the situation for the poorest 2/3 of humanity, and at the same time alter the consumption patterns of the affluent world, to make it possible to attain political stability.

The common scientific approach is to express a problem as hypothesis. Our hypothesis would then be: "Through a creative combination of scientific knowledge, technology, experience and common sense, it should be possible to design agricultural systems that both support and work in harmony with the global ecosystem." A hypothesis of this kind is unfortunately difficult, or impossible, to disprove experimentally in the manner of Sir Karl Popper, but may serve as an overall guide for the work of creating sustainable agricultural systems.

AGRICULTURAL SYSTEMS OF TODAY

Agriculture of today may be defined as goal oriented manipulation of ecosystems for human gains. This means that people impose on the environment a system of survival of what they want to use, replacing the Darwinian system of survival of the fittest. We have thus taken over the responsibility of regulating the system according to our needs. This sets agricultural systems apart from natural ecosystems, which are self-regulating via subsystem feedback and larger-scale control mechanisms. Each interference with the natural succession, such as harrowing and plowing, means that resources are lost or degraded. In addition, we also have an outflow of products (harvest) from the agroecosystems and consequently the support from the surrounding ecosystems is of major importance.

According to Vitousek et al. (1986), conventional agriculture almost always produces less, in total biomass, than natural ecosystems. This difference could sometimes be offset or reversed by use of perennial crops, multiple cropping, nutrient subsidies and, especially, irrigation. Vitousek et al. (1986) have estimated humankind's total appropriation of the products of photosynthesis. They conclude that nearly 40 per cent of potential terrestrial net primary production is used either directly or indirectly for human activities. Furthermore, humans also affect much of the remaining 60 per cent of the terrestrial net primary production, often heavily.

AGROECOSYSTEM IN CONTRAST TO NATURAL ECOSYSTEMS

Characteristic ecosystem designs result from self-maximizing energy flow through the system. During the process of self-organization, species and relationships are being selectively reinforced as more energy becomes available to those designs that feed products back into increased production (Odum, 1983, 1996). Natural ecosystems are almost always sustainable, whereas our present agricultural systems are not. However, in contrast to natural systems, agroecosystems have to support people living outside the system.

Agricultural ecosystems or agroecosystems can be seen as domesticated ecosystems that are in many ways intermediate between natural ecosystems, such as grassland and forests on one hand, and fabricated ecosystems, such as cities, on the other hand. They are solar powered, as the natural ecosystems, but differ in some important aspects (mainly after Odum, 1984):

- The auxiliary energy sources that enhance productivity are processed fuels (along with animal and human labor) rather than natural energies.
- Diversity is greatly reduced by human management in order to maximize yield of specific food and other products.
- The dominant plants and animals are under artificial rather than natural selection.
- The control of agroecosystems is largely external and goal-oriented whereas natural ecosystems are self-regulated via internal subsystem feedback.
- Agroecosystems are more open towards the surrounding environment. They have large inflow from and outflow to the environment. They "leak" in both controlled and uncontrolled ways.
- Agroecosystems are disturbed, unstable and young which are important factors in maintaining productivity. They function only through constant interference (care) by the farmer.

AGRICULTURAL SYSTEMS: TOWARDS A SUSTAINABLE FUTURE

Nature must be seen as a dynamic system where subsystems constantly reorganize. In a new paradigm this view is taken one major step further as described by Odum et al. (1995), where they state that rather than reaching the steady state as the final stage nature is pulsing towards a pulsing steady state. "Since pulses occur at all scales, the larger scales impose their bursts on the smaller scales. Each part of nature is composed of pulsing components and is occasionally impacted by a pulse from the larger scale" (Odum et al., 1995). During the pulses, the system may shift and species not contributing to the whole may be excluded.

The purpose of future agricultural systems is to assure the continued existence of the human race as well as the environment. This raises conflicts between short-term productivity and long-term sustainability. Haberl (1997) shows that productivity can be increased at the cost of biodiversity. On the other hand, simple agricultural systems are less sustainable than complex ones (Vandemeer et al., 1998). In order to manage conflicts, we must consider economical and social aspects as well as environmental issues (Allen et al., 1991; Porter and Petersen, 1997; Smith and McDonald, 1998).

Productivity and theoretical sustainability in agricultural, like in other systems, rest on several fundamental principles:

- Life-supporting ecosystems must be preserved or enhanced.
- Agricultural land, other land, water and air must be regarded as storage resources. They must be used in a way so that they are maintained or upgraded.
- Renewable resources must be used in such a way that their use does not cause a degradation of the environment. On the contrary, their use should, where possible, result in an upgrading in natural ecosystems. These resources, basically solar and geological energy, are by definition degraded when used. The potential ability to perform work decreases, i.e., the thermodynamic quality is degraded whereas the product resulting from the process should represent an upgrading in quality.
- Non-renewable resources are also degraded when used. In a geological time perspective they will be "re-upgraded" through environmental work, e.g., plate tectonics, earthquakes, volcanic activity and recycling through the atmosphere. The degradation in a shorter time perspective must be kept within acceptable limits. This requires recycling.
- Non-renewable fossil fuels should not be used to a larger extent than is permitted by the ability of the global ecosystem to recycle the residual products through environmental work into biomass or rock deposits.

For instance, the carbon dioxide generated must be absorbed by the ecosphere.

It is obvious that both for sustainability and for productivity, in the long run, recycling of non-renewable resources is a critical element. Models of future development may be found in traditional high productive sustainable systems (Ellis and Wang, 1997) as well as in recently created farming systems (Gumbricht, 1993).

DISCUSSION AND VISIONS

Future agricultural systems should be aimed at goal-oriented management of sustainable ecosystems for both human and ecosystem gains. Consequently, we must take over the responsibility not only of regulating the system according to our needs, but also of supporting the system that serves us and of which we are a part. This agricultural human-regulated system is included in the larger natural ecosystems which are self-regulating through subsystem feedback and larger scale control mechanisms. Looking at natural resources in this perspective also means that natural resources cannot be substituted by capital or labor as is possible in a short-term monetary perspective.

If agroecosystems were designed to mimic natural ecosystems, and less effort were put into physical interference, it might be possible to create an agricultural system that uses fewer inputs, produces enough food and other desired products, and still proves sustainable in a longer time perspective (Soule and Piper, 1992). It is also important to consider the agroecosystem not only at field level, but also at higher hierarchy levels like farms, villages and regions (Conway, 1985).

For sustainability and productivity the future society must, to a much larger extent than today, be based on recycling. The products of a system must be useful for that system, either directly within the system, or by feedback through other surrounding systems, otherwise the system will be degraded. In unsustainable systems we pay high costs for services that to a much higher extent can be performed in sustainable systems, e.g., for reclamation, restoration and maintenance (Ekins, 1997).

It is necessary to find methods for evaluation of the external energy basis of economies, of both nature and man, so that changes in the environment and resources can be related quantitatively and their impact on future economies can be estimated. One tempting method of environmental accounting is described thoroughly in Odum (1996), but as no method can be expected to be suitable for all situations, at all times, other methods (Bockstaller et al., 1997; Giupponi, 1998) may reveal interesting aspects. Rees (1996) and Wackernagel et al. (1997) have developed the method of addressing resource use by calculating ecological footprints. Material intensity per unit service (MIPS) estimates environmental impact of infrastructure, goods and services (Schmidt-Bleek, 1993).

In the long run, all agricultural systems must be productive and sustainable and produce suitable products in an acceptable social system, i.e., they must be environmentally adapted, resource efficient, and socially sound. To optimize the flow of energy and nutrients, and minimize their leakage, animal production must be integrated with crop production. The choice of crops and animals should be guided primarily by their potential role in an integrated system. However, the upgrading in quality, as always, involves loss in quantity (e.g., crops transformed into meat).

Obviously, agricultural systems cannot function or be changed in isolation. Changes in resource efficiency, and thereby sustainability, in the agricultural system have to be accompanied by alterations in the production and social systems of society as a whole. Agriculture needs to be regarded and analyzed from a systems perspective if resource efficiency is to be improved. If the time perspective is too short, there is a risk that the work gets tied up in present systems. Resource efficiency is important in any time perspective while sustainability in a very short, perspective becomes less relevant. It is important that the risk of crop failure is small in the agroecosystem. In the short time frame, this risk is reduced by making the system stable in the sense that the coefficient of variation in yield is small. Thereby stability is defined, according to Conway (1985), as the degree to which productivity is constant in the face of small disturbances caused by the normal fluctuations of climate and other environmental factors. In the longer time perspective, the system must also be resilient, i.e., be able to return to the original state when recovering from a disaster. An agroecosystem that possesses the properties of both stability and resilience will be sustainable in the long term.

REFERENCES

Allen, P., Van Dusen, D. Lundy, J. and Gliessman, S. 1991. Integrating social, environmental, and economic issues in sustainable agriculture. *Am. J. Alt. Agric.* *6*: 34-39.

Bockstaller, C., Girardin, P. and van der Werf, H. M. G. 1997. Use of agro-ecological indicators for the evaluation of farming systems. *Eur. J. Agron.* *7*: 261-270.

Conway. G. R. 1985. Agroecosystem analysis. *Agric. Adm.* *20*: 31-55.

Ellis, E. C. and Wang, S. M. 1997. Sustainable traditional agriculture in the Tai Lake region of China. *Agric. Ecosyst. Environ.* *61*: 177-193.

Ekins, P. 1997. Sustainability as the basis of environmental policy. *In*: Dragun, A. K. and Jakobsson, K. M. (eds.). *Sustainability and global environmental policy.* Edward Elgar, Cheltenham: 33-61.

Giupponi, C. 1998. Environmental evaluation of alternative cropping systems with impact indices of pollution. *Eur. J. Agron.* *8*: 71-82.

Gumbricht, T. 1993. Minimum entropy in small farming–Children's ecological village Tatui. *In: Integrated measures to overcome barriers to minimizing harmful fluxes from land to water. Proceedings of the third Stockholm water symposium 10-14 August 1993, Stockholm, Sweden*: 215-222.

Haberl, H. 1997. Human appropriation of net primary production as an environmental indicator: implications for sustainable development. *Ambio 26*: 143-146.

Hall, C. A. S., Cleveland, C. J. and Kaufmann, R. 1986. *Energy and resource quality:the ecology of the economic process*. John Wiley & Sons, New York. 577 pp.

Odum, E. P. 1984. Properties of agroecosystems. *In:* Lowrance, R., Stinner, B. R. and House, G. J. (eds.). *Agricultural ecosystems:unifying concepts*. John Wiley & Sons, New York: 5-11.

Odum, H.T. 1983. *Systems ecology:an introduction*. Wiley, New York. 644 pp.

Odum, H. T. 1996. *Environmental accounting. Emergy and environmental decision making*. John Wiley & Sons, New York. 370 pp.

Odum, W. E., Odum, E. P. and Odum, H. T. 1995. Nature's pulsing paradigm. *Estuaries 18*: 547-555.

Porter, J. R. and Petersen, E. H. 1997. Danish agriculure and its sustainability: a profile. *Ambio 26*: 462-465.

Rees, W. E. 1996. Revisiting carrying capacity: area-based indicators of sustainability. *Popul. Environ.: J. Interdiscip. Stud. 17*: 195-215.

Schmidt-Bleek, F. 1993. Toward universal ecology disturbance measures. Basis and outline of a universal measure. *Regul. Toxicol. Pharmacol. 18*: 456-462.

Smith, C. S. and McDonald, G. T. 1998. Assessing the sustainability of agriculture at the planning stage. *J. Environ. Manag. 52*: 15-37.

Soule, J. D. and Piper, J. K. 1992. *Farming in nature's image: an ecological approach to agriculture.* Island Press, Washington, D.C. 286 pp.

Vandemeer, J., van Noordwijk, M., Anderson, J., Ong, C. and Perfecto, I. 1998. Global change and multi-species agroecosystems: concepts and issues. *Agric. Ecosyst. Environ. 67*: 1-22.

Vitousek, P. M., Ehrlich, P. R., Ehrlich, A. H. and Matson, P. A. 1986. Human appropriation of the products of photosynthesis. *BioScience, 36*: 368-373.

Wackernagel, M., Onisto, L., Linares, A. C., Falfán, I. S. L., García, J. M., Guerro, A. I. S., and Guerro, G. S. 1997. *Ecological footprints of nations. How much nature do they use? How much nature do they have?* The Earth Council, Costa Rica.

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II

Evaluation of the Resource Efficiency and Sustainability of the Swedish Economy Using Emergy-Based Indices

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Abstract

The resource flows supporting the Swedish economy, i.e. market commodities and trade as well as environmental support, were explored for 1988 and 1996. The total economy expanded by 30 percent during the period due to an increase in use of local resources (19 percent) and an even greater increase in imported goods and services (43 percent). As much of the increase was non-renewable resources the environmental loading increased. The indigenous sources in 1996 were 29 percent of the total. Import as well as export increased showing that the economy of 1996 was more dependent of international trade. Comparing trade in 1988 with 1996, the export of raw materials decreased while the export of upgraded goods and services increased. The purchasing power of unrefined material declined during the period, somewhat benefiting Sweden as an exporter because less resources were spent per US dollar received. Renewable resources were considered constant over the period and comprised 13 percent of total inputs in 1996 compared to 16 percent in 1988. To enhance sustainability the present policy of replacing non-renewable resources with renewable ones and improving the efficiency in utilisation of available resources has to be strengthened.

Keywords: appropriated resource ratio, environmental accounting, energy, environmental loading, resource dependency, solar emergy, solar transformity, trade

Introduction

Today it is widely recognized that the welfare of economic systems is closely connected to the status of environmental systems. Societies depend on markets where natural resources, sometimes from distant economies, are exploited and sold. This resource use affects the environment as well as the economies of the seller and buyer. In order to reach sustainability of societies, policy makers must make long-term decisions concerning environmental resource management. Thus the need for measures reaching beyond short-term economic market values is obvious. There is a need to address the intrinsic values of natural resources, i.e. values which are not captured by market pricing, and values of resources like sunlight and ocean currents which are not even marketable. In order to visualize the contributions of these resources to an economy, it is necessary to base investigations on assessment of the total resource use needed to make a product available on the market.

Schmidt-Bleek (1997) addressed this problem by the concept *of Material intensity per unit service* (MIPS) quantifying the amount of raw natural material (given in mass or energy units) disturbed in order to make a unit of a product available. Schmidt-Bleek stresses that by using MIPS, different systems producing the same products can be compared. However, the MIPS-system has some disadvantages. Because natural materials themselves require different inputs performed by natural systems, one kilogramme or Joule of one resource may not be directly comparable to a kilogramme or Joule of another resource. Consequently systems may only be compared using the MIPS approach if the internal relationship of inputs between the resources used are the same.

The *Ecological footprint* (Wackernagel and Rees, 1996; Wackernagel et al., 1997) expresses the land and water area required to absorb the carbon dioxide from fossil fuel use, and to produce the food, fish, forests and land needed for settlements occupied by the population in question. The ecological footprint is considered a measure of the dependency of man to nature and states the area required to sustain a population at its present standard of living using present technology. In its simplicity, this is an attractive and pedagogic approach. Even so, the ecological footprint does not recognize that embodied energies of fuels are by no means true indicators of resource use, but of use of fuels and that use of fuels is not proportional to the use of natural resources. The fact that different types of energy require different environmental input results in an energy hierarchy. This hierarchy reflects the fact that products with the same energy content may have required different amounts of resources to make them, which is not reflected by the heat content of the product itself. Another disadvantage is that land use is not weighted in accordance with the intensity and difference in use, together with the fact that productivity of land and sea is considered to reflect the resources utilized.

The *Emergy analysis* (Odum and Odum, 1983; Odum, 1988; Odum, 1996) provides valuable perspectives on some of the problems above. With this tool we can compare parallel processes, i.e. alternative modes of action resulting in the same product, as well as to compare products at different hierarchical levels (Odum, 1987; Brown and Ulgiati, 1997). Emergy (sometimes referred to as "energy memory"; Scienceman, 1987), which involves energy accumulated over time, expresses the amount of resources required to generate a piece of goods or service weighted in a common type of energy. When the common measure is solar energy, the emergy unit is solar emjoules (sej). The emergy analysis assigns values to resources lacking direct market values and to resources not associated with fuel use. It is capable of assigning values to natural resources as well as to materials, fuels and human service supplied via the economic system. By expressing all inputs in one common unit, straightforward comparisons between systems using different sources of inputs can be made.

The object of this study was to analyze the resource basis of the Swedish economy in 1996 using emergy-based indices to describe the environmental load and sustainability of the system. An emergy analysis of the Swedish economy of 1988 (Doherty et al., 1993) was revised and utilized for comparison in addressing tendencies and policy issues. Of major interest was the question whether the Swedish economy had become more or less sustainable during the period.

Materials and Methods

Emergy is defined as the accumulated resources used to produce merchandise, service, or fuel, available in its present form, and expressed in a common type of energy, solar Joules. To indicate that we are dealing with emergy, *EM*, the unit is called *solar emjoules*. Emergy can be described by the function;

$$EM = \sum_{i=1}^{n} I_i + \sum_{j=1}^{m} F_j \qquad (1)$$

where I_i denotes environmental inputs and F_j are purchased inputs. In order to express different types of energy as emergy, conversion factors called solar transformities, *ST*, are used (Figure 1). For the merchandise or service *A*, the transformity, ST_A, can be expressed as;

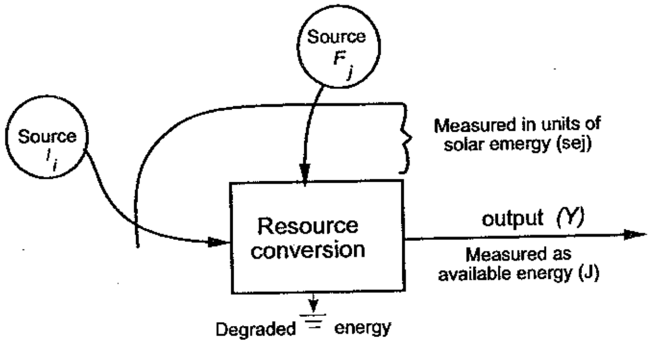
$$ST_A = \frac{EM_A}{Y_A} \qquad (2)$$

where Y_A denotes the energy contents of A, while EM_A is the total emergy needed to produce A. With Y_A and ST_A defined, EM_A can be estimated from a conversion of Eq. 2:

$$EM_A = Y_A \, ST_A \qquad (3)$$

The unit for the solar transformaty is normally *solar emjoules per Joule* (sej/J), but sometimes it is also expressed as emergy per unit flow, e.g. sej/kg A. A high transformity value of an item indicates that consumption of the same item will cause a large decrease in accumulated resources in relation to the energy that is extracted.

Human services employed in extraction, development and transport of natural and market capital are usually evaluated from market values (USD), reflecting associated human services of the commodity, and converted to solar emergy using sej/GDP metrics for source countries. By summing all emergy flows supporting the entire economy and dividing by the monetary flow, i. e. the gross domestic product (GDP), an emergy to currency ratio reflecting the average service carried by each unit currency is obtained. This ratio is used to convert money flows to emergy flows of the economy, multiplying the money flow by the emergy to currency ratio. Sometimes the gross national product (GNP) has been used for computing the emergy to currency ratio. The GNP, however, involves foreign earnings resulting from the use of energy elsewhere, and therefore the GDP is preferred.



$$\text{Solar transformity for output} = \frac{\text{solar emergy of inputs (sej)}}{\text{energy of output (J)}} = \frac{\sum_{i=1}^{n} I_i + \sum_{j=1}^{m} F_j}{Y_A}$$

Figure 1. Calculation of solar transformity made for resource-conversions. I designates the direct environmental inputs.

Converting all flows into one common energy unit, reflecting the history of the resources and services used in the process, makes it possible to calculate a number of indices (Ulgiati et al., 1994; Odum, 1996; Brown and Ulgiati, 1997) for comparing different flows and processes. Please see Tables 4 and 5 for definitions of flows and indices.

The net yield ratio (NYR) is calculated by dividing the total emergy by the emergy supplied from outside the system under study. The imports to local resources ratio (ILR) is derived by dividing the emergy imported from outside the system by the local renewable and local non-renewable emergy. The imports to local resources ratio indicates whether the process is efficient in its use of imported (purchased) emergy. The environmental loading ratio (ELR) reflects the pressure that the process exerts on the local environmental systems. It is calculated by dividing purchased emergy and local non-renewable emergy use by the local renewable emergy. The sustainability index (SI) (Brown and Ulgiati, 1997) is given by the ratio of the emergy yield ratio and environmental loading ratio. Thus it depends on the relationships between renewable, non-renewable and imported emergy. An appropriated resource ratio (ARR) was derived by dividing the total emergy use by the emergy of the resources extracted locally, within the country. By including resources extracted and exported as raw material, the denominator reflects the emergy that would be available for direct use in the Swedish economy given today´s level of domestic resource extraction. The ARR thus indicates how many times the potential domestic resource use, given the limits above, is used in the present situation.

Sweden's natural resource base includes extensive forests, wetlands, agricultural lands and fisheries, as well as an active extractive sector of minerals and metal ores. Exogenous renewable and indigenous non-renewable resources (Table 1) generate natural capital, support functions essential to ecosystem and human health and provide the basis for sustainable economic progress. Renewable sources include incident solar energy and precipitation over land and water, soil uplift and tidal energy and wave action within a portion of the Baltic Sea attributed to Sweden. Non-renewable resources are those earth materials mined at a rate exceeding recycling, including ores and wetland peat. Net loss of soil organic matter from erosion was not found to be significant in Sweden and is not evaluated in this study.

To avoid double counting of emergy flows originating from the same source, in accordance with the method (Odum, 1996), by convention only the largest byproduct flow is used when summing the indigenous renewable inputs. Thus, e.g. the inputs of sun and wind were omitted, being already accounted for in the rain factor.

Quantitative information on environmental parameters, resource-use, market commodities and trade for Sweden were obtained from scientific and technical literature and from national statistical yearbooks and databases (e.g. SMHI, 1997; Statistics Sweden 1992; 1997a; 1997b; 1998a; 1998b; 1998c; 1998d; 1998e; SMHI, personal communication). Baseline data were compiled into annual quantities and reported as available energy (J), mass (kg), or money flow (USD) for 1996. A previous study by Doherty et al (1993) for 1988 was revised to facilitate comparisons.

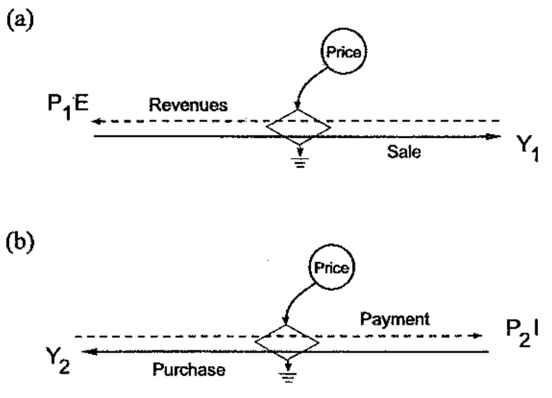


Figure 2. Calculation of resource exchange ratios for economic transactions. A) Exports: P_1E = monetary revenue multiplied by sej/GDP ratio for Sweden and Y_1 = export product (sej). b) Imports: P_2I = monetary expenditures multiplied by sej/GDP ratio for trade partner and Y_2 = import product (sej).

Data and evaluations were organized in tables and summarized in systems diagrams. Citations, calculations and estimates are referenced as footnotes to each table corresponding to line item numbers. References for values discussed in the text identify table-footnote notation. The service component of referenced transformities was subtracted to reduce the error of double counting inputs.

For trade commodities that were not reported in physical units (termed other goods, items 49 and 67 of Tables 2 and 3), market values were multiplied by a sej/GDP index calculated for Sweden in 1996 (exports) and estimated for trade nations (imports). A proportion derived directly from environmental sources was then estimated by dividing by a ratio of imports to indigenous resources for the source country (items 2.49 and 3.67).

From aggregations of computed values, indices of resource-use were calculated relating environmental sources, imports and exports to population, country area, resource origin, economic product and trade. Ratios of net yield (NYR), environmental loading (ELR), appropriated resources (ARR) and an index of sustainability (SI) (Odum, 1996; Brown and Ulgiati, 1997), were calculated for

Sweden in 1988 and 1996 and for a sample of other countries for comparison and discussion (Tables 5 and 7). Other derived metrics related resource (sej) and market values (USD) (Table 7). Exchange ratios (Figure 2) measured resources received or exported (sej) relative to import expenditures or export revenues (USD). A measure of resource-proportioned value equates a monetary value for all resources used annually by dividing the resources (sej) by that year's resource-use/GDP index (sej/USD). In this way all resources, including environmental sources and ecosystem services outside the market, were proportioned to the annual gross economic product.

Comparison statistics measuring less than a 5% difference between parameters were considered insignificant.

Results

Figures 3 and 4 summarize the annual resource flows of Sweden, and Tables 1-3 give more detailed values.

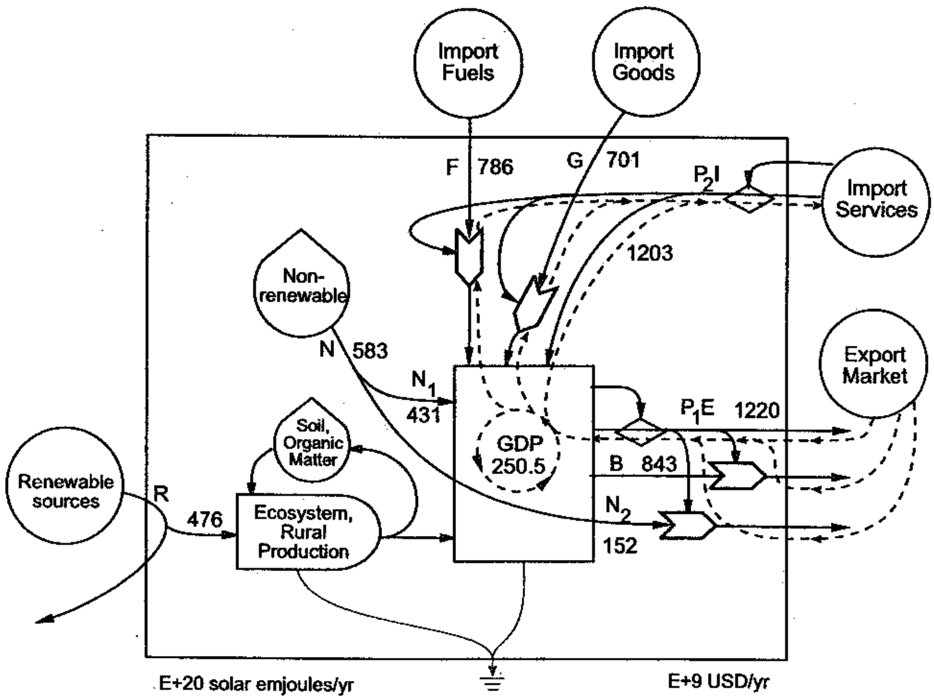


Figure 3. Systems diagram summarizing annual resource flows (E+20 sej/yr) and gross domestic product (E+9 USD/yr) for Sweden, 1996. Derivations for values are given in Table 4.

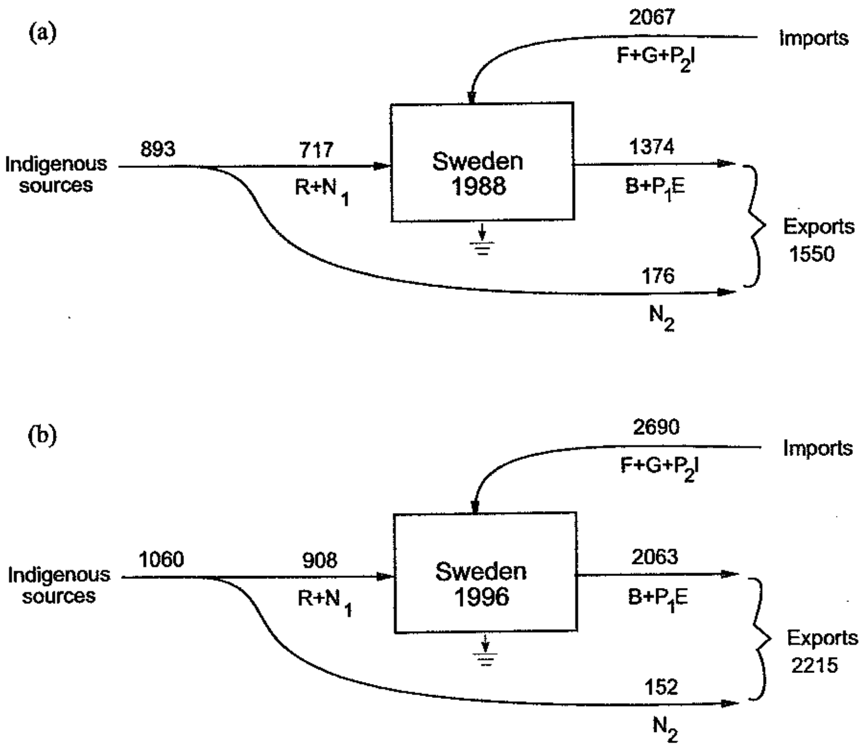


Figure 4. Aggregated diagrams summarizing annual resource flows for Sweden (a) 1988 and (b) 1996. Derivations are given in Tables 4 and 5. Numbers on pathways are given in E+20 sej/year.

Annual precipitation, averaging 750 mm/yr, including rainfall and snowmelt, was the largest renewable energy source, accounting for 36% of the indigenous resource base. An estimated 47% of the precipitation was used in evapotranspiration and measured as chemical potential energy (142.7E+20 sej/yr), supporting ecosystem production (Table 1, note 3). The remaining 53% was runoff, collecting in streams and measured as geopotential energy (237.0E+20 sej/yr), sculpting the landscape and redistributing nutrients and sediments (Table 1, note 4). Tidal and wave energy comprised 11% of the country's renewable resources, supporting Baltic Sea ecosystems.

Sweden mined 33E+9 kg of iron ore in 1996 (Table 1, note 13), comprising 56% of extracted material and 31% of the total indigenous resource base. Other mineral rock, sedimentary material and copper were also important. Wetland peat (3.4E+6 m^3) was extracted in 1996 for energy systems and horticulture, contributing an estimated 3.9E+20 sej (Table 1, note 12). In 1996 a total of 45% of indigenous natural resources were delivered by renewable sources and 55% by non-renewable resources (Table 4).

Table 1. Indigenous resource base of Sweden, 1996

Note*	Item, unit	Annual resource flow (unit/year)	Conversion factor (sej/unit) **	Solar emergy (E+20 sej/year)
RENEWABLE RESOURCES				
Physical energy received over land				
1	Solar insolation, J	1.02E21	1	10.2
2	Wind, kinetic energy, J	3.08E15	1.5E+03	0.0
3	Rain, chemical, J	7.84E17	1.8E+04	142.7
4	Rain, geopotential, J	8.54E17	2.8E+04	237.0
5	Net uplift, J	1.34E11	3.2E+10	43.3
Physical energy received over the Baltic Sea				
6	Solar insolation, J	5.40E20	1	5.4
7	Surface wind absorbed, J	2.31E15	1.5E+03	0.0
8	Rain, chemical, J	6.89E16	1.8E+04	12.5
9	Runoff, chemical, J	1.26E17	4.9E+04	61.1
10	Tide, J	5.35E16	1.7E+04	9.0
11	Waves, J	1.45E17	3.1E+04	44.4
INDIGENOUS NON-RENEWABLE EXTRACTION				
12	Peat, J	1.10E16	3.5E+04	3.9
13	Iron ore, kg	3.29E10	1.0E+12	329.0
14	Gold, kg	7.07E3	5.0E+12	0.0
15	Silver, kg	2.56E5	5.0E+12	0.0
16	Copper, kg	3.12E8	4.5E+12	14.0
17	Lead, kg	1.37E8	4.5E+12	6.2
18	Zinc, kg	3.04E8	4.5E+12	13.7
19	Other mineral rock, kg	3.07E10	5.0E+11	153.4
20	Sedimentary material, kg	6.31E9	1.0E+12	63.1

* footnotes given in Appendix A

** sej/J, sej/g, or sej/USD

The import of raw material, fuels, goods and services was 2.5 times greater than the amount delivered from local natural resources, in 1996. Imported fossil hydrocarbons (Table 2, notes 22-26) constituted about 45% of imported goods and fuels. Another 8% of imports were received from purchased uranium, peat and electricity. Fortyseven percent of imports were market commodities (Table 2, notes 29-49); fertilizers (<2%), metals (8%), agricultural and forest products (8%), and other goods (30%). Human services supporting imports (Table 2, note 50) were estimated at 45% of all imports, including services.

In 1996, refined fuels and electricity comprised 33% of exported goods and services (Table 3, notes 51-53); metals and machinery, 23% (Table 3, notes 56-59); and forest products, 17% (Table 3, notes 63-66). Almost half of the iron mined (Table 2, note 13) was sold overseas as unrefined ore (Table 3, note 55), transferring 18% of exported resources to trade partners. Human services supporting exports (Table 3, note 68) were estimated to 59% of total exports, including services in 1996.

Table 2. Import fuels, goods and services to Sweden, 1996

Note*	Item, unit	Annual resource flow (unit/year)	Conversion factor (sej/unit)**	Solar emergy (E+20 sej/year)
21	Uranium, J	9.18E17	1.8E3	16.4
22	Crude petroleum, J	8.95E17	4.7E4	421.7
23	Refined fuels, J	2.89E17	5.6E4	162.3
24	Coal, J	9.80E16	3.4E4	33.3
25	Natural gas, J	3.39E16	4.1E4	13.8
26	Propane, butane, J	3.83E16	1.0E5	38.6
27	Electricity, J	5.72E16	1.7E5	99.5
28	Peat, J	1.70E15	3.5E4	0.6
29	Nitrogen fertilizer, kg	5.24E8	3.8E12	19.9
30	Potassium fertilizer, kg	1.37E8	1.1E12	1.5
31	Phosphorus fertilizer, kg	1.00E6	3.9E12	0.0
32	Copper, kg	1.83E8	4.5E12	8.2
33	Aluminum, kg	4.47E8	7.0E12	31.1
34	Zinc, kg	4.21E7	4.5E12	1.9
35	Iron ore, kg	1.50E8	1.0E12	1.5
36	Pig iron, kg	2.18E8	1.6E12	3.4
37	Steel, kg	2.50E9	2.2E12	54.0
38	Vehicles, kg	2.64E8	6.7E12	17.7
39	Wool, J	2.79E13	2.4E6	0.7
40	Cotton, kg	4.22E14	1.9E6	8.0
41	Meats, J	3.51E14	1.9E6	6.5
42	Fish, J	7.80E14	3.5E6	27.3
43	Sugar, J	2.32E15	8.5E4	2.0
44	Other agricultural products, J	4.10E16	7.4E4	30.1
45	Wood products, J	1.20E17	6.6E3	8.0
46	Paper pulp, paper waste, J	2.87E16	1.0E5	29.0
47	Rubber, J	3.03E7	4.3E12	1.3
48	Plastics, kg	1.09E9	3.8E11	4.1
49	Other goods***			444.8
50	Services in imports, USD****	6.68E10	1.8E12	1203.0

* Footnotes given in Appendix A

** sej/J, sej/g, or sej/USD

*** Natural resources in "other goods" calculated in proportion to IR from trade partners; $IR_2 = IR_1(P_1/P_2)$

**** 1996 exchange rate, 6.70 SEK/USD; estimated sej/GDP for trade partners, European countries and U.S.

Table 3. Export commodities from Sweden, 1996

Note*	Item, unit	Annual resource flow (unit/year)	Conversion factor (sej/unit) **	Solar emergy (E+20 sej/year)
51	Refined fuels, J	3.92E17	5.6E4	220.1
52	Propane, butane, J	1.03E16	1.0E5	10.4
53	Electricity, J	3.51E16	1.3E5	44.9
54	Peat, J	6.74E14	3.5E4	0.2
55	Iron ore, kg	1.52E10	1.0E12	151.7
56	Pig iron, kg	3.75E8	1.6E12	5.9
57	Steel products, kg	3.97E9	2.2E12	85.7
58	Machines, kg	1.03E9	6.7E12	69.3
59	Vehicles, kg	4.99E8	6.7E12	33.4
60	Fish, J	1.18E15	3.5E6	41.1
61	Cereals, unmilled, J	1.55E16	6.8E4	10.6
62	Meats, J	3.52E14	1.9E6	6.6
63	Wood products, J	1.59E17	6.6E3	10.5
64	Chemical paper pulp, J	4.91E16	5.1E4	24.9
65	Mechanical paper pulp, J	2.73E15	1.8E5	5.0
66	Paper products, J	1.54E17	6.9E4	105.8
67	Other goods***			168.6
68	Services in exports, USD****	8.50E10	1.4E12	1220.4

* Footnotes given in Appendix A

** sej/J, sej/g, or sej/USD

*** Natural resources in "other goods" calculated in proportion to IR from trade partners; $IR_2 = IR_1(P_1/P_2)$

**** 1996 exchange rate, 6.70 SEK/USD; sej/GDP calculated for Sweden from this study

Together, indigenous natural resources and imports form the basis for Sweden's ecosystems, lifestyle support, industries and markets. Indigenous renewable sources (R) contributed 13% of the total in 1996, 12% came from non-renewable material drawn from within the country (N), 22% from purchased fuels (F), 20% from imported goods (G), and 33% was contributed indirectly from services in support of imports (Table 5).

Net economic balance from trade was 18.12E+9 USD in 1996 (Table 4, notes 9 and 15). Net resource balance from trade measured a surplus of 475.2E+20 sej (Table 5, note 10), or 13% of the Sweden's total resource-use for 1996 (Table 5, note 11). Imports deliver 75% of the resources used, with imports used contributing three times the use of local natural resources (Table 5, note 23).

While Sweden's population density increased by 5%, from 20.5 persons/km^2 in 1988 to 21.5 in 1996, resource-use per unit area increased by 29% (Table 5, note 21). Resource-use per capita correspondingly increased 23% (Table 5, note 13) while per capita GDP increased by 32%.

Renewable sources as a percentage of total resource-use declined by 23%, from 17% of the total in 1988 to 13% in 1996 (Table 5, note 1). While use of other resources increased, renewable sources supporting ecosystem processes were considered unchanged (Table 4, note 1). Imports and use of non-renewable material from within Sweden rose by 30% and 40%, respectively (Table 4, notes 2 and 4). Direct export of metal ores (N_2), however, decreased across years (14%) (Table 4, note 10).

Comparing Sweden's resource base in 1996 to 1988, an additional 814E+20 sej (29% increase) was used (U) to generate a 38% increase in GDP. This was reflected in a 6% reduction in the resource-use/GDP metric (note 4.19). Imported fuels and electricity rose by 32% from 1988 to 1996 (Table 4, note 4), with per capita use of fossil fuels (excluding uranium) increasing by 17% during this period (Table 5, note 17). Electricity use declined from 144 TWh in 1988 to 142 TWh in 1996 and as a percentage of total resource-use from 23% to 18% during this period (Table 5, note 6). Per capita use of electricity declined from 16.9 MWh/p in 1988 to 16.1 MWh/p in 1996 (Table 5, note 18).

Table 4. Summary and percentage change in resource and monetary flows in Sweden, 1988* and 1996.

Note	Item	1988	1996	Units	Percent change
	Local indigenous resources:				
1	Indigenous renewable sources (R)	476.4	476.4	E+20 sej/yr	0
2	Indigenous non-renewable resources (N)	416.6	583.3	E+20 sej/yr	40
3	Minerals, metals refined within country (N_1)	240.2	431.3	E+20 sej/yr	80
	Import commodities:				
4	Imported fuels (fossil fuels, uranium and electricity) (F)	594.0	786.3	E+20 sej/yr	32
5	Imported goods, minerals, fertilizers (G)	559.2	701.0	E+20 sej/yr	25
6	Resources supporting import services (P_2I)	914.2	1203.0	E+20 sej/yr	32
7	Expenditures for imported fuels (I_F)	3.4	5.8	E+9 USD/yr	69
8	Expenditures for imported goods (I_G)	42.4	61.2	E+9 USD/yr	44
9	Total monetary expenditures paid for imports (I)	45.7	66.8	E+9 USD/yr	46
	Export commodities:				
10	Non-renewable resources exported without use (N_2)	176.4	152.0	E+20 sej/yr	-14
11	Exports transformed within country (B)	611.6	842.8	E+20 sej/yr	38
12	Resources supporting export services (P_1E)	762.0	1220.4	E+20 sej/yr	60
13	Revenues from exported raw materials (E_{N2})	0.4	0.5	E+9 USD/yr	32
14	Revenues from export of upgraded products (E_B)	49.3	84.5	E+9 USD/yr	71
15	Total monetary revenues received for exports (E)	49.7	85.0	E+9 USD/yr	71
16	National resource-use (U)	2783.9	3598.1	E+20 sej/yr	29
17	Gross Domestic Product (GDP)	181.5	250.5	E+9 USD/yr	38
18	Currency exchange rate	6.14	6.70	SEK/USD	9
19	Sweden's resource-use/GDP ratio (P_1)	1.53	1.44	E+12 sej/USD	-6
20	Trade partner's resource-use/GDP ratio (P_2)	2.00	1.80	E+12 sej/USD	-10

Table 4 continued

1988 measures from Doherty et al (1993; revised in this study); derivations for 1996 measures are from this study and referenced below.

1 (R) items 3, 4, 5, 10, 11, Table 1
2 (N) N_1+N_2; items 12 through 20, Table 1
3 (N_1) N minus N_2; items 12-20, Table 1 minus items 52 and 53, Table 3
4 (F) items 21-28, Table 2
5 (G) items 29-49, Table 2
6 (P_2I) import expenditures (I) * emergy/GDP ratio (P_2) for trading partners, 1996
7 (I_F) expenditures for uranium, fossil fuels, electricity and peat (Statistics Sweden, 1997, 1998c)
8 (I_G) items 49+50, Table 2, minus I_F
9 (I) sum I_F+I_G
10 (N_2) items 52 and 53, Table 3
11 (B) items 51 and 54 through 67, Table 3
12 (P_1E) export earnings (E) * emergy/GDP ratio (P_1) for Sweden, 1996
13 (E_{N2}) revenues earned from export of raw materials, N_2 (Statistics Sweden, 1998c)
14 (E_B) items 67+68, Table 3, minus I_{N2} (Statistics Sweden, 1998c)
15 (E) sum $I_{N2+}I_B$
16 (U) sum N1+R+F+G+P2I
17 (GDP) Gross Domestic Product for Sweden, 1988 = 1.11E12 SEK, 1996 = 1.68E12 SEK (Statistics Sweden, 1998d)
18 Statistics Sweden (1998d)
19 (P_1) total resource influx (U; Table 5) divided by GDP for Sweden, 1996
20 (P_2) average emergy/GDP ratio for trading partners (U.S. and European countries)

While imported resources increased by 30% (Table 5, note 7), export of resources increased more sharply by 43% from 1988 to 1996 (Table 5, note 8). This is reflected in a greater change in per capita exports than per capita imports during this period (Table 5, notes 14 and 15). Although the net trade balance of resources remained positive, the surplus declined by 8% between 1988 and 1996 (Table 5, note 10). The ratio of imports to exports measured a 9% decline from 1988 (Table 5, note 9).

Import expenditure increased by 46% from 1988 to 1996 (Table 4, note 9), while resources received as imports increased by 30% on average during this period (Table 5, note 7). Export earnings increased by 71% while resources delivered in export increased by 43% during the period (Table 5, note 8).

Table 6 shows computed policy and market values of the Swedish economy in 1988 and 1996, respectively. Exported raw materials (N_2) and imported fuels (F) delivered more resources (sej) at their market value (USD) than upgraded goods (G and B) (Table 6). Generally, resource-proportioned values were larger than market values for all trade commodities in both 1988 (Table 6, notes 3 and 8) and 1996 (notes 10 and 13), but percentage difference was greatest for raw materials (notes 5 and 12) and fuels (notes 2 and 9). In contrast, the resource-proportioned values for upgraded goods ranged from 30% larger to 30% smaller than their market values. Table 7 shows resource-use patterns in Sweden compared with those of other countries. Data and index values were compiled from previously published studies of nations.

Table 5. Comparative indices and percent change of resource use in Sweden, 1988 and 1996

Note	Index	Expression [a]	1988	1996	Units	Percent change
Resource contributions:						
1	% indigenous renewable	R / U	17.1	13.2	%	-23
2	% indigenous non-renewable	N_1 / U	8.6	12.0	%	40
3	% imported fuels and electricity	F / U	21.3	21.9	%	3
4	% imported goods	G / U	20.1	19.5	%	-3
5	% imported services	P_2I / U	32.8	33.4	%	2
6	% Electricity use [b]	(electric) / U	23.0	17.8	%	-23
International trade:						
7	Imports	$F+G+P_2I$	2067.3	2690.4	E+20sej/yr	30
8	Exports	N_2+B+P_1E	1550.0	2215.2	E+20sej/yr	43
9	Ratio of imports to exports	$(F+G+P_2I) / (N_2+B+P_1E)$	1.33	1.21		-9
10	Trade surplus/deficit (imports - exports)	$(F+G+P_2I) - (N_2+B+P_1E)$	517.3	475.2	E+20sej/yr	-8
11	Net trade as % of total use	$[(F+G+P_2I)-(N_2+B+P_1E)] / U$	18.6	13.2	%	-29
Per capita resource-use [c]:						
12	Population		8.4	8.8	E+6 people	5
13	Total resource-use per person	U / population	33.0	40.7	E+15 sej/capita	23
14	Imports per person	$(F+G+P_2I)$ / population	24.5	30.4	E+15 sej/capita	24
15	Exports per person	(N_2+B+P_1E) / population	18.4	25.1	E+15 sej/capita	36
16	Net trade surplus per person	(net trade) / population	6.1	5.4	E+15 sej/capita	-11
17	Fossil fuel-use per person [e]	(F-uranium-electricity) / population	6.5	7.6	E+15 sej/capita	17
18	Electricity-use per person [b]	(electric) / population	7.7	7.2	E+15 sej/capita	-6
19	GDP per person	GDP / population	21515	28330	USD/capita	32
20	Carrying capacity using local resources	((R+N)/U) * (population)	2.7	2.6	E+6 people	-4
21	Resource-use per unit area [d]	U / (land area)	677.5	875.6	E+9 sej/m^2	29

Table 5 cont.

Resource-use indices:					
22	Non-renewable to renewable sources, NRR	N / R	0.87	1.22	40
23	Imports to local resources, ILR	$(F+G+P_2I) / (R+N_1)$	2.89	2.96	2
24	Appropriated resources ratio, ARR	U / (R+N)	3.12	3.40	9
25	Environmental loading ratio, ELR	$(F+G+P_2I+N) / R$	5.21	6.87	32
26	Net yield ratio, NYR	$U / (F+G+P_2I)$	1.35	1.34	-1
27	Sustainability index, SI	NYR / ELR	0.26	0.19	-27

Footnotes to Table 5.

a. variables defined and calculated in Table 4

b. total annual electricity-use = (National generation + imports) - export electricity
1988:(144 TWh electricity)*(3.6E+15 J/TWh)*(1.25E+5 sej/J) = 646.1E+20 sej/yr (Statistics Sweden, 1991)
1996:(142 TWh electricity)*(3.6E+15 J/TWh)*(1.25E+5 sej/J) = 639.9E+20 sej/yr (Statistics Sweden, 1998d)

c. Sweden population: 1988, 8.5 million (Statistics Sweden, 1993); 1996, 8.8 million (Statistics Sweden, 1998d)

d. Sweden land surface area, 0.41 million km^2 (Statistics Sweden, 1998d)

e. imported fuels, excluding uranium and electricity

Table 6. Public policy and market values of the Swedish economy, 1988 and 1996

Note	Contribution	Market value [a] (E+9 USD)	Resource-proportioned value [b] (E+9 USD)	% difference [c]	Purchasing power [d] (E+12 sej/USD)
1988					
1	Imported goods (G)	42.4	55.9	32	1.3
2	Imported fuels (F)	3.4	29.7	768	17.4
3	Total imports (I)	45.7	103.4	126	4.5
4	Exported goods (B)	49.3	40.0	-19	1.2
5	Exported raw materials (N_2)	0.4	11.5	2934	46.4
6	Total exports (E)	49.7	101.3	104	3.1
7	Trade surplus/deficit [e]	4.0	2.1	---	---
1996					
8	Imported goods (G)	61.2	38.9	-36	1.2
9	Imported fuels (F)	5.8	43.7	654	13.6
10	Total imports (I)	66.8	149.5	124	4.0
11	Exported goods (B)	84.5	58.5	31	1.0
12	Exported raw materials (N_2)	0.5	10.6	2012	30.4
13	Total exports (E)	85.0	153.8	81	2.6
14	Trade surplus/deficit [e]	18.1	- 4.4	---	---

a Sources are identified in Table 4 footnotes.

b Resource-proportioned value. Defined as the resource (sej) divided by the resource-use/GDP metric (sej/USD) for the country/region of origin for the trade commodity. The resulting value is the proportion of Sweden's GDP supported by that resource.

1998
G = (559.2E+20 sej)/(2.0E+12 sej/USD) = 55.92E+9 USD
F = (594.0E+20 sej)/(2.0E+12 sej/USD) = 29.70E+9 USD
I = (G+F+P_2I) = (2067.3E+20 sej)/(2.0E+12 sej/USD) = 103.37E+9 USD

B = (611.6E+20 sej)/(1.53E+12 sej/USD) = 39.97E+9 USD
N_2 = (176.4E+20 sej)/(1.53E+12 sej/USD) = 11.53E+9 USD
E = (B+N_2+P_1E) = (1550.0E+20 sej)/(1.53E+12 sej/USD) = 101.37E+9 USD

1996
G = (701.0E+20 sej)/(1.8E+12 sej/USD) = 38.94E+9 USD
F = (786.3E+20 sej)/(1.8E+12 sej/USD) = 43.68E+9 USD
I = (G+F+P_2I) = (2690.4E+20 sej)/(1.8E+12 sej/USD) = 149.47E+9 USD

B = (842.8E+20 sej)/(1.44E+12 sej/USD) = 58.53E+9 USD
N_2 = (152.0E+20 sej)/(1.44E+12 sej/USD) = 10.56E+9 USD
E = (B+N_2+P_1E) = (2215.2E+20 sej)/(1.44E+12 sej/USD) = 153.83E+9 USD

c Percentage difference calculated as ((column 2)-(column 1))/(column 1)*100

d Purchasing power. Defined as the amount of resource (sej) purchased per USD. It is an inverse measure of price, corrected for energy quality and proportioning the GDP to all resources within a country.

1988
G/I_G = (559.2E+20 sej)/(42.38E+9 USD) = 1.32E+12 sej/USD
F/I_F = (594.0E+20 sej)/(3.42E+9 USD) = 17.37E+12 sej/USD
(G+F+P_2I)/I_{tot} = (2067.3E+20 sej)/(45.71E+9 USD) = 4.52E+12 sej/USD

Table 6. continued

$B/E_B = (611.6E+20\ sej)/(49.30E+9\ USD) = 1.24E+12\ sej/USD$
$N_2/E_{N2} = (176.4E+20\ sej)/(0.38E+9\ USD) = 46.42E+12\ sej/USD$
$(B+N_2+P_1E)/E_{tot} = (1550.0E+20\ sej)/(49.68E+9\ USD) = 3.12E+12\ sej/USD$

1996
$G/I_G = (701.0E+20\ sej)/(61.21E+9\ USD) = 1.15E+12\ sej/USD$
$F/I_F = (786.3E+20\ sej)/(5.79E+9\ USD) = 13.58E+12\ sej/USD$
$(G+F+P_2I)/I_{tot} = (2690.4E+20\ sej)/(66.84E+9\ USD) = 4.02E+12\ sej/USD$

$B/E_B = (842.8E+20\ sej)/(84.46E+9\ USD) = 1.00E+12\ sej/USD$
$N_2/E_{N2} = (152.0E+20\ sej)/(0.50E+9\ USD) = 30.4E+12\ sej/USD$
$(B+N_2+P_1E)/E_{tot} = (2215.2E+20\ sej)/(84.96E+9\ USD) = 2.61E+12\ sej/USD$

e Net trade surplus/deficit

Market value: (Export revenues) – (Import expenditures)
1988: 49.68E+9 USD – 45.71E+9 USD = 3.97E+9 USD
1996: 84.96E+9 USD – 66.84E+9 USD = 18.12E+9 USD

Resource-proportioned value: (Import emergy) – (Export emergy)
1988: 103.37E+9 USD – 101.31E+9 USD = 2.06E+9 USD
1996: 149.47E+9 USD – 153.83E+9 USD = -4.37E+9 USD

Table 7. Comparison of resource-use metrics for Sweden and other countries, 1983-89

Note	Index [a]	Sweden[1)]	Italy[2)]	USA[3)]	Taiwan[4)]	Thailand[5)]	Ecuador[6)]
1	% indigenous renewable	17	10	10	11	52	50
2	% imports	74	62	24	67	32	6
3	% net trade	19	38	11	11	-28	-26
4	Resource-use/capita (E+15 sej/p)	33.0	22.0	33.8	10.2	3.0	10.0
5	Local resources/capita (E+15 sej/p)	10.6	8.3	26.7	3.3	2.0	11.8
6	Imports/capita (E+15 sej/p)	24.5	13.7	8.1	6.8	0.6	0.6
7	Net trade/capita (E+15/p)	6.1	8.3	3.6	1.1	-0.8	-2.0
8	GNP/capita (USD/p)	21515	15058	14103	558	849	1159
9	Resource-use/ area (E+12 sej/m^2)	0.7	4.2	0.8	5.6	0.3	0.3
10	Resource-use/GNP (E+12 sej/USD)	1.5	1.5	2.0	1.9	3.5	8.7
11	Non-renewable to renewable, NRR	0.9	3.0	6.6	2.1	0.3	1.4
12	Imports to local resources, ILR	2.9	1.7	0.3	2.0	0.5	0.1
13	Appropriated resources ratio, ARR	3.1	2.6	1.3	3.0	1.4	0.9
14	Environmental loading ratio, ELR	5.2	9.5	8.9	8.4	1.0	1.5
15	Net yield ratio, NYR	1.4	1.6	4.2	1.5	3.1	15.6
16	Sustainability index, SI	0.3	0.2	0.5	0.2	3.2	10.5

a) Definitions of indices are given in Table 5.

1) c. 1988 (Doherty et al., 1993; revised in this study), GDP used instead of GNP
2) c. 1989 (Ulgiati et al., 1994)
3) c. 1983 (Odum and Odum, 1983; revised in Odum, 1996)
4) c. 1987 (Huang and Odum, 1991; revised in Huang, 1998)
5) c. 1985 (Brown and McClanahan, 1996)
6) c. 1986 (Odum and Arding, 1991)
7) c. 1987 (Doherty and Brown, 1993)

Discussion

Sustainability and policy issues

The Swedish economy was less sustainable in 1996 than 1988 because the environmental loading (ELR) increased while the net yield ratio (NYR) remained the same.

Long-term sustainability would be enhanced by supporting the use of locally renewable emergy flows, i.e. replacement of imported and fossil fuels with domestic renewable fuels. Börjesson and Gustavsson.(1996) and Gustavsson et al. (1995) estimated that the present use of biofuels from logging residues and energy crops of about 80 TWh/year (250 PJ) could increase to around 200 TWh (720 PJ) in the year 2015. As pointed out by Gustavsson et al. (1995), the use of willow (Salix) and other biofuels would reduce net carbon dioxide emissions significantly. The sustainability of the Swedish economy would certainly benefit from the increased use of logging residues. According to Doherty (1995) it is, however, uncertain whether the use of Salix plantations give such net yields of energy as promised by energy analysis when analysed with emergy analysis. District heating in Sweden with Salix in Doherty´s (1995) investigation, which was performed on a willow plantation system of the late eighties, had a net yield ratio of just above one. Primary energy sources usually have net yield ratios above five (Brown and Ulgiati, 1997). It is, of course, crucial that the fuels used make a net contribution to the economy, i. e. the net yield ratio must be more than one.

During recent years, the political interest in reducing resource use has increased in Sweden. In 1995, 128 PJ of electricity was used in Swedish households (Statistics Sweden, 1998d). Unfortunately, this high quality energy has often been used for low quality work like heating instead of interacting with low grade inputs to stimulate the optimum use of large amounts of low-quality resources, i. e. low transformity resources.

The total potential for reducing electricity use has been estimated at 15-19 TWh (54-68 PJ) and 15-51 TWh (54-180 PJ) for reducing fuel use until 2015 (SOU, 1995). Coproduction of electricity and heat from biomass in district heating plants would reduce losses and thus increase overall efficiency of electricity production. Electricity generated from biomass in this way equals about one third of today´s nuclear electricity use (Börjesson and Gustavsson, 1996).

Saving fuels and electricity would reduce imports and total resource use would then decrease. Consequently, the renewable fraction of the total resource use would increase as well as the carrying capacity. The ratio of imports to local resources would decrease, indicating a more efficient overall resource use. The decrease in environmental loading, combined with the increase in the NYR would most likely increase the sustainability of the economy.

In the long run, sustainability requires a high percentage of renewable resource use. This could be achieved by reducing total emergy use, i. e. by reducing imports and use of non-renewable resources. Reducing imports would raise the emergy yield ratio and lower the environmental impact, thus raising the sustainability index. This reduction of imported fuels would cause the appropriated resource ratio to decrease as would any reduction in imports. The electricity use was shown to have decreased from 1988 to 1996. However, the increase in use of imported fuels was greater than this reduction in electricity use.

The SI is inversely proportional to economic development status in the sense that developed industrialized economies are often highly dependent on non-renewable energy and purchase a lot of commodities from abroad while exerting large environmental stress (Brown and Ulgiati, 1997). According to Brown and Ulgiati (1997), SIs of less than one may be typical for highly developed consumer-oriented economies while SIs of one to 10 signify so-called developing economies. Sustainability indices greater than 10 may be associated with undeveloped countries. The declining SI of Sweden seems to be in accordance with the trend in SI of Taiwan shown by Brown and Ulgiati (1997).

Details concerning indices

The overall increase in emergy use, causing a percentage decrease in locally renewable use between 1988 and 1996, was attributed to increased use of domestic non-renewable resources, as well as increased import of fuels and goods. Combined with the fact that the indigenous renewable resource use remained the same, the increased use of non-renewable resources causes the non-renewable to renewable ratio (NRR) to increase. The high non-renewable to renewable ratio (NRR) indicates that the Swedish economy uses large amounts of local non-renewables to match small amounts of renewable resource use.

The self-sufficiency of Sweden is only moderate as given by the 29% of emergy derived from indigenous resources while 71% originated from imports. A combination of a large resource base developed from rainfall and snow melt in mountainous terrain giving rise to potential hydroelectric power production, large productive forest areas and a net benefit from trade, gives Sweden a large resource basis supporting its relatively sparse human population. Consequently its per capita emergy was, as expected, confirmed to be large in comparison with other countries (Table 7).

Both resource-use per unit area and emergy per capita increased, indicating that on average, Sweden required more resources in 1996 than in 1988. Consequently, the local carrying capacity was expected to decrease but there was only a slight decrease, again confirming that the increased resource demand was mainly matched by indigenous non-renewable resource outtake. The indigenous resources, renewable and non-renewable, could only support less than a third of the Swedish population in 1996. Using only renewable indigenous resources, the carrying capacity would drop to 13% of the 1996 population, sustaining existing consumption patterns.

The Swedish ILR remained nearly the same between 1988 and 1996. The Swedish economy may thus, relatively seen, be equally efficient or inefficient in using imports to exploit indigenous resources in both years. The net yield ratio (NYR) was also the same, showing that the increase in inputs did not draw more natural resources per input.

Purchasing power, defined as resources received (sej) per unit economic cost (USD), for unrefined materials and fuels is an order of magnitude greater than sej/USD measures for average imports, exports and upgraded goods (Table 6, notes 1, 4, 8 and 11). Purchasing power identifies a gross price for trade commodities; the larger the value, the greater the benefit derived from a market purchase, with low purchasing power benefitting the seller. From this, it follows that Sweden benefits from importing fuels, these being cheap in comparison with upgraded goods which contribute less resources per USD paid in the transaction. In contrast, the export of raw materials contributes more resources to the buyer´s economy than upgraded goods. Thus, the Swedish economy benefits from exporting more upgraded goods and less raw materials. Comparing trade in 1988 with 1996, the export of raw materials indeed decreased while the export of upgraded goods increased. The services associated with exports also increased more (60% increase) than services associated with imports (32% increase), indicating that Sweden exported more high grade products in 1996 than in 1988.

In 1988, purchased fuels delivered less sej/USD than in 1996 (Table 6, notes 2 and 9). Thus, Sweden benefited less from the import of fuels in 1996 than eight years earlier. The purchasing power of unrefined material also declined during this period, benefiting Sweden as the exporter because less emergy was spent per USD received. In general Sweden benefited from external trade. Imports as well as exports increased, showing that the economy of 1996 was more dependent on international trade. Sweden receives more emergy in imports than leaves the country in exports and receives more emergy in trade than its trade partners. Consequently Sweden has its economy stimulated more by this trade. There was a surplus in net resource balance from trade (Table 5, note 11), expressed in a positive import/export ratio of 1.2 (Table 5, note 9) with Sweden receiving 1.2 unit resources for every unit delivered in 1996 external trade.

The emergy to USD ratio decreased between 1988 and 1996, indicating that less emergy was associated with each USD or SEK in 1996. The per capita income rose faster than resource use per person, with fewer resources supporting increased economic activity. This declining emergy to currency ratio is in accordance with trends found by Huang and Odum (1991), who showed that world emergy to USD ratio as well as the Taiwan emergy to USD ratio decreased between 1969 and 1987. This decline reflects the development of economies in the sense that as economies develop, more so-called high-tech commodities are used. These represent relatively more services reflected by higher prices. Thus more money (services) circulates for the same amount of resource emergy, causing the emergy to currency ratio to decrease. In both import and export transactions, more money (USD) was required to purchase fewer resources (sej) in 1996 than in 1988. This inflation, however, was greater for exports than imports, benefiting Sweden, as revenues earned per unit resource exported rose more quickly than the quantity of resources imported per unit expenditure paid out. This was largely due to the increase in imported fuels and electricity and the decrease in the export of unrefined, non-renewable material between 1988 and 1996.

The appropriated resource ratio (ARR) is affected by the total resource use but also by the amounts of indigenous renewable and non-renewable resources sustaining the economy. This ARR may be expected to be affected by the territorial area of the country, i.e. the size of the solar collector (collector of direct environmental inputs) in the sense that a large country collects a large amount of direct environmental inputs. A larger country may also be expected to possess relatively larger stores of non-renewable resources available for mining. Furthermore, the more imports and the more services in imports, the higher the ARR. The ARR implies that Sweden used 3.4 times more resources than it extracted from local resources in 1996 (Table 5, note 24). Sweden extracted more local resources in 1996 than in 1988, but this increase in local resource extraction was overshadowed by the larger increase in imports and therefore the ARR increased despite the increase in local resource use.

According to Brown and Ulgiati (1997), an environmental loading ratio (ELR) of about two indicates a relatively small or diluted environmental loading, a ratio between three and 10 may be regarded as moderate, while ELRs higher than 10 indicate a large or concentrated environmental impact. Sweden, having an ELR of 5.2, would then be considered to exert a moderate pressure on its environment. The ELR of Sweden increased from 5.2 to 6.9 between 1988 and 1996, because imports as well as the use of local non-renewable sources of emergy increased during the period. This indication of external dependency is also reflected in a net resource yield ration near unity (NYR = 1.34; Table 5, note 26). Furthermore, use of non-renewable and purchased resources placed a load on local ecosystems 7 times greater than the renewable support base (Table 5, note 26). These conditions resulted in a small sustainability metric below unity (SI = 0.2, note 5.27).

Comparisons between nations

High ratios of imports to local resources (ILR) indicate high dependency on imported inputs. This is often the case for small countries possessing few indigenous resources or highly developed industrial nations. Consequently, it is not surprising to find that e.g. Thailand and Equador had lower ILRs than e.g. Taiwan, Italy and Sweden (Table 7). The relatively low ILR of USA was due to the vast area of the country, capturing a lot of renewable energies, as well as possessing large stores of non-renewable resources available for domestic use.

Per capita resource-use (Table 7, note 4) is high for industrial nations due to their dependence on high quality fossil fuels and other imports, but may also be high in rural countries with abundant local resources. Local resource-use per person (Table 7, note 5), however, is higher in rural areas rich in renewable sources or in countries with active extractive sectors of non-renewable resources. High population densities act to lower per capita values.

Differences in per capita income, expressed as GDP/p or GNP/p (Table 7, note 8), reveal economic and cost of living disparities between industrial and rural nations. By relating resource-use (sej/yr) to gross domestic product or gross national product (USD/yr) an opposite trend is identified (Table 7, note 10), with more resources supporting smaller economies in less developed nations and limited and declining resources supporting large and expanding economies. Viewed this way, the currency (USD) of developing nations is supported by more resources (sej) and has a greater purchasing power, yet inequities occur in transactions between trade partners based on currency exchange rates and market prices because natural capital and ecosystem services are not fully accounted for by markets.

Conclusion

In conclusion, it is possible to improve the sustainability of the Swedish economy as well as its efficiency in resource use. The present energy policy, encouraging a reduction in electricity and fuel use and conversion of household heating systems to systems using renewable resources is supported by this emergy analysis as being in the right direction. Naturally, the economy would benefit from other sectors using renewable fuels to a larger extent than today as well. The question of planting willow on a large scale may, however, need further investigation. Finally, since reduction of non-renewable imports may be an important policy objective when directing the national economy towards sustainability, more studies on the effects of globalization of markets on an increasing scale would be called for.

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References

Brown, M. T. and Arding, J. (1991). *Transformities. Working paper. Center for Wetlands, University of Florida, Gainesville, USA.*

Brown, M. T. and Mc Clanahan, T. R. (1996). Emergy analysis perspectives of Thailand and Mekong River Dam proposals. *Ecological Modelling 91*, 105-130.

Brown, M. T. and Ulgiati, S. (1997). Emergy indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. *Ecological Engineering* **9**, 51-69.

Börjesson, P. and Gustavsson, L. (1996). Regional production and utilisation of biomass in Sweden. *Energy - The International Journal* **21**, 747-764.

Doherty, S. J. (1995). *Emergy evaluation of and limits to forest production. Dissertation. Department of Environmental Engineering Sciences, Univerity of Florida, Gainesville, USA.*

Doherty, S. J. Brown, M. T. (1993). Emergy synthesis perspectives, sustainable development, and public policy options for Papua New Guinea. *CFWWR Publication 93-06. Center for Wetlands and Water Resources, University of Florida, Gainesville, USA.*

Doherty, S. J. Nilsson, P. O. and Odum, H. T. (1993). Emergy analysis of forest production and industries in Sweden. *Report to Vattenfall (Swedish Energy Board) and the Royal Swedish Academy of Agriculture and Forestry. Swedish. Univ. Agric. Sci., Garpenberg, Sweden. Manuscript.*

Ekman, M. (1993). Postglacial rebound and sea level phenomena, with special reference to Fennoscandia and the Baltic Sea. In: *Kakkuri, J. (ed.). Geodesy and geophysics. Lecture notes for NKG-autumn school 1992 organized by Nordiska kommissionen för geodesi, Korpilampi, Finland, September 7-13 1992*. Helsinki.

Fluck, R. (1992). Energy of agricultural products. In: Fluck, R. (Ed.). *Energy in farm production. Energy in world agriculture vol. 6*. Elsevier, Amsterdam, 39-43.

Gustavsson, L. Börjesson, P. Johansson, B. and Svenningsson, P. (1995). Reducing CO_2 emissions by substituting biomass for fossil fuels. *Energy - The International Journal* **20**, 1097-1113.

Haukoos, D. (1994). *An Emergy analysis of various construction materials. ENV 6905. Department of Environmental Engineering Sciences, Univerity of Florida, Gainesville, USA.*

Huang, S. (1998). Urban ecosystems, energetic hierarchies, and ecological economics of Taipei metropolis. *Journal of Environmental Management* **52**, 39-51.

Huang, S. and Odum, H. T. (1991). Ecology and economy: Emergy synthesis and public policy in Taiwan. *Journal of Environmental Management* **32**, 313-333.

LKAB. (1997). *Årsredovisning 1996.* [Annual Report].

Odum, H. T. (1987). Living with complexity. In: *Craaford Prize in the Biosciences, Craaford lectures.* Royal Swedish Academy of Sciences, Stockholm, 19-85.

Odum, H. T. (1988). Self organization, transformity and information. *Science* **242**, 1132-1139.

Odum, H. T. (1996). *Environmental accounting. Emergy and environmental decision making*. New York: Wiley.

Odum, H. T. and Arding, J. E. (1991). Emergy analysis of shrimp mariculture in Ecuador. *Department of Environmental Engineering Sciences and Center for Wetlands, University of Florida, Gainesville, USA.*

Odum, H. T. and Odum, E. C. (1983). Energy analysis overview of nations, with sections by G. Bosch, L. Braat, W. Dunn, G. de R. Innes, J. R. Richardson, D. M. Scienceman, J. P. Sendizimir, D. J. Smith, and M. V. Thomas. *Working Paper (WP-83-82). International Institute of Applied Systems Analysis, Laxenburg, Austria.*

Odum, H. T. Odum, E. C. and Brown, M. T. (1998). *Environment and society in Florida.* Lewis Publishers: Boca Raton.

Scienceman, D. M. (1987). Energy and Emergy. In: Pillet, G. and Murota, T. (eds.). *Environmental Economics*, 256-276. Roland Leimgruber, Geneva.

Schmidt-Bleek, F. (1997). The ecological reform of the economy. In: Smith, P. and Tanner, T. (eds.). *Dimensions of sustainability. Proceedings of the congress challenges of sustainable development, Amsterdam 22-25 August 1996*, 69-80. Baden-Baden: Nomos Verlagsgesellschaft.

SMHI [Swedish Meteorological and Hydrological Institute]. (1997). Väderåret 1996. *Väder och Vatten – En tidning från SMHI* **1**.

SOU 1995:140. Omställningen av det svenska energisystemet. Underlagsbilaga 12. (Official investigation by the Swedish government)

Statens Livsmedelsverk. (1986). *Livsmedelstabeller. Energi och näringsämnen.*

Statistics Sweden. (1991). *Statistical yearbook of Sweden.*

Statistics Sweden. (1992). *Statistical yearbook of Sweden.*

Statistics Sweden. (1993). *Statistical yearbook of Sweden.*

Statistics Sweden. (1997a). *Manufacturing 1995. Part 2.*

Statistics Sweden. (1997b). Peat 1996. Resources, use, environmental impact. *Na25SM9701.*

Statistics Sweden. (1998a). Division of Foreign Trade. Personal communication.

Statistics Sweden. (1998b). Energy supply the 4[th] quarter and the whole years 1996 and 1997. Preliminary data. E20SM9802.

Statistics Sweden. (1998c). Statistical database on the Internet. Homepage: http://www.scb.se. Limited access.

Statistics Sweden. (1998d). *Statistical yearbook of Sweden.*

Statistics Sweden. (1998e). *Yearbook of agricultural statistics.*

Sveriges Nationalatlas. (1992). *Hav och kust.*

Sveriges Nationalatlas. (1994). *Berg och jord.*

Sveriges Nationalatlas. (1995). *Klimat, sjöar och vattendrag.*

Ulgiati, S. Odum, H. T. and Bastianoni, S. (1993). Emergy analysis of Italian agricultural system. The role of energy quality and environmental inputs. In: Bonati, L. (ed.). *Trends in ecological physical chemistry. International workshop on ecological physical chemistry 2 1992, Milano*, 187-214.

Ulgiati, S. Odum, H. T. and Bastianoni, S. (1994) Emergy use, environmental loading and sustainability. An emergy analysis of Italy. *Ecological Modelling 73*, 215-268.

Wackernagel, M. and Rees, W. (1996). *Our ecological footprint. Reducing human impact on the earth.* Gabriola Island, BC: New Society Publishers.

Wackernagel, M. Onisto, L. Linares, A. C. Falfán, I. S. L. García, J. M. Guerro, A. I. S. and Guerro, G. S. (1997). *Ecological footprints of nations. How much nature do they use? How much nature do they have?* The Earth Council, Costa Rica.

Westing, A. H. (ed.). (1989). *Comprehensive security for the Baltic: an environmental approach.* International Peace Research Insitute, Oslo. UN environmental programme.

Personal Communications

SMHI (1997). Personal communication.

Appendix A. Footnotes to Tables 1-3.

1. Average global insolation 1961-1990 estimated to 950 kWh/m^2 over land and lakes from Sveriges Nationalatlas (1992), Sveriges Nationalatlas (1995), and SMHI (1997). Energy received over land = 410934E6[m^2, land]x950[kWh]x3.6E6[J/kWh] x(1-0.37)[1-albedo] = 8.8540E20 J.
   Energy received over lakes = 39030E6[m^2,lakes]x950[kWh]x3.6E6[J/kWh] = 1.3348E20 J.
   Sum = 8.8540E20+1.3348E20 = 1.019E21 J. Transformity by definition 1 sej/J.

2. Surface wind is 60 % of the wind speed at 1000 m, i.e. 40 % of the wind speed at 1000 m is absorbed. Average wind speed at ground level = 5.0 m/s (Sveriges Nationalatlas, 1995). Wind energy absorbed = 449964E6[m^2]x1000[m, height of boundary layer] x1.23[kg/m^3, density of air]x$(0.4x5.0[m/s]/0.6)^2/2$ = 3.075E15 J. Transformity from Odum (1996).

3. Precipitation = 750 mm/year (Sveriges Nationalatlas, 1995; SMHI, 1997).
   Evaporation = 350 mm/year (Sveriges Nationalatlas, 1995; SMHI, 1997) = 350/750 = 47 % of precipitation.
   Rain, chemical = evapotranspired rain = 449964E6[m^2]x750[mm]x1E-3[m/mm]x0.47 [47 % evapotranspiration]x1000[kg/m^3, density of water]x4940[J/kg, Gibbs free energy of rainwater] = 7.835E17 J. Transformity from Odum (1996).

4. ET = 350 mm/year = 47 %.
   Runoff = Rainfall-ET = 750-350 = 400 mm/year = 53 %.
   Geopotential energy of rain = 400[mm]x1E-3[m/mm]x410934E6[m^2, land area]x530 [m, mean elevation of land mass]x1000[kg/m^3, density of water]x9.8[m/s^2, gravity] = 8.538E17 J. Transformity from Odum (1996).

5. Geologic uplift = 5 mm/year (Ekman, 1993; Sveriges Nationalatlas, 1994).
   Density of rock = standard density of materia between surface and geoide = 2670 kg/m^3 (Sveriges Nationalatlas, 1994). Mass lifted = 5[mm]x1E-3[m/mm]x410934E6 [m^2]x2670[kg/m^3] = 5.486E12 kg.
   Assuming that the centre of gravity is ½ of uplift, the work done is estimated as 5.486E12[kg]x5[mm]/2x1E-3[m/mm]x9.8[m/s^2] = 1.344E11 J. Transformity from Doherty et al. (1993).

6. Global insolation over sea = 1000 kWh/m^2 (Sveriges Nationalatlas, 1992; SMHI, personal communication). Territorial waters = 60000 km^2, Inner waters between baseline and coastline = 20000 km^2, Economic zone = 70000 km^2; sum = 150000 km^2 = 1.50E11 m^2.
   Energy over the Swedish part of the Baltic Sea = 1.50E11[m^2]x1000[kWh/m^2] x3.6E6[J/kWh] = 5.4E20 J.

7. Average wind speed over sea (SMHI, personal communication) = 7.5 m/s.
   Energy = 1.50E11[m^2]x1000[m, height of boundary layer]x1.23[kg/m^3, density of air] x$(0.4x7.5[m/s]/0.6)^2/2$ = 2.306E15 J.

8. Salinity of rainfall = 1.2 ppm. Salinity of Baltic seawater = 6000 ppm.
   Gibbs free energy (Odum, 1996) = 0.00199[kcal/K/mole]x300[K]/18[g/mole] xln((1E6-1.2)/(1E6-6000))x4186[J/kcal]x1000[g/kg] = 835.4 J/kg. Chemical potential energy of rainfall over the Baltic Sea = 550[mm precipitation; Sveriges Nationalatlas, 1992]x1E-3[m/mm]x1.50E11[m^2]x999.84[kg/m^3, density]x835.4[J/kg] = 6.891E16 J.

Appendix A continued.

9. Salinity of runoff = 150 ppm. Salinity of Baltic seawater = 6000 ppm.
   Gibbs energy (Odum, 1996) = 0.00199[kcal/K/mole]x300[K]/(18[g/mole] x1E-3[kg/g])xln((1E6-150)/(1E6-6000))x4186[J/kcal] = 814.7 J/kg.
   Area of the Baltic Sea (incl. the Gulf of Bothnia, Gulf of Finland, Gulf of Riga, Belt Sea, Sound/Öresund, and Kattegat) (Westing, 1989) = 4.15E11 m^2.
   Portion of the Baltic Sea attributed to Sweden = 1.50E11[m^2]/4.15E11[m^2] = 36.14 %.
   Total stream inflow to the Baltic Sea = 430E9 m^3/year (Westing, 1989).
   Chemical potential energy = 430E9[m^3]x1.50E11[m^2, Swedish part of Baltic Sea] /4.15E11[m^2, Baltic Sea]x999.85[kg/m^3]x814.7[J/kg] = 1.266E17 J.
   Transformity from Odum (1996).

10. Area of shelf = 1.60E11 m^2 (Sveriges Nationalatlas, 1994). 50 % of tidal energy is assumed to be absorbed by shelf, i.e. 50 % is received at shoreline.
    Tidal energy = 1.60E11[m^2]x0.31^2[m, tidal range^2]x706[tides/year]x1006[kg/m^3, density of seawater]x9.8[m/s^2]x0.5[50 %] = 5.351E16 J.
    Transformity from Odum (1996).

11. Length of shoreline = 2600 km (SMHI, personal communication).
    The Baltic Sea is frozen and thus without wave action during 2-3 months/year (Sveriges Nationalatlas, 1992). Wave energy = 1/8x9.8[m/s^2]x1006[kg/m^3, density of seawater]x0.5^2[m, mean wave height]x(9.8[m/s^2, gravity]x6)$^{1/4}$[m, mean shoaling depth]$^{1/2}$x31.54E6[s/year]x2600[km]x1000[m/km] x9/12[months/year with wave action] = 1.453E17 J. Transformity from Odum (1996).

12. Peat production (Statistics Sweden, 1997b) = 2278E3[m^3, peat for energy]+1084E3 [m^3, peat for horticultural use] = 3.362E6 m^3. 4.3E6 m^3 peat corresponds to 3.91E3 MWh ⇒ energy contents = 3.91E3[MWh] x3.6E12[J/MWh]/4.3E6[m^3] = 3.27E9 J/m^3.
    Energy = 3.362E6[m^3]x3.27E9[J/m^3] = 1.099E16 J.
    Transformity from Odum et al. (1998).

13. Iron ore (LKAB, 1997) = 3.29E10 kg. Transformity from Odum (1996).

14. Gold (Statistics Sweden, 1997a) = 7.065E3 kg.

15. Silver (Statistics Sweden, 1997a) = 2.556E5 kg.

16. Copper (Statistics Sweden, 1997a)=3.120E8 kg. Transformity from Odum (1996).

17. Lead (Statistics Sweden, 1997a) = 1.372E8 kg. Transformity from Odum (1996).

18. Zinc (Statistics Sweden, 1997a) = 3.039E8 kg. Transformity from Odum (1996).

19. Other mineral rock (Statistics Sweden, 1997a) = 4.8819E7[kg, pyrites]+5.413159E9 [kg, granite]+1.988887E9[kg, quartz]+2.353E6[kg, marble]+ 6.00E4E8[kg, sand other than quartz]+2.1875E10[kg, other pebbles and gravel]+1.357E9[kg, macadam] = 3.069E10 kg. Transformity of granitic rocks from Odum (1996).

20. Sedimentary material (Statistics Sweden, 1997a) = 5.482215E9[kg, limestone] +3.10E8[sandstone]+1.771E7[kg, schist]+4.7226E7[kg, feldspar]+1.08043E8[kg, chalk]+ 3.45427E8[kg, dolomite]+3.86E5[kg, mica]+4E3[kg, talc] = 6.311E9 kg. Transformity from Odum (1996).

Appendix A continued.

21. 71 384 GWh of net electricity (excl. consumption in power plants) was generated from nuclear fuel (Statistics Sweden, 1998d). This corresponds to 71384E6[kWh] x2.31E-5[kg U_3O_8/kWh] = 1.6489704E6 kg of natural uranium. 1.6489704E6[kg U_3O_8]x0.007[0.7 % U235 in U_3O_8]x7.95E13[J/kg U235] = 9.176E17 J in U235. Transformity from Odum (1996).

22. Crude petroleum (Statistics Sweden, 1998c) = 1.9898524E10[kg]x45E6[J/kg] = 8.954E17 J. Using sedimentary coal for derivation of transformity in accordance with Odum (1996), p. 308; 3.4E4[sej/J]*1.65/1.23=4.71E4 sej/J.

23. Refined fuels incl. lubricants and other processed mineral oils (Statistics Sweden, 1998c) = 6.908723E9 kg. Energy = 6.908723E9[kg]x4.187E7[J/kg] = 2.893E17 J. Using sedimentary coal for derivation of transformity in accordance with Odum (1996), p. 308; 3.4E4[sej/J]*1.65=5.61E4 sej/J.

24. Coal (Statistics Sweden, 1998c) = 3.60194E9[kg]x2.72141E7[J/kg] = 9.802E16 J. Transformity from Odum (1996).

25. Natural gas (Statistics Sweden, 1998b) = 3.386E16 J.
Using sedimentary coal for derivation of transformity in accordance with Odum (1996), p. 308; 3.4E4[sej/J]*1.2=4.08E4 sej/J.

26. Propane and butane (Statistics Sweden, 1998b) = 3.832E16 J.
Using sedimentary coal for derivation of transformity of natural gas and then propane in accordance with Odum (1996), p. 308; 3.4E4[sej/J]*1.2*93.8[MJ/m^3, enthalpy of propane]/38.0[MJ/m^3, enthalpy of natural gas]=1.007E5 sej/J.

27. Electricity (Statistics Sweden, 1998b) = 5.719E16 J. World average transformity from Odum (1996).

28. Peat (Statistics Sweden, 1997b) = 1.55572E8[kg]/300[kg/m^3]x3.27E9[J/m^3, note 12] = 1.696E15 J.

29. Nitrogen fertilizer (Statistics Sweden, 1998a) = 5.23565E8 kg. Transformity from Odum (1996).

30. Potassium fertilizer (Statistics Sweden, 1998a) = 1.372E8 kg. Transformity from Odum (1996).

31. Phosphorus fertilizer (Statistics Sweden, 1998a) = 1E6 kg. Transformity from Odum (1996).

32. Copper (Statistics Sweden, 1998c) = 1.826E8 kg. Transformity from Odum (1996).

33. Aluminum (Statistics Sweden, 1998c) = 4.469E8 kg.

34. Zinc (Statistics Sweden, 1998c) = 4.210E7 kg. Transformity from Odum (1996).

35. Iron ore (Statistics Sweden, 1998c) = 1.503E8 kg. Transformity from Odum (1996).

36. Pig iron (Statistics Sweden, 1998c) = 2.180E18 kg.

Appendix A continued.

37. Steel (Statistics Sweden, 1998c) = 3.353E8[kg, ingots and other primary forms] +1.185416E9[kg, flat-rolled products]+5.91302E8[kg, iron and steel bars, rods] +2.2637E7[kg, rail and railway track materials]+5.68720E7[kg, wire of iron and steel]+3.06510E8[kg, tubes, pipes and fittings]+3.33331E8[kg, scrap iron and steel, remelted ingots] = 2.831E9 kg. Transformity from Haukoos (1994).

38. Vehicles (Statistics Sweden, 1998c) = 2.641E8 kg. Transformity from Brown and Arding (1991)

39. Wool (Statistics Sweden, 1998a, c) = 1.334E6[kg]x5E3[kcal/kg]x4186[J/kcal] = 2.792E13 J. Transformity from Odum and Odum (1983).

40. Cotton (Statistics Sweden, 1998c) = (1.3209E7[kg, cotton]+1.2000E7[kg, cotton fabrics]x4E3[kcal/kg] x4186[J/kcal] = 4.221E14 J. Transformity from Brown and Arding (1991).

41. Meat (Statistics Sweden, 1998c) = 6.7241E7[kg]x0.22[22 % protein]x2.37E7[J/kg protein; Fluck, 1992)] = 3.506E14 J. Transformity from Ulgiati et al. (1993).

42. Fish (Statistics Sweden, 1998c) = 1.55384E8[kg]x5020E3[J/kg] = 7.800E14 J. Transformity from Doherty et al. (1993).

43. Sugar (Statistics Sweden, 1998c) = 1.3635E8[kg]x1.7E7[J/kg, (Statens Livsmedelsverk, 1986)] = 2.318E15 J. Transformity from Ulgiati et al. (1993).

44. Other agricultural products (Statistics Sweden, 1998c) = 2.52447E8[kg, grains and cereals, incl. processed]+6.22345E8[kg, fruits and nuts]+1.01541E8[kg, coffee] +8.06812E8[kg, animal feed]+2.31793E8[kg, oil-seeds and nuts]+3.471E6[kg, tea] +9.124E6[kg, tobacco]+5.6918E7[kg, dairy products and eggs]+4.58838E8[kg, vegetables, incl. potatoes] = 2.543289E9 kg.
Energy = 2.543289E9[kg]x3.85E3[kcal/kg]x4186[J/kcal] = 4.099E16 J.
Transformity from Ulgiati et al. (1993).

45. Wood products (Statistics Sweden, 1998c) = 4.6934E7[kg, fuel wood and charcoal]+6.99494E8[kg, chips and wood waste]+4.540006E9[kg, wood in the rough or roughly squared]+1.39020E8[kg, lumber sawn and planed]+3.6112E8[kg, veneers, plywood and particle board]+7.2703E7[other wood products] = 5.859277E9 kg.
Energy = 5.859277E9[kg]x2.052E7[J/kg] = 1.202E17 J.
Transformity of forest products from Doherty (1995).

46. Paper pulp, paper and paper waste (Statistics Sweden, 1998c) = 1.3994E9 [kg] x2.052E7[J/kg] = 2.872E16 J. Mean transformity of chemical pulp, mechanical pulp and paper products from Doherty (1995).

47. Rubber (Statistics Sweden, 1998c) = 3.026E7 kg. Transformity from Brown and Arding (1991).

48. Plastics (Statistics Sweden, 1998c) = 1.086E9 kg.

50. Services in imports (Statistics Sweden, 1998c) = 4.47800E11[SEK]/6.70[SEK/USD] = 6.6836E10 USD.

Appendix A continued.

51. Refined fuels and other processed mineral oils, incl. lubricants (Statistics Sweden, 1998c) = 9.37112E9[kg]x4.187E7[J/kg] = 3.924E17 J.

52. Propane, butane (Statistics Sweden, 1998b) = 1.032E16 J.

53. Electricity (Statistics Sweden, 1998b) = 3.508E16 J. Mean transformity of Swedish hydroelectric power and world average (Odum, 1996).

54. Peat for horticultural use (Statistics Sweden, 1997b) = 6.1845E7[kg]/300[kg/m^3] x3.27E9[J/m^3, note 12] = 6.741E14 J.

55. Iron ore (Statistics Sweden, 1998c) = 1.517E10 kg.

56. Pig iron (Statistics Sweden, 1998c) = 3.751E8[kg].

57. Steel products (Statistics Sweden, 1998c) = 1.0532E8[kg, ingots and other primary forms]+1.236124E9[kg, flat rolled iron, not clad]+4.16445E8[kg, flat rolled iron, clad]+8.65644E8[kg, flat rolled alloy products] +6.94857E8[kg, iron and steel bars] +1.6523E7[rails and railway track material]+8.9191E7[kg, wire of iron or steel] +2.45007E8[kg, pipes]+2.96654E8[kg, scrap for remelting] = 3.966E9 kg.

58. Machines (Statistics Sweden, 1998c) =1.034E9 kg.

59. Vehicles (Statistics Sweden, 1998c) = 4.988E8 kg.

60. Fish (Statistics Sweden, 1998c) = 2.34152E8[kg]x5.020E6[J/kg] = 1.175E15 J.

61. Cereals, unmilled (Statistics Sweden, 1998c) = 9.6462E8[kg]x3.85E3[kcal/kg] x4186[J/kcal] = 1.555E16 J. Transformity from Brown and Arding (1991).

62. Meats (Statistics Sweden, 1998c) = 6.7602E7[kg]x0.22[22 % protein]x2.37E7[J/kg protein] = 3.525E14 J.

63. Wood products (Statistics Sweden, 1998c) = 7.724775E9[kg]x2.052E7[J/kg] = 1.585E17 J.

64. Chemical paper pulp (Statistics Sweden, 1998a) = 2.3914E9[kg dry weight]x2.052E7[J/kg] = 4.907E16 J. Transformity from Doherty (1995).

65. Mechanical paper pulp (Statistics Sweden, 1998a) = 1.33127E8[kg dry weight]x2.052E7[J/kg] = 2.732E15 J. Transformity from Doherty (1995).

66. Paper products (Statistics Sweden, 1998c) = 7.484396E9[kg]x2.052E7[J/kg] = 1.536E17 J. Transformity from Doherty (1995).

68. Services in exports (Statistics Sweden, 1998c) = 5.69200E11[SEK]/6.70 = 8.496E10 USD.

Improving Agricultural Sustainability: The Case of Swedish Greenhouse Tomatoes

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Abstract

Of major concern to agriculturists and society are issues of sustainability and land and resource requirements for food and fiber. Sustainability of Swedish domestic agriculture is explored using production of tomatoes in greenhouses as a case study. Issues of sustainability are related to net yields, environmental loading, greenhouse gases, employment and land use. A model for evaluation of sustainability is developed and illustrated using the concepts and theories of EMERGY analysis. The intensive tomato production system investigated was shown to be highly dependent on non-renewable resources and human service fed back from society. Substituting wood powder from logging residues for the oil used for heating reduced the environmental load and improved the sustainability of the system significantly.

Keywords: emergy, energy, environmental load, resource use, sustainability, wood powder

Introduction

Sustainability is an elusive concept. The broadest definition and the one most often quoted is from the Brundtland report[1] as follows: "Sustainable development is a new form of development which integrates the production process with resource conservation and environmental enhancement. It should meet the needs of the present without compromising our ability to meet those of the future.". This paper suggests that the sustainability of agriculture is related to the net yield (higher the better), i. e. the net output of the system under consideration, and its load on the environment (lower the better). It also relates agricultural production to energy and resources as well as to requirements for environmental and human services.

Quantitatively evaluating these flows based on production cycles within the same analysis for comparative purposes requires that they be in common units. It is not possible to compare hours of human service to gallons of fuel for instance unless they are given values within the same reference system. Money has been used in the past, but price has significant problems where no markets exist, not to mention that it is a strongly egocentric concept of value.

During recent years different kinds of energy analysis have been employed to address resource use in processes. Exergy analysis[2] is suitable for optimizing transfer of mechanical work in tecnical processes. Input-output analysis[3] assigns energy values of fossil fuels and electricity to sectors of society in accordance with its monetary flows. Cleveland[4] presents another method using monetary costs to address use of fossil fuels and electricity in American agriculture. The most common energy analysis used is the technique of energy analysis according to the process method. With this method the direct and indirect use of fossil fuels by all inputs to processes are summed. Several researchers have used process analysis to analyze agricultural crops. Stanhill[5] compared direct and indirect fuel inputs of six tomato production systems. Similar analyses were performed by Pimentel and Pimentel[6] who calculated the fuel energy inputs to a number of crops. Jolliet[7] estimated the energy inputs and pollution of tomato production in Switzerland. The energy requirements of a large number of agricultural and horticultural crops were investigated by Fluck, Panesar and Baird[8]. Reist and Gysi[9] estimated the energy inputs and pollution from soilless tomato cropping in the greenhouse and field production in several European countries whereas Nienhius and de Vreede[10] performed life cycle assessments of Dutch tomato production.

Most investigations employing the process analysis approach do not account for energy flows other than those of fossil fuels. Although life cycle assessment estimates the depletion of material storages and pollution from mining and other human activities, few investigations assess the wider environmental support to the system under investigation. In addition, the problem of how to handle energy inputs from human labor, i.e. services from the human economy, remains unsolved within the process analysis.

EMERGY[11, 12, 13] is a scientifically based measurement of the accumulated energy inputs required to produce a product or service, calculated on a common basis of solar energy. Its unit is solar emergy joule (sej). By expressing the energies previously required to generate a product or service in a common unit, EMERGY analysis offers possibilities to compare systems in a straightforward way. The method embraces environmental inputs as well as inputs from the human economy. It also assigns EMERGY values to human labor, i.e. services. Weighting of the inputs to a process is based on the amount of resources that it took to make them, for instance a coal joule is given an EMERGY value of 43000 sej/J whereas the EMERGY value of diesel fuel is 71000 sej/J (including human service, calculated from Odum[13]).

The EMERGY analysis may be used in order to investigate the resource basis and policy alternatives for single processes as well as for regional or countries' economies.[13, 14]

This present study presents an EMERGY analysis of a Swedish conventional tomato production system, exploring the environmental load and sustainability of the system. In an attempt to enhance the sustainability performance of the system, wood powder from logging residue (branches, needles and cones) considered renewable was substituted for fossil fuel used in heating the greenhouse facility.

Methodology

The tomato production system

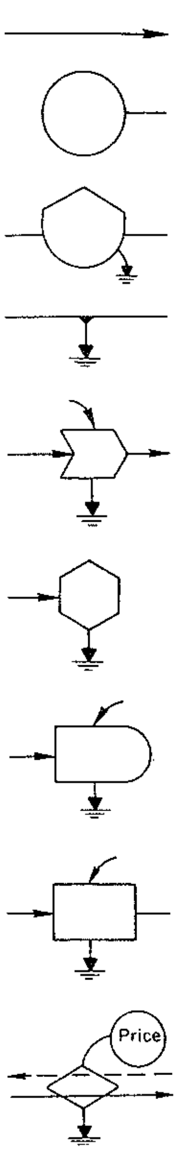
The tomato system was designed to represent a real conventional well managed production system. Since the domestic tomato producing sector of Sweden is very heterogenious, the system was chosen to operate at harvest level above the country´s average although not belonging to the best performing companies. The company was placed in the South of Sweden, which is the country´s major tomato producing region, within 50 km distance from the city of Malmö in the Southwestern part of the region. As Swedish tomatoes are produced in heated greenhouses and the dominant system is a soilless system with rockwool substrate, this system was chosen for the study.

The system constituted a fairly new (less than five years old) 9000 m^2 Venlo type greenhouse of glass, of which 8000 m^2 was plant area. An area of 4500 m^2 grounds outside the greenhouse, of which 1000 m^2 were covered with macadam (crushed stone) and 3500 m^2 was grassy grounds, also belonged to the facility. Materials, energies and services within this boundary were included in the system. Consequently, the resulting analysis was an analysis of a company totally specialized in tomato production, which is usually the case among the conventional growers at this harvest level, rather than of a single subsystem of a company. To facilitate future comparisons with other growing systems and companies, transportation of the produce to retail was not considered in the evaluation.

In keeping with industry norms, the greenhouse was considered to be heated with oil and propane and artificial light from high pressure sodium lamps was used in seedling production. The propane also supplied carbon dioxide (CO_2) to the tomato crop. In these greenhouses water is not recycled and generally there is excess watering of 25 % to ensure no buildup of salts in the rockwool slabs. In these types of production systems seeding takes place in late December and the tomatoes are harvested from mid March to late October. In November, the greenhouse is cleared and cleaned in preparation for the seeding. The harvest was set to 42 kg per m^2, a harvest level that is above industry averages, but not among the highest yielding companies. Materials, energies and services associated with the building and equipment of the tomato company as well as the annual inputs for operating the system were quantified. When wood powder from logging residues was substituted for oil, accompanying adjustments in material inputs and costs were also made. The transportation of material and fuel inputs were included in the analysis, estimated by the direct use of fuels and electricity by the vehicles. Data were collected from manufacturers and retail as well as from a tomato growing company and the extension service. Distances of transportation were obtained from transportation companies and measured on road maps[15]. Inputs were scaled to annual flows in accordance with their economic depreciation times. In general, the assigned depreciation times ranged from 10 to 20 years. Data from 1995 and 1996 were used.

EMERGY analysis

EMERGY analysis starts with a systems diagram drawn in accordance with the energy circuit language[11]. This helps to identify the systems boundary as well as the main components and interactions within and across the boundary. Figure 1 shows energy systems symbols and definitions. All processes are accompanied by energy transformations and loss of available energy in the resulting product. The systems diagram is used to organize thinking and as a device to inventory all flows of energy, materials, and human services that are required by the process. An EMERGY evaluation table is constructed from the systems diagram, where each flow that crosses the systems boundary becomes a row in the table to be evaluated. Flows of energy, materials and services are first evaluated in energy terms, then converted to EMERGY by multiplying by a transformity (whose units are sej/J). Transformities are generally calculated in previous evaluations similar to the present study.



Energy circuit. A pathway whose flow is proportional to the quantity in the storage or source upstream.

Source. Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

Tank. A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

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.

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.

Consumer. Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.

Producer. Unit that collects and transforms low-quality energy under control interactions of high-quality flows.

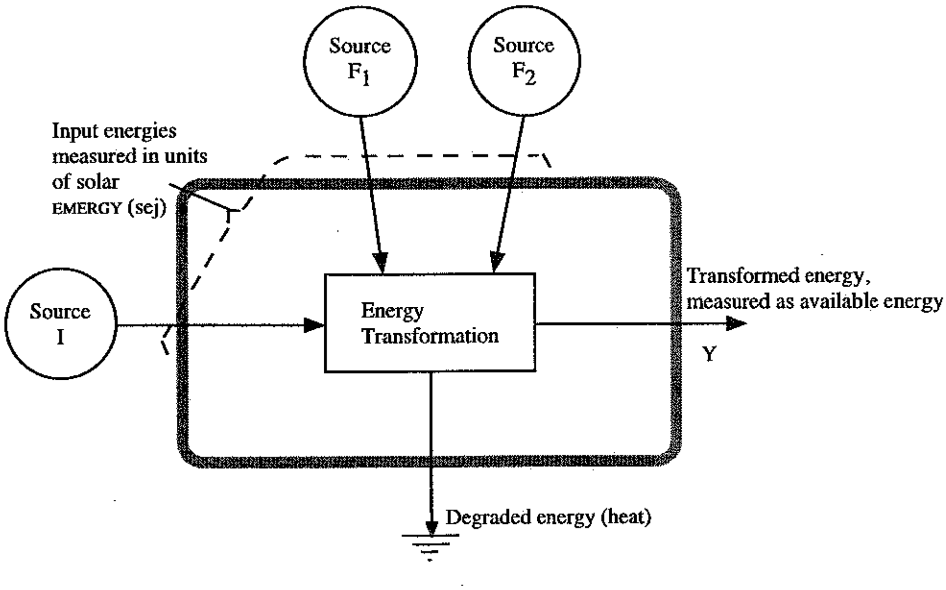
Box. Miscellaneous symbol to use for whatever unit or function is labeled.

Transaction. A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed). Price is shown as an external source.

Figure 1. Selected symbols of the energy circuit language. Modified from Odum[23]. Printed with the permission of University Press of Colorado.

Figure 2 explains the key concept of transformity. The system draws resources directly from nature as well as inputs fed through the economic system. The EMERGY increases with each transformation along the chain or web of processes that generate the product or service. The transformity is the EMERGY of the inputs divided by the energy of the product and is thus expressed in sej/J. The transformity, measured in solar EMERGY joule per joule (sej/J), is a quality index by which the EMERGY of an item can be calculated by multiplying its available energy by its its transformity. The transformity indicates how much environmental work has been invested, directly or indirectly through the economic system, in order to produce a given service or product and also reflects the amount of environmental activity needed to match the use of this product or service[14].

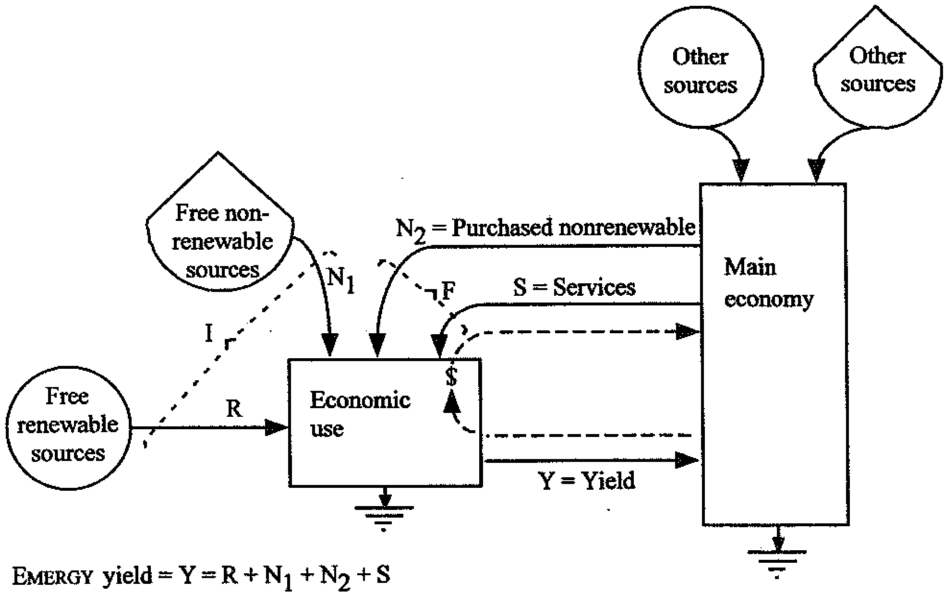
Money paid for the purchase of energy and materials corresponds to the inputs of human services that accompany them. EMERGY in human services is evaluated using a standard conversion for an economy that is derived from the ratio of total emergy used in the economy to the GDP (sej per unit currency). This transformation of the currency reflects the average resource basis required in support of currency circulation. Thus services from the human economy are assigned EMERGY values through the price paid in the economy.



Solar transformity of output = EMERGY of inputs/energy of output = $(I + F_1 + F_2)/Y$

Figure 2. Energy flows involved in an energy transformation process and calculation of the transformity of the resulting product.

Once EMERGY evaluation tables are complete several emergy ratios can be calculated and compared to other processes and products for perspective. Figure 3 is a simplified diagram of a generic process (economic use) that uses some free renewable and nonrenewable sources from the environment, purchased non-renewable energies from the economy, and some human services (labor). All flows are in EMERGY terms (sej). Dashed lines represent money flows and always flow opposite the direction of EMERGY flows.



EMERGY yield = $Y = R + N_1 + N_2 + S$

EMERGY yield ratio of products (EYR) = $Y/(N_2 + S)$

EMERGY investment ratio (EIR) = Purchased/free = $(N_2 + S)/(R + N_1)$

Nonrenewable to renewable ratio (NRR) = $(N_1 + N_2)/R$

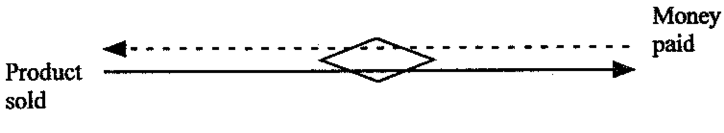
Services/free inputs = $S/(N_1 + R)$

Services/resources = $S/(R + N_1 + N_2)$

Empower density = Y/(area of system)

Environmental loading ratio (ELR) = $(N_1 + N_2 + S)/R$

EMERGY sustainability index = EYR/ELR = $Y*R/((N_2 + S)(N_1 + N_2 + S))$



EMERGY exchange ratio = EMERGY of product/EMERGY of money paid

Figure 3. Emergy indices for evaluation of a local system.

Using Figure 3 as a guide, the following ratios and indices may be calculated: The EMERGY yield ratio (EYR) is calculated by dividing the EMERGY yield by the purchased EMERGY inputs from the economy. The EMERGY yield is the result of summing all the inputs. The EYR indicates how dependent a process is on non-local inputs. In the case of fuels, EYR gives information on whether the process is competitive in supplying a primary energy source for the economy.

The EMERGY investment ratio (EIR) is calculated by dividing the purcased inputs by the EMERGY received free from the environment. The EIR indicates whether the system is an efficient user of the inputs from the economy, compared with alternative processes. If the process draws less inputs from the economy and more free from the environment than competing processes, the EIR is less. The price of products from this process will the be lower than for products from competing processes. In like manner, if a process draws more inputs from the economy per unit of input from the environment, the process may be less competitive and product prices may be higher.

The Environmental loading ratio (ELR) is calculated as the sum of the EMERGY of non-renewable goods and services supplied by the economy and the local free non-renewable sources, divided by the free renewable EMERGY drawn from the environment, i. e. developed resource flows divided by renewable flows. The ELR indicates the stress or load exerted by the process upon the local ecosystem. The EMERGY sustainability index (ESI) is defined as the ratio between the EYR and ELR and is thus an aggregate measure of yield and environmental loading, both of which are key components of sustainability[14]. The empower density is calculated by dividing the total EMERGY use by the area of the system. It is thus a measurement of the intensity or spatial concentration of EMERGY. The EMERGY exchange ratio is the ratio of EMERGY of the product to EMERGY of the money paid in a transaction. The economy receiving the larger amount of EMERGY is stimulated the most.

System boundaries

Figure 4 shows the system boundaries for the two conditions evaluated in this study. In the top diagram the system boundary is drawn more or less at the property boundary. In the bottom diagram the system boundary is expanded to include the forest and wood powder production to adress the renewable resources accompanying the wood powder. Based on evaluations by Doherty[16], thirtyseven percent of the wood powder EMERGY flow was regarded as free renewable.

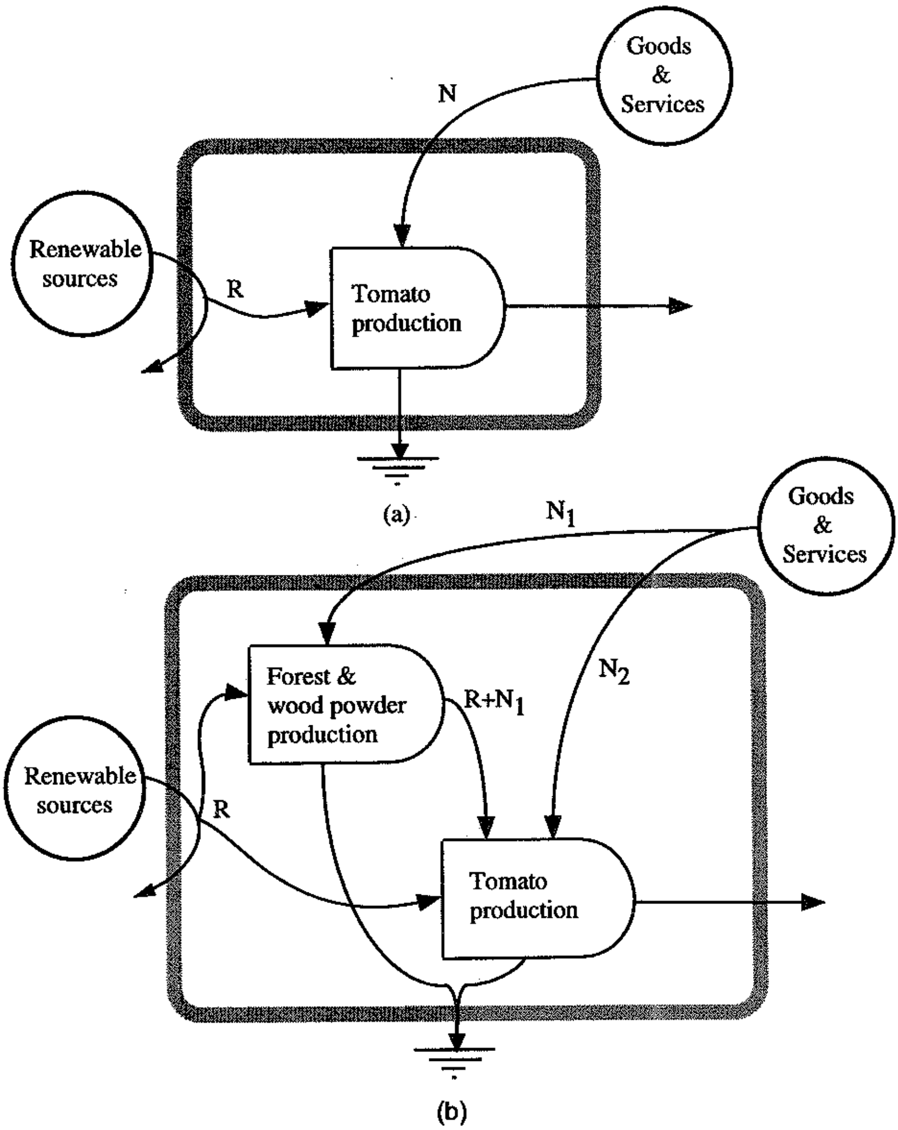


Figure 4. Simplified diagram showing the difference in boundary between the system using oil and the system using wood powder for heating. (a) oil. (b) wood powder.

Results

Figure 5 shows a systems diagram of Swedish tomato production showing the main flows supporting the system. Direct environmental inputs to the left as well as materials and services fed through the economic system of society interact to run the system. The accumulated energy (EMERGY) is increasing while the energy contents of the product is decreasing to the right of the diagram. The solar energy is thus converging through the system, reading the diagram from left to the right. Leaving the system are tomatoes ready for the market and waste. The numbers on inputs correspond to numbered rows in the emergy table (Table 1).

Tables 1 and 2 give the results from the EMERGY analysis. The EMERGY inputs from sun, wind and rain (items 1, 2 and 3 of Table 1) are byproducts of the same global flow. To avoid double counting, as explained by Odum[13], only the largest of these components was counted in the analysis. The direct environmental input (i.e. the rain component) was extremely small compared with the purchased inputs to the system, which constituted nearly 100 % of the total EMERGY inflow.

Fuels and electricity and associated services constituted the major input to the system, about 67 %, including the fuels for transportation of about 1 %. Direct fuels and electricity contributed by 57 % and the associated services contributed 9 % of the EMERGY running the system. About 39 % of the total EMERGY flow was accounted for by the oil for heating the greenhouse facility, including services. The propane contributed fifteen percent of the total EMERGY.

The EMERGY of the services, amounting in total to about 37 %, constituted a significant part of the resource flow. Nearly 13 % originated from direct labor inputs (item 33).

Of the 2 % of total EMERGY attributed to materials associated with the construction of the greenhouse facility, steel (item 7) contributed the major part. Fertilizers (items 16-24) contributed 2 % to the total EMERGY supporting tomato production. EMERGY indices and ratios of the Swedish oil heated system as well as a comparison with a system where the oil was substituted by wood powder from logging residues from an 80 year rotation spruce/pine forest of Southern Sweden[16] are given in Table 2. Table 2 also presents indices of Florida tomatoes produced in the field[17] for

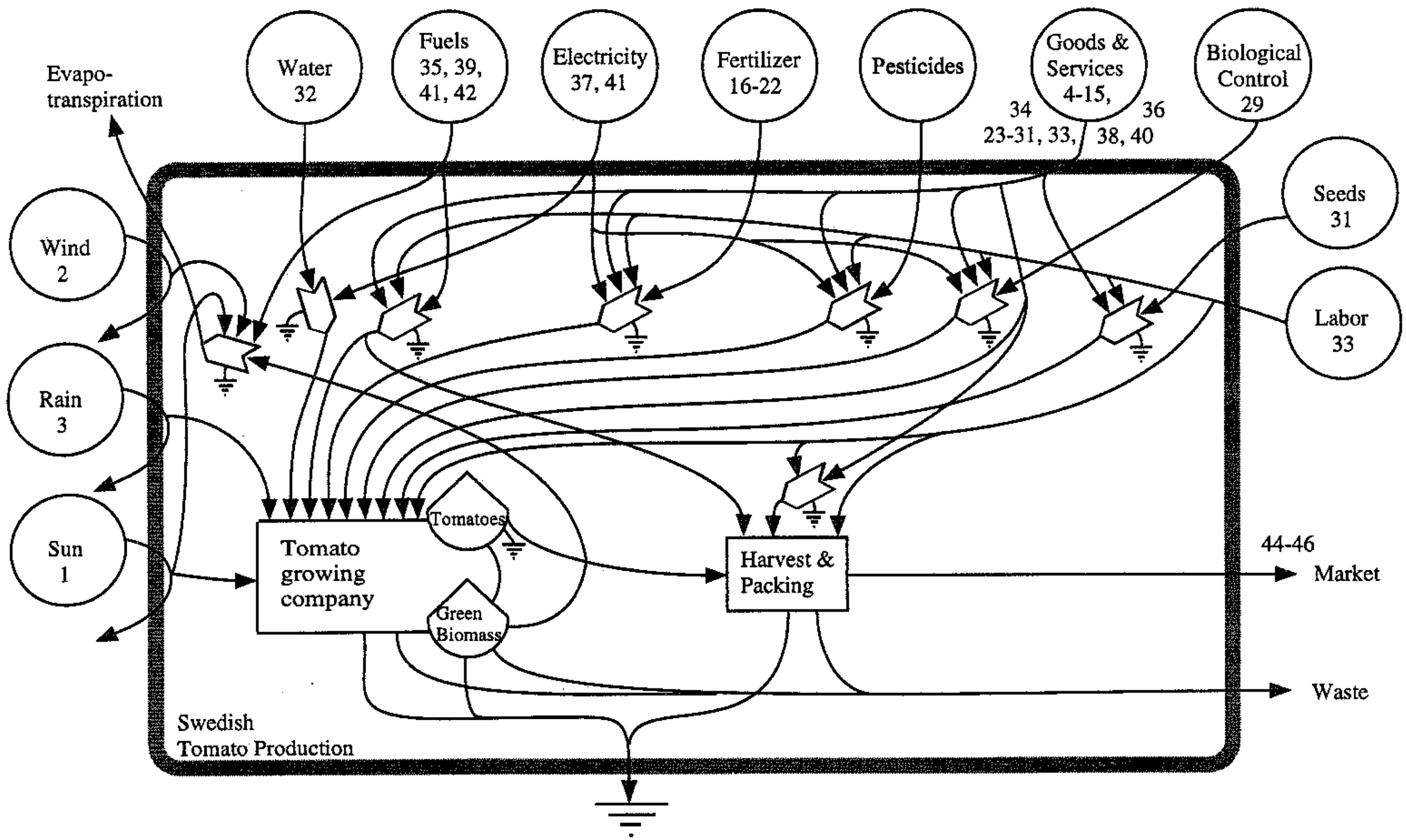


Figure 5. Overview of the tomato production system under study. Numbers on flows refer to items in the emergy analysis table.

Table 1. Emergy evaluation of Swedish tomato production under glass 1996. 8000 m^2 plant area, 1000 m^2 non-plant area and 4500 m^2 outside area. Annual flows.

Note **	Item, Unit	Data (units/year)	Transformity (sej/unit)	Solar EMERGY (sej/year)	% of total EMERGY	Reference for transformity
LOCAL RENEWABLE INPUTS					0.01	
1	Sun, J	2.88E+13	1.00E+00	2.88E+13	0.00	13
2	Wind, J	5.34E+10	1.50E+03	8.01E+13	0.00	13
3	Rain, chemical potential, J	1.10E+10	1.82E+04	2.00E+14	0.01	13
NONRENEWABLE INPUTS					32.82	
4	Macadam, kg	2.99E+04	9.75E+05	2.92E+10	0.00	13
5	Concrete blocks, kg	1.61E+03	3.54E+11	5.70E+14	0.03	24
6	Concrete ready mix, kg	2.23E+04	4.40E+11	9.81E+15	0.50	24
7	Steel, kg	6.36E+03	2.16E+12	1.37E+16	0.69	24
8	Cast iron, kg	4.45E+02	1.74E+12	7.74E+14	0.04	24
9	Aluminum, kg	5.40E+02	1.77E+13	9.56E+15	0.48	Appendix B
10	Glass, kg	7.15E+03	8.40E11	6.01E15	0.30	26
11	Service in building, SEK*	3.24E+05	2.14E+11	6.95E+16	3.51	25
12	Plastics, kg	8.52E+02	3.80E+11	3.24E+14	0.02	26
13	Remaining metals, kg	2.14E+01	1.00E+12	2.14E+13	0.00	13
14	Cardboard, kg	1.42E+04	1.41E12	2.01E+16	1.01	16
15	Rockwool, kg	4.30E+03	1.86E+12	8.00E+15	0.40	27
16	Nitrogen, kg	1.53E+03	4.60E+12	7.04E+15	0.36	13
17	Phosphorus, kg	5.62E+02	1.78E+13	1.00E+16	0.51	13
18	Potassium, kg	1.97E+03	1.74E+12	3.43E+15	0.17	13
19	Calcium, kg	7.56E+02	1.00E+12	7.56E+14	0.04	13
20	Sulphur, kg	2.17E+02	1.00E+12	2.17E+14	0.01	13
21	Magnesium, kg	1.64E+02	1.00E+12	1.64E+14	0.01	13
22	Micronutrients, kg	2.06E+01	1.00E+12	2.06E+13	0.00	13
23	Service in macronutrients, SEK	4.92E+04	2.14E+11	1.05E+16	0.53	25
24	Service in micronutrients, SEK	5.69E+03	2.14E+11	1.22E+15	0.06	25
25	Slaked lime, kg	7.40E+01	5.41E+11	4.00E+13	0.00	13, Appendix B
26	Soft soap, J	2.40E+09	7.20E+05	1.73E+15	0.09	11
27	Farbanet, kg active subst.	1.47E+01	1.48E+13	2.18E+14	0.01	26
28	Wetting agent, kg active subst.	3.10E-01	1.48E+13	4.59E+12	0.00	26
29	Biological control, SEK	6.83E+03	2.14E+11	1.46E+15	0.07	25
30	Pollinators, SEK	4.26E+04	2.14E+11	9.13E+15	0.46	25
31	Seed, SEK	3.33E+04	2.14E+11	7.14E+15	0.36	25
32	Water, J	3.56E+10	1.10E+05	3.92E+15	0.20	19
33	Direct human services in labor, SEK	1.17E+06	2.14E+11	2.51E+17	12.68	25
34	Remaining human services, SEK	9.47E+05	2.14E+11	2.03E+17	10.26	25

Table 1 continued.

FUELS AND ELECTRICITY					65.87	
35	Oil, J	1.36E+13	5.61E+04	7.63E+17	38.57	13
36	Indirect services in oil, SEK	5.77E+05	2.14E+11	1.24E+17	6.25	25
37	Electricity, J	5.56E+11	1.28E+05	7.12E+16	3.60	13
38	Indirect services in electricity, SEK	9.27E+04	2.14E+11	1.99E+16	1.00	25
39	Propane, J	2.85E+12	1.01E+05	2.87E+17	14.50	13
40	Indirect services in propane, SEK	1.79E+05	2.14E+11	3.84E+16	1.94	25
TRANSPORTATION OF MAIN COMPONENTS					1.30	
Transportation of material inputs						
41	Oil, J	9.78E+09	4.71E+04	4.61E+14	0.02	13
	Diesel oil, J	2.18E+10	5.61E+04	1.22E+15	0.06	13
	Electricity, J	4.53E+07	1.28E+05	5.80E+12	0.00	13
Transportation of fuels						
42	Oil, J	3.61E+11	4.71E+04	1.70E+16	0.86	13
	Diesel oil, J	1.24E+11	5.61E+04	6.96E+15	0.35	13
43	SUM OF INPUTS			1.98E+18	100.00	
OUTPUTS						
44	Harvest, kg fresh weight	3.36E+05	5.89E+12	1.98E+18		
45	Harvest, kg dry matter	1.68E+04	1.18E+14	1.98E+18		
46	Harvest, J	2.82E+11	7.01E+06	1.98E+18		
47	Sales value of harvest, SEK	3.74E+06	2.14E+11	8.02E+17		

* SEK = Swedish Crowns, the currency of Sweden. In 1996, the currency exchange ratio was 6.70 SEK/USD

** The footnotes are given in Appendix A

further comparison. In this present study the water (item 32 of Table 1) extracted by far exceeds the recharge of water generated on the systems area and the water is regarded as a non-renewable resource which is depleted faster than it is renewed. If, however, the pressure on the water resources is low enough on the regional scale the use of water may be considered renewable on this larger scale.

As expected, the substitution of fuels resulted in a reduced environmental load and a dramatic increase in the sustainability of the production. The ELR decreased about sevenhundredfold, from close to ten thousand to fourteen, and the ESI increased eighthundredfold, from 0.0001 to 0.08. The sustainability index was, in fact, shown to be higher than that for the Florida field tomatoes. The substitution also resulted in a twentyfour percent decrease of the empower density. The EMERGY investment ratio decreased from above four hundred to less than fourteen. The non-renewable to renewable ratio changed significantly, decreasing from 6230 to six. The ratio of services to free inputs also decreased substantially and the ratio of services to resources was doubled.

Comparisons with field grown tomatoes in Florida, showed that the greenhouse tomatoes are very energy intensive having an empower density between 70 and 90 times that of the field tomatoes. Yields are very high in the greenhouse system where total annual yield was about 420 000 kg/ha as compared with the annual yields of about 36 900 kg/ha for the Florida field tomatoes. Yet, even with these very high yields, the transformity for the greenhouse tomatoes was about nineteen times that of the field tomatoes. Since transformity measures the extent of convergence of materials and energy in a production process, comparisons of transformities of similar products yields information about overall efficiency. When wood powder is used in place of oil, the efficiency of greenhouse tomato production increases by about 24 %. Indices of CO_2 production and employment suggest that wood powder use increases the requirement of human services (6 % increase in the total service requirement) and decreases overall CO_2 production.

Table 2. Emergy indices for three different tomato production systems: oil heated greenhouse in Sweden, wood powder heated greenhouse in Sweden, and Florida field tomatoes. Indices are defined in Figure 3.

Indices	Oil*	Wood powder**	Florida field tomatoes***
EMERGY yield (sej/year)	1.98E18	1.51E18	1.62E16
EMERGY yield ratio	1.00	1.07	1.06
EMERGY investment ratio	480	13.5	16.2
Nonrenewable to renewable ratio	6230	6.3	8.7
Services/free inputs	179	7.5	7.6
Services/resources	0.59	1.06	0.8
Empower density(sej/m^2)	1.47E14	1.12E14	1.62E12
Environmental loading ratio	9910	14.1	16.4
EMERGY sustainability index	0.0001	0.08	0.06
Transformity (sej/J)	7.01E6	5.36E6	3.7E5
Transformity (sej/kg fresh weight)	5.89E12	4.50E12	4.38E11

* R = 2.00E14 sej/year
N_1 = 3.92E15 sej/year
N_2 = 1.24E18 sej/year
S = 7.35E17 sej/year
**R = 1.00E17 sej/year
N_1 = 3.92E15 sej/year
N_2 = 6.29E17 sej/year
S = 7.79E17 sej/year
***Brandt-Williams, S. and Odum, H. T. Procedure for agricultural emergy* evaluation. In: Ortega, E. Safonor, P. and Comar, V. (eds.). Introduction to ecological engineering with emergy analysis of Brazilian case studies. (in press).

Discussion

As expected, tomato production in greenhouses is an intensive operation, requiring large inputs and producing large output on a relatively small area of land. Consequently, the empower density was about ninety times that of field grown tomatoes in Florida. The intensity was also detected by the high EIR, indicating that this system is highly dependent on EMERGY inputs fed back from the economy. One must remember, though, that this present EMERGY analysis concerns a whole company, including offices, outside economic areas, all buildings and all the machinery and tools, services like extension service, taxes, loans etc. Previous studies concerning agricultural crops[18, 19, 20] are concerned with the inputs applied to the field and leave out many of the inputs attributed to the whole company. This present study therefore most likely accounts for more materials and services associated with the production system.

Emergy indices

The overall resources required to produce tomatoes, reflected by the transformities, was less within the system using wood powder instead of oil. The transformity (in sej/kg fresh weight) of the tomatoes grown in oil heated greenhouses was about thirteen times the transformity of Florida field tomatoes. The lower transformity of the tomatoes produced with wood powder heating was caused by the decrease in overall emergy use, i.e. the lower EMERGY yield. The extremely high ELR of the oil heated system not only originates from the large amount of feedback from the economy but also from the large percentage of non-renewable feedback. As was pointed out by Brown and Ulgiati[14], a system requiring large inputs from the economy may be considered sustainable, provided that a large portion of these inputs can be regarded as renewable flows.

Human labor

The impact of human labor is often underestimated by process analysis, which merely accounts for the services associated with the direct inputs of labor measured in Joules. In the intensive production systems analysed by Stanhill[5] and Pimentel and Pimentel[6], only a negligible part of the total energy requirements were assigned to labor inputs. This present analysis, attributing 37 % of the total EMERGY to direct (13 %) and indirect (25 %) services, clearly recognized the systems dependence on human labor. In fact, the difference between high tech products and low tech ones may lie in that more of the services of the high tech system are embedded in their previous history. Therefore a low tech system requiring more direct services may seem more labor intensive while it may in fact not be when analysed according to the EMERGY method, and vice versa.

Wood powder substitution

The present tomato production systems dependence on direct inputs of fossil fuel for heating was confirmed by the EMERGY analysis and consequently the substitution of the oil by a fuel considered to be renewable proved to be an interesting experiment. In addition to reducing the non-renewable to renewable ratio dramatically, the wood powder used for substitution was a domestic regionally produced fuel. A system using more domestic labor, i.e. where more of the production takes place within the domestic or regional economy would prove interesting to policy makers concerned with unemployment and social welfare of the population.

Replacing oil with wood powder would also reduce the release of carbon dioxide (CO_2) into the atmosphere from heating which is another important aspect of sustainability. The oil combustion in the oil heated system would release about 1.2E6 kg of CO_2 annually including precombustion activities (extraction, refining etc.) whereas with wood powder this CO_2 emissions would be reduced to about 0.1E6 kg annually. Since combustion of wood powder does not in itself contribute a net release of CO_2, the CO_2 released with the wood powder alternative originate from fossil fuel use in precombustion activities (including forestry). Extrapolated to include all of the domestically produced tomatoes of Sweden (1.82E7 kg fresh weight), this present system would reduce CO_2 emissions by 60E6 kg annually. Substitution of oil for heating with wood powder would then require logging residue from an area of 84 000 ha (estimated from about 1550 ha for the present system). This may not pose any problem in the present economy of Sweden, where land is not in shortage. Also, the forest producing wood powder produces lumber in a sustainable way. In the future, however, there may be new uses competing for land and other resources.

Space, time and EMERGY

It has long been known that there is a strong relationship between space and time. Spatial scale, i.e. the area over which something acts, is related to temporal scale[21, 22], for instance. Small things that act over small spatial areas turn over quickly (i.e. have small temporal scale), while larger things occupy larger spatial areas and turn over at an increasingly slower pace. It is also true that small things require less energy than do large things. Consider for instance the energy requirements of microbes verses elephants. The total requirements during a lifetime for a microbe is infinitesimally small compared to the elephant. Not only is the magnitude quite different, but the flux is as well. During a typical day, the elephant will consume millions of times the energy that a microbe will and will cover millions of times the distances in order to gather the energy.

Space, time, and EMERGY are interrelated and may be substitutable, one for the other. It is possible to maintain large things in relatively small areas (an elephant in a zoo, for instance), but only with large amounts of supporting EMERGY. Increases in the speed at which a process functions are usually accompanied by increases in driving energy. Therefore a general principle that may hold for all systems is that decreases in either space or time required for a process will result in an increase in the required EMERGY to drive the process. Agriculture is no different. Yields for agricultural commodities are more or less fixed, given a certain technology assumption. To drastically decrease the area and maintain the same yield requires significant increases in energy and material inputs. The green revolution accomplished meaningful increases in yields per hectare, but at a large energy cost. Reducing energy costs of agriculture will, by necessity, require an increase in the area of land that is farmed. The greenhouse tomato system clearly illustrates these tradeoffs between time, space and energy. Producing the same amount of tomatoes as the greenhouse system in the field under Swedish conditions would require about 7 ha. Alternatively, producing the same amount of tomatoes in the field on the same area as the present intensive system (0.8 ha plant area) would prolong the time needed for production to about 9 years. Thus an increase in energy inputs may reduce the acreage needed and also the time of production.

From a quantitative perspective, sustainability is a function of yield and environmental load. Since agricultural crops have relatively low net yields (as they should because they are not sources of concentrated energy, but are the result of transformations of fuels, technology and human service) sustainability becomes more dependent on minimizing environmental load. In this paper we have used several EMERGY indices to demonstrate agricultural sustainability of alternative tomato production systems. An alternative that used wood residues for heating in place of fossil fuels was found to increase sustainability and reduce environmetal loading.

Improving sustainability can be quantitatively evaluated when flows of materials and energies that drive production processes are expressed in EMERGY. Comparisons are possible when all required inputs are expressed in the same form of energy and indices of production and efficiency that lead to quantitative determination of sustainability are possible. In this paper we have demonstrated the EMERGY methodology applied to agricultural production in Sweden and have evaluated increases in sustainability by using renewable wood by-products for heating greenhouses for the production of tomatoes.

Conclusions

There is potential for improving the performance of the analysed tomato system in the direction of increasing its sustainability. Since the fuel for heating the greenhouse was a dominating input, replacing fossil fuels with more renewable ones will be an important strategy. Substitution of oil for heating with wood powder from logging residues reduced the environmental load and enhanced the sustainability of the tomato production. The EMERGY analysis clearly visualized the dependence of the larger economic system of which the tomato system is a part. If the larger economy, i.e. society, does not act sustainably, the chances of the subsystem to do so are small.

In all, increasing sustainability of agriculture depends on increasing the use of renewable energy sources. This can be done, to a certain extent, through substitution like the wood powder derived from forest residues, or through careful resource management like insuring water resources are used no faster than they recharge, or by increasing land area (and therefore the use of environmental energies like sunlight and rain). Technological "fixes" to agriculture, while possibly increasing yields somewhat, have high nonrenewable energy use, driving down sustainability and increasing environmental loads. Future improvements of sustainability in agriculture will lie in improving the use of renewable energies, which will either increase time or space (or both) devoted to food production.

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References

1 World Commission on Environment and Development, 1987. Our common future. Oxford University Press, 400 pp.

2 McGovern, J. A., 1990. Exergy analysis - a different perspective on energy. Part 1: the concept of exergy. Proc. Instn. Mech. Engrs. 204: 253-262.

3 Brown, M. T. and Herendeen, R. A., 1996. Embodied energy analysis and emergy analysis: a comparative view. Ecol. Econ., 19:219-235.

4 Cleveland, C. J., 1995. The direct and indirect use of fossil fuels and electricity in USA agriculture, 1910-1990. Agriculture, Ecosystems and Environment 55,111-121.

5 Stanhill, G., 1980. The energy cost of protected cropping: a comparison of six systems of tomato production. J. Agric. Engng Res., 25: 145-154.

6 Pimentel, D. and Pimentel, M., 1979. Energy, food and society. Edward Arnold. p. 92.

7 Jolliet, O., 1993. Bilan écologique de la production de tomates en serre. Revue Suisse Vitic. Arboric. Hortic. 25, 261-267.

8 Fluck, R. C., Panesar, S. B. and Baird, C. D., 1992. Florida agricultural energy consumption model (FAECM), for Lotus 1-2-3 Release 3.1, Final report. Report prepared for Florida Energy Office, Tallahassee. Agr. Eng. Dept., IFAS, University of Florida, Gainesville, USA, 34 pp.

9 Reist, A. and Gysi, C., 1990. Cultures hors sol: bilan écologique. Revue Suisse Vitic. Arboric. Hortic. ,22: 223-235.

10 Nienhuis, J. and de Vreede, P., 1994. Milieugerichte levenscyclusanalyse in de glastuinbouw: bruikbaarheid. Research Station for Floriculture and Glasshouse Vegetables, Naaldwijk, Netherlands.

11 Odum, H.T. and Odum, E. C., 1983. Energy analysis overview of nations. Working Paper WP-83-82. International Institute of Applied Systems Analysis, Laxenburg, Austria, 469 pp.

12 Odum, H. T., 1988. Self organization, transformity, and information. Science 242, 1132-1139.

13 Odum, H. T., 1996. Environmental accounting. Emergy and environmental decision making. Wiley, New York, 370 pp.

14 Brown, M. T. and Ulgiati, S., 1997. Emergy indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. 9, 51-69.

15 The Swedish Automobile Association, 1997. Motormännens Europa vägatlas. Vägatlas med ortsförteckning och stadsplaner. Hallwag AG, Bern, 341 pp.

16 Doherty, S. J., 1995. Emergy evaluation of and limits to forest production. A dissertation presented to the graduate school of the University of Florida in partial fulfillment of the requirements for the degree of doctor of philosophy. Department of Environmental Engineering Sciences, University of Florida, Gainesville, USA, 215 pp.

17 Brandt-Williams, S. and Odum, H. T. Procedure for agricultural emergy* evaluation. In: Ortega, E. Safonor, P. and Comar,V. (Editors.). Introduction to ecological engineering with emergy analysis of Brazilian case studies. (in press)

18 Odum, H. T. and Odum, E. C. (eds.), 1987. Ecology and economy: "emergy" analysis and public policy in Texas. Policy Research Project Report 78, Lyndon B. Johnson School of Public Affairs, The University of Texas at Austin, USA, 178 pp.

19 Brown, M. T. and McClanahan, T. R., 1992. Emergy analysis perspectives of Thailand and Mekong river dam proposals. Report to The Cousteau Society. Research studies conducted under contract no. 89092601. Center for Wetlands and Water Resources, University of Florida, Gainesville, USA, 60 pp.

20 Ulgiati, S., Odum, H.T. and Bastianoni, S., 1993. Emergy of Italian agricultural system, The role of energy quality and environmental inputs. In: L. Bonati, U. Cosentino, M. Lasagni, G. Moro, D. Pitea and A. Schiraldi (Editors). Trends in ecological physical chemistry. Elsevier, Amsterdam, pp 187-215.

21 Thompson, A. W., 1961. On growth and form. An abridged edition., edited by J. T. Bonner. University Press, Cambridge, 345 pp.

22 Peters, R. H., 1983. The ecological implications of body size. Cambridge studies in ecology. Cambridge, 329 pp.

23 Odum, H. T., 1994. Ecological and general systems. An introduction to systems ecology. Revised edition. University press of Colorado, p. 8.

24 Haukoos, D. S., 1994. An EMergy analysis of various construction materials. ENV 6905. Department of Environmental Engineering Sciences, University of Florida, Gainesville, USA, 67 pp.

25 Lagerberg, C., Doherty, S. J. and Nilsson, P. O. Evaluation of the resource efficiency and sustainability of the Swedish economy using emergy based indices. (manuscript)

26 Brown, M. T. and Arding, J., 1991. Transformities. Working paper. Center for Wetlands, University of Florida, Gainesville, USA, 4 pp.

27 Björklund, J. Geber, U. and Rydberg, T. Emergy analysis of municipal wastewater, its treatment and the generation of electricity from digestion of sewage sludge; a case study from Sweden. (manuscript)

28 SMHI, 1996. Väder och Vatten. En tidning från SMHI. Väderåret 1995. p. 4.

29 Mc Graw-Hill Encyclopedia of Science & Technology, 1992. p. 499.

30 Fluck, R. C. (Editor), 1992. Energy in farm production. Energy in world agriculture, volume 6. Elsevier, Amsterdam, 367 pp.

31 Statens Livsmedelsverk, 1988. Livsmedelstabeller. Energi och näringsämnen. p. 22

32 Tillman, A-M., Baumann, H., Eriksson, E. and Rydberg, T., 1991. Miljön och förpackningarna. Livscykelanalyser för förpackningsmaterial—beräkning av miljöbelastning. Statens offentliga utredningar 1991:77 Miljödepartementet, 205 pp.

Appendix A. Footnotes to table 1.

1. The normal value 1961-1990 of the global insolation in Lund[28] = 972.9 kWh/m^2. Consequently, the insolation on 9000 m^2 would be area x insolation x (1-albedo) = 9000[m^2]x972.9[kWh/m^2]x3.6E6[J/kWh]x 0.60[assumed transmission of light into the greenhouse] = 1.8913E13 J/year.

   The remaining 4500 m^2 outside areas receive 4500[m^2]x972.9[kWh/m^2]x3.6E6[J/kWh] x(1-0.37) = 9.9294E12 J/year.

   Sum: 1.8913E13+9.9294E12 = 2.884E13 J/year.

2. Water uptake by the plants amounts to 75 % of the total water consumption. The transpired water from the 8000 m^2 plant area is then given by 75 % of total water consumption - water in harvest[harvest x water contents] - water in plant tissue = 0.75x7200[m^3]x0.9982E3[kg/m^3, at 20 °C]-336000[kg]x0.95[%] -0.1E-3[m^3/plant]x0.9982E3[kg/m^3]x2.5[plants/m^2]x8000[m^2]x30[weeks, assumed incorporation febr.-decapitation] ≈ 5.011E6 kg of water.

   This water would raise the humidity in the greenhouse to approximately 100 %, if there was no ventilation. Optimum humidity in the greenhouse is 75-80 %. The humidity of the outside air is 65-75 % and 85-90 % during the summer and winter respectively in the Malmö region. The 5.004E6 kg of water has to be moved out of the greenhouse in order to decrease the RH from 100 % to an assumed seasonal average of 75 %.

   Air of 100 % RH [1 kPa, 21 °C] can hold 15.14 g of water per kg dry air whereas air of 75 % RH can hold about 83[grains/pound]x1/7[g/kg per grain/pound]≈11.86 g of water per kg dry air[29]. ⇒ 1 kg of 75 % air can remove 15.14 - 11.86 = 3.28 g of water to remove 5.011E6 kg = 5.011E9 g of water we thus need 5.011E9/3.28 ≈ 1.53E9 kg of 75 % air. The kinetic energy required to move this air mass is given by KE = $mv^2/2$ ⇒ 5.0011E9/3.28x5.5^2[m/s, wind speed estimated from data from the Swedish Meterological and Hydrological Institute]/2 ≈ 2.31E10 J.

   Wind contribution on remaining area = kinetic energy = (air mass)x(windspeed absorbed; 40 % of windspeed at 1000 m)^2/2 = 4500[m^2]x1000[m, boundary layer]x1000[kg/m^3, density of air]x(0.4x5.5[m/s]/0.6)^2/2 = 3.025E10 J.

   Sum: 2.31E10+3.025E10 = 5.34E10 J.

3. The normal value of precipitation in Lund 1961-1990[28] = 658 mm = 0.658 m.
   25 % of the total rainfall was considered to be evapotranspired. Free energy of rainfall = (area)*(evapotranspired rain) *(density of water)*(Gibbs free energy) = 13500[m^2]*0.658[m]*0.25[25 %]*1000[kg/m^3]*4.94E3[J/kg] = 1.097E10 J

4. The mean transformity of granitic rock and metamorphic rock was used.

11. Services associated with the greenhouse building, major components (incl. artificial light) and maintenance.

13. Brass, cupper and unknown metals.

15. Transformity excl. indirect inputs.

25. The molecular weight of slaked lime, $Ca(OH)_2$, is 40.08+2x16.00+2x1.01 = 74.10 g/mole, of which 40.08/74.10 = 54.1 % is Ca. 74 kg then contain 0.541x74 = 40.034 kg of Ca. The transformity of mineral ore in the earths crust is 1E9 sej/g [13] ⇒ transformity of $Ca(OH)_2$ = 40.034[kg Ca]x1E9[sej/g]x1E3[g/kg]/74[kg $Ca(OH)_2$] = 5.41E11 sej/kg.

26. The energy contents of lauric acid (the predominant fatty acid of soap) is 8.816 kcal/g [11]. Assuming that soft soap contains about 0.5 kg soap per dm^3, gives an energy contents of 130 dm^3]x0.5[kg/dm^3] x8.816E3[kcal/kg]x4186[J/kcal] = 2.40E9 J in 130 dm^3 soft soap.

27-28. Assuming that the active substance contents is 50 %.

Appendix A continued.

29-31. Since the energy contents of biological control agents, incl. predators and yellow sticky traps, seed and pollinators are so small, the emergy values of these items were estimated by their service component.

32. Water used for irrigation = 7200[m^3]x4.94E6[J/m^3]= 3.56E10 J.

33. Incl. tax.

34. Incl. costs for remaining materials, insurance, interest on loans and costs for amortization on remaining materials.

35. Oil used for heating is more refined than the oil for transportation. Therefore the transformity of refined fuels was used.

37. Mean transformity of world average[13] and Swedish hydropower[16] = (1.74E5+8.02E4)/2 = 1.28E5 sej/J.

39. Assume that the relationship with the energy contents of natural gas corresponds to the relationship between the transformities. The enthalpy of propane is 93.8 MJ/m^3 and 38.0 MJ/m^3 of natural gas[30]. The transformity of natural gas is 4.08E4 sej/J excl. services (calculated from sedimentary coal in Odum[13]). Thus, the transformity of propane is 93.8[MJ/m^3]/38.0[MJ/m^3]x4.08E4[sej/J natural gas] = 1.007E5 sej/J propane.

41-42. The transportation of inputs was evaluated by the inputs of fuels and electricity.

43. Items 1, 2, and 3 are byproducts of the same solar emergy flow. To avoid double counting, only the largest of these components (rain) are used when summing the emergy inputs to the system.

45. 95 % water contents.

46. 1.68E7 J/kg dry matter calculated from tables of protein, fat and carbohydrate contents of fresh tomatoes[31]. Energy contents of protein, fat and carbohydrates[30].

Appendix B. Transformity of aluminum, based on data from Tillman et al.[32]

Note	Item, unit	Data (units)	Transformity (sej/unit)	Solar EMERGY (sej/year)
INPUTS				
1	Bauxite, kg	4.81E+03	1.00E+12	4.81E+15
2	Rock salt for NaOH manufacturing, kg	315.00	1.00E+12	3.15E+14
3	Limestone, kg	87.90	1.00E+12	8.79E+13
4	Carbon anode, kg	430.00	1.03E+12	4.43E+14
5	H2SiF6, kg	15.40	1.70E+13	2.62E+14
6	Electricity, J	5.89E+10	1.74E+05	1.02E+16
7	Oil, J	3.26E+10	4.71E+04	1.54E+15
8	Diesel, J	1.81E+08	5.61E+04	1.02E+13
10	Sum			1.77E+16
OUTPUT				
11	Cast aluminum, kg	1000	1.77E+13	1.77E+16

Notes

1. Transformity of in situ bauxite[13].
2. Transformity of in situ sedimentary minerals[13].
3. Transformity of in situ limestone[13].
4. The transformity of sedimentary coal is 3.4E4 sej/J[13]. Hard coal has a heat contents of 30.23E6 J/kg[30]. The transformity of coal would then be 3.4E4[sej/J]x30.23E6[J/kg] = 1.03E12 sej/kg, excl. services.
5. H2SiF6 is a by-product of phosphorus extraction. Since the H2SiF6 accompanies the phosphorus, it is considered a coproduct and thus carries the same transformity as the mined phosphorus, i. e. 1.70E13 sej/kg P or 1.70E13 sej/kg H2SiF6 (Odum[13], human service excluded on p. 124).
6. Mean transformity of electricity incl. human services of plant operations in Odum[13], p. 305.
7. Transformity of crude oil calculated from Odum[13], excl. human services.
8. Transformity of refined petroleum, excl. services, calculated from Odum[13].

IV

Emergy Evaluation of Five Greenhouse Tomato Production Systems

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Abstract

Five different Swedish greenhouse tomato production systems were analysed with emergy analysis. The method embraces direct environmental inputs as well as purchased fuels, materials and human labour. Organic production systems, using compost and clover mulch as fertilizer, was compared to conventional systems using inorganic fertilizer. The impact of alternative organic fertilizer strategy on the resource efficiency, environmental stress and sustainability of the systems was addressed. The effects of replacing fossil fuels for heating with a wood derived fuel was also studied. Due to the higher harvest level of the conventional system, the conventional systems were shown to utlize resource inputs more efficiently than the organic systems. This emphasises the importance of raising yields in organic production systems. The oil-heated conventional system was shown to be less sustainable than the corresponding organic system. When the fossil fuel was replaced with a more renewable fuel derived from logging residue, the environmental impact decreased as did the overall resource use and the sustainability increased. It was concluded that replacing fossil fuels with more renewable fuels is an important strategy in order to improve the sustainability of tomato production systems. The task of increasing harvest levels for organic systems should also be given high priority

Keywords: conventional, energy, environmental load, mulch, organic production, resource use, sustainability, Sweden, wood powder

Introduction

In many cases it is assumed that organic agricultural production methods are more environmentally friendly than conventional methods. The sustainability aspect of production methods can be evaluated by emergy analysis (Odum, 1987; 1988;

1996) where the sustainability is related to the net output (yield) of the system (the higher, the better), and its load on the environment (the lower, the better) (Brown and Ulgiati, 1997). Emergy is the total amount of environmental resources required to manufacture a product, fuel or service, weighted into one common unit of solar energy. Its unit is solar emjoules (sej). The weighting procedure accounts for direct environmental inputs as well as resources accessed through the market, i.e. purchased fuels, materials and human labour. Emergy is sometimes referred to as "energy memory" (Scienceman, 1987), indicating that it is not a property which can be measured on the item itself but addresses the history of the item.

In this study different systems for tomato production were analysed in accordance to the emergy method. The aim was to demonstrate the importance of different inputs into the system on its sustainability, and to elucidate the consequences of different yield levels.

Materials and Methods

In the study two existing production systems were originally analysed with regard to emergy. The first was an experimental system based on organic fertilizing, and the second was a conventional high technological system. In both cases heating for the greenhouses was generated through the combustion of fossil fuels. The potential of using wood powder as a source of heating was investigated. This resulted in a final analysis where five combinations of production systems and fuel for heating were compared. These five theoretical systems constituted entire greenhouse nurserys specialised in tomato production. The nurserys were located in Southern Sweden, which is the major horticultural area of the country.

Production systems

The experimental system using organic fertilizers has previously been described by Gäredal and Lundegård (1998). Tomato plants were cultivated in a bed of compost, consisting of farmyard manure, soil and straw mixed with peat and gypsum. The beds were considered to be restricted by a soft plastic film between the natural ground and the compost. The heating was generated from oil. The tomato crop was fertilized with red clover mulch during the production period. The fruit were harvested in the period from early June until late October. The short production period was caused by the lack of mulches during the earlier and later parts of the year. Data for the three years presented in Gäredal and Lundegård (1998) were used when determining the annual avarage inputs of substrate and mulch. The composts were considered to be renewed every three years.

The second system in the study was a modern commercial nursery in the South of Sweden. This has previously been described by Lagerberg and Brown (1999). The plants were grown on Rockwool and chemical fertilizers were given as a full nutrient solution using a conventional drip irrigation system. The plants were grown according to procedures normally adopted in modern tomato production in northern Europe. Heating was generated from oil and propane, which also enriched the greenhouse climate with CO_2 to guarantee a maximum yield. The fruit were harvested from mid March until late October.

Studied system combination

A problem in the comparison of the two systems was that system using organic fertilizers had a shorter production period than the conventional system. The yield of the first system was therefore extrapolated over a time period corresponding to the conventional production system. In reality, this would imply that it would be possible to store mulches for a longer production period.

Another important question in the emergy analysis was how a system, based on heating from a renewable organic energy source, would perform in relation to heating from oil. Wood powder was chosen since it is renewable, easily accessible in Sweden, and has a high heat content. An earlier emergy analysis of Swedish wood powder from logging residue (Doherty, 1995) where the forest was considered to produce lumber in a sustainable manner, was accessed. The final analysis would thus present information of the impact both of the fertilizing system and the energy source for heating on the sustainabilty of the production systems. The analysed systems were;

a) an upscaled version of the organic trial system; harvest level 23.2 kg/m^2
b) a version of the organic trial system, where the harvest period was prolonged; harvest level 35 kg/m^2
c) system b) where oil heating was replaced by wood powder; harvest level 35 kg/m^2
d) a conventional production system; harvest level 42 kg/m^2
e) system d) where oil heating was replaced by wood powder; harvest level 42 kg/m^2

The harvest level chosen for the organic systems b) and c) was extremely high compared to levels in today´s Swedish organic tomato production. However, we expect the organic systems of tomorrow to be more efficient. Considering that the best growers today reach 48-50 kg/m^2, the harvest level of the conventional systems d) and e) was not very high. However, this was regarded as the mean of nurserys using modern technique. An increase in the harvest level would not raise inputs proportionally. All five combinations of tomato production systems can be described as presented in Figure 1. In the case of oil-based heating the component containing "Forest & wood powder production" is omitted. The oil is considered as being outside the production system in "Fuels, goods & services".

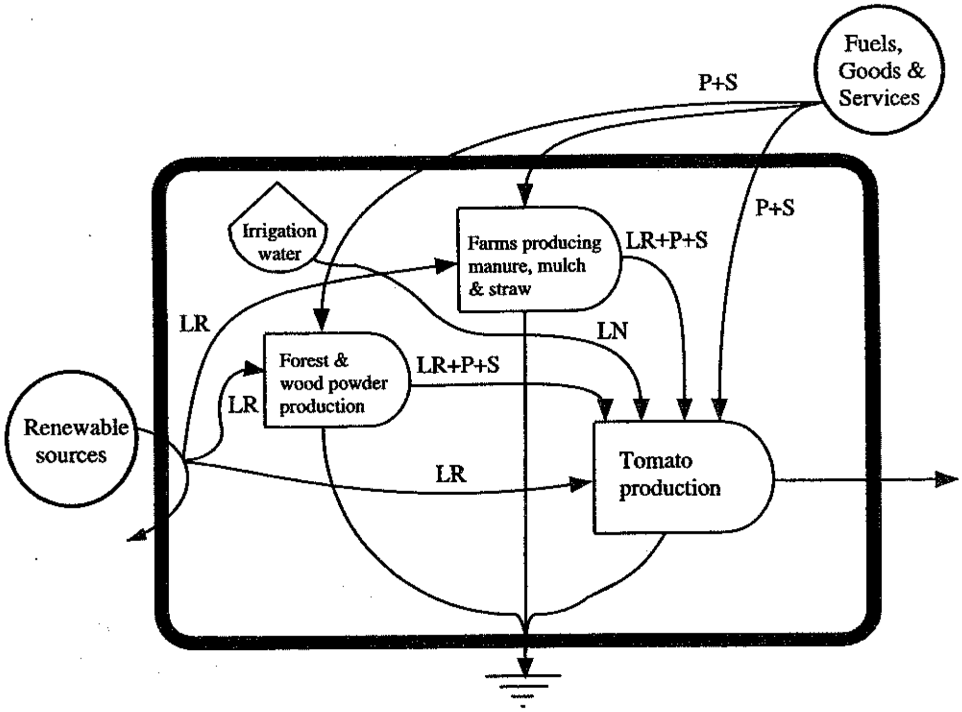
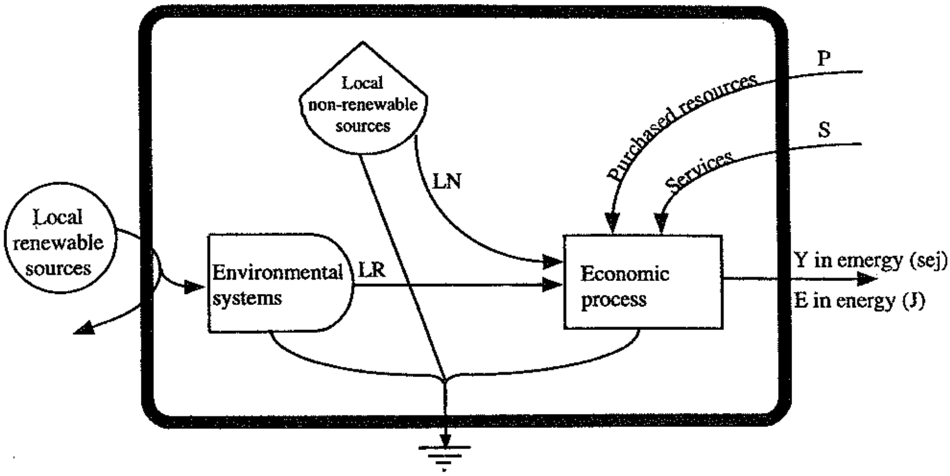


Figure 1. Overview of the resource flows supporting the analysed tomato production system. LR = local renewable resources, LN = local non-renewable resources, P = purchased resources, S = services associated with purchased inputs.

The emergy analysis

Emergy analysis is thoroughly described in Odum (1996). The transformities, i.e. the conversion factors used to express the inputs to the tomato production systems in emergy, were mostly available from other studies. Transformities for the organic substrate and clover mulch were estimates in this study.

Figure 2 explains the calculation of the transformities and some indices. The economic process studied, the tomato production system, is supported by direct local renewable (LR) and local non-renewable (LN) resources and resources (P) and labour (S) purchased from outside the system. The purchased resources are accompanied by indirect human labour (services) required for processing raw resources and handling them within the economic system. The total resource support required to run the tomato production is the emergy yield (Y). The transformities of the tomatoes from the different systems are all the accumulated resources required to generate them (Y), expressed in emergy (sej) and divided by the energy content (E) of the tomato crops (J).



Emergy yield (Y) = LR + LN + P + S

Transformity = Y/E

Emergy yield ratio (EYR) = Y/ (P + S)

Emergy investment ratio (EIR) = (P + S)/(LR + LN)

Non-renewable to renewable ratio (NRR) = (LN + P)/LR

Services to resources = S/(LR + LN + P)

Empower density = Y/(area of system)

Environmental loading ratio (ELR) = (P + S + LN)/LR

Sustainability index (SI) = EYR/ELR

Figure 2. Calculation of transformity and emergy indices. All input flows and Y are expressed in emergy terms (solar emjoules, sej). E designates the energy content of the product resulting from the process and is expressed in J. LR = local renewable resources. LN = local non-renewable resources.

The emergy yield ratio (EYR, Figure 2) was estimated to indicate the process' dependency on purchased inputs. The emergy investment ratio (EIR) is the purchased emergy divided by the local emergy supply. This ratio gives information on whether the system uses the inputs from the economy efficiently compared with alternative processes. A lower EIR indicates that the process runs less on inputs from the economy and more on local resources.

The environmental loading ratio (ELR, Figure 2) was calculated to quantify the potential amount of stress laid on the local system by the process. The higher the ELR, the greater the environmental stress. The emergy sustainability index (SI, Figure 2) is determined by yield, environmental stress and renewable resource use (Odum, 1996; Brown and Ulgiati, 1997; Ulgiati and Brown, 1998).

Inputs purchased from outside the system were regarded as non-renewable, in accordance to the method. As this study deals with the effects of organic fertilizers and wood powder supplied from a local market and considered to be partly derived from renewable resources, the manufacturing of these inputs were placed within the system boundary (Figure 1).

The transformities of manure, red clover mulch and straw, which were considered to be purchased from nearby farms, were calculated in this study. Based on emergy evaluations for these substrate components, 39% of the straw emergy, 20% of manure emergy and 43% of the clover mulch emergy was regarded as locally renewable. From Doherty (1995), 37% of the wood powder emergy was estimated to be of locally renewable origin. The emergy to currency ratio used for assigning emergy value to human labour was obtained from Lagerberg et al. (1999).

Results

Table 1 shows the emergy table of the organic tomato system with the shorter harvest period (system a). Details regarding inputs listed in Table 1 are given in the Appendix.

The tomato production system b) was highly dependent on purchased and non-renewable resources (Table 1). Purchased fuels, materials and services contributed to nearly 100%, while renewable resources constituted less than 1% of the emergy driving the tomato production system. The water for irrigation, considered local non-renewable, contributed to 0.2% of the total inputs to the system. Approximately 43% of the inputs were attributed to services. Of this 16% was accounted for by direct inputs of labour. Another 7% of the services originated from indirect services associated with inputs of oil and electricity. Direct inputs of oil and electricity constituted a major part of the resources running the tomato production system. About 51% of the total emergy requirement, including the associated services, was assigned to oil and electricity for running the greenhouse facility. Another 1% of the total was attributed to fuels for transportation of goods and fuels, while 7% of the emergy requirements were contributed by the substrate and the red clover mulch (Table 1, items 15-22).

Table 1. Emergy evaluation of an organic tomato production system under glass in Southern Sweden. 1996. 8000 m^2 plant area, 1000 m^2 non-plant area and 4500 m^2 outside area. Annual flows.

Note **	Item, Unit	Data (units/year)	Transformity (sej/unit)	Solar EMERGY (sej/year)	% of total EMERGY
DIRECT ENVIRONMENTAL INPUTS					0.01
1	Sun, J	2.88E+13	1.00E+00	2.88E+13	0.00
2	Wind, J	4.48E+10	1.50E+03	6.72E+13	0.00
3	Rain, chemical potential, J	1.10E+10	1.82E+04	2.00E+14	0.01
PURCHASED INPUTS					47.23
4	Macadam, kg	2.99E+04	9.75E+05	2.92E+10	0.00
5	Concrete blocks, kg	1.61E+03	3.54E+11	5.70E+14	0.04
6	Concrete ready mix, kg	2.23E+04	4.40E+11	9.81E+15	0.72
7	Steel, kg	5.95E+03	2.16E+12	1.29E+16	0.94
8	Cast iron, kg	4.43E+02	1.74E+12	7.71E+14	0.06
9	Aluminum, kg	5.40E+02	1.77E+13	9.56E+15	0.70
10	Glass, kg	7.15E+03	8.40E+11	6.00E+15	0.44
11	Service in building, SEK*	3.10E+05	2.14E+11	6.64E+16	4.85
12	Plastics, kg	1.01E+03	3.80E+11	3.83E+14	0.03
13	Remaining metals, kg	8.80E+00	1.00E+12	8.80E+12	0.00
14	Cardboard, kg	7.84E+03	1.41E+12	1.11E+16	0.81
15	Soil			7.48E+16	5.45
16	Peat, J	4.23E+11	3.50E+04	1.48E+16	1.08
17	Straw, kg	1.19E+04	5.42E+11	6.45E+15	0.47
18	Manure, kg	1.54E+04	2.39E+11	3.68E+15	0.27
19	Gypsum, kg	2.30E+02	1.04E+12	2.39E+14	0.02
20	Clover mulch, kg dry matter	2.72E+04	7.50E+10	2.04E+15	0.15
21	Bonemeal, kg	2.00E+00	4.27E+11	8.54E+11	0.00
22	Bloodmeal, kg	2.75E+02	1.05E+12	2.89E+14	0.02
23	Indirect services in substrate, SEK	1.22E+05	2.14E+11	2.62E+16	1.91
24	Soft soap, J	2.40E+09	7.20E+05	1.73E+15	0.13
25	Biological control, SEK	6.83E+03	2.14E+11	1.46E+15	0.11
26	Pollinators, SEK	4.26E+04	2.14E+11	9.13E+15	0.67
27	Seed, SEK	3.33E+04	2.14E+11	7.14E+15	0.52
28	Water, J	2.22E+10	1.10E+05	2.45E+15	0.18
29	Direct human services in labour, SEK	1.04E+06	2.14E+11	2.24E+17	16.31
30	Remaining human services, SEK	7.27E+05	2.14E+11	1.56E+17	11.37
Fuels and electricity					51.33
31	Oil, J	9.90E+12	5.61E+04	5.55E+17	40.50
32	Indirect services in oil, SEK	4.18E+05	2.14E+11	8.95E+16	6.53
33	Electricity, J	3.60E+11	1.28E+05	4.61E+16	3.36
34	Indirect services in electricity, SEK	6.00E+04	2.14E+11	1.29E+16	0.94

Table 1 cont.

TRANSPORTATION OF MAIN COMPONENTS					1.43
Transportation of material inputs					
35	Oil, J	1.99E+09	4.71E+04	9.37E+13	0.01
36	Diesel oil, J	5.13E+10	5.61E+04	2.88E+15	0.21
37	Electricity, J	4.53E+07	1.28E+05	5.80E+12	0.00
Transportation of fuels					
38	Oil, J	2.59E+11	4.71E+04	1.22E+16	0.89
39	Diesel oil, J	7.76E+10	5.61E+04	4.35E+15	0.32
40	SUM OF INPUTS			1.37E+18	100.00
OUTPUTS					
41	Harvest, kg fresh weight	1.86E+05	7.39E+12	1.37E+18	
42	Harvest, kg dry matter	9.28E+03	1.48E+14	1.37E+18	
43	Harvest, J	1.56E+11	8.79E+06	1.37E+18	

* SEK = Swedish Crowns, the currency of Sweden. In 1996, the currency exchange ratio was 6.70 SEK/USD

** The footnotes are given in the Appendix

Table 2. Emergy indices for Swedish tomato production systems: a) upscaled organic trial system, b) improved upscaled organic system, c) improved upscaled system with oil replaced by wood powder heating, d) conventional oil heated system, and e) conventional system with oil replaced by wood powder for heating. 1996.

Indices	(a)	(b)	(c)	(d)	(e)
Emergy yield (Y)	1.37E18	1.90E18	1.35E18	1.98E18	1.51E18
Emergy yield ratio (EYR)	1.00	1.00	1.10	1.00	1.07
Emergy investment ratio (EIR)	202.5	241.6	9.8	480	13.5
Non-renewable to renewable ratio (NRR)	180	270	3.6	6230	6.3
Services/resources	0.76	0.63	1.41	0.59	1.06
Empower density(sej/m^2)	1.02E14	1.41E14	1.00E14	1.47E14	1.12E14
Environmental loading ratio (ELR)	318	441	10.1	9910	14.1
EMERGY sustainability index (SI)	0.003	0.002	0.11	0.0001	0.08
Transformity (sej/kg fresh weight)	7.39E12	6.78E12	4.84E12	5.89E12	4.50E12
Transformity (sej/J)	8.79E6	8.06E6	5.75E6	7.01E6	5.36E6

(a)
LR = 4.29E15 sej/year
LN = 2.45E15 sej/year
P = 7.72E17 sej/year
S = 5.92E17 sej/year

(b)
LR = 4.29E15 sej/year
LN = 3.53E15 sej/year
P = 1.16E18 sej/year
S = 7.33E17 sej/year

(c)
LR = 1.22E17 sej/year
LN = 3.53E15 sej/year
P = 4.37E17 sej/year
S = 7.92E17 sej/year

(d), (e)
Lagerberg, C. and Brown, M. T. 1999. Improving agricultural sustainability: The case of Swedish greenhouse tomatoes. *Journal of Cleaner Production* 7. (in press)

The oil-heated tomato production systems (a, b and d) were all shown to rely much on resources and services purchased from outside (Table 2). For these systems, the total resource use was the greatest for the conventional system (d). When weighted according to the output of the system, the resource use was however shown to be less than for the organic systems (a and b). Although the conventional system uses more purchased non-local resources per unit local environmental resource, the conventional system uses less overall resources per unit output. This indicates at the importance of the harvest level. The resource use per unit tomato output was greatest for system a). The sustainability for systems a) and b) was more or less the same and shown to be significantly greater than for the oil and propane heated conventional system. Because of the great difference in resource efficiency, system b) would be preferred over a). It should be noted that system a) was the original non-optimised experimental system. The transformities were lowest in systems c) and e). The environmental loading ratio was largest in system d) and least in the systems using wood powder in place of oil (c and e). The sustainability index was larger in systems c) and e) while the lowest index was found for system d). Significant for the wood powder heated systems (c and e) was also the lower non-renewable to renewable ratio and the higher services to resources ratio.

Discussion

Replacing the oil for heating, improved the performance of the systems significantly. Total resource use decreased, with a somewhat larger decrease for the organic system. Again, when related to tomato yield, the analysis showed a greater improvement for the conventional system which was more efficient than the organic one. It is noteworthy that the wood powder fuel is comparatively more expensive for the nursery, so this again emphasises the importance of a high yield. The dependency on imported purchased resources decreased dramatically when the oil was replaced with wood powder. The potential environmental stress decreased substantially and the sustainability increased. These findings are supported by Ulgiati and Brown (1998), showing that a large input from outside the process may favour its sustainability, provided that it enhances the exploitation of large amounts of emergy from renewable sources.

The improvements in performance were greater when replacing the oil for heating with wood powder than when the Rockwool system was replaced with an organic fertilizing strategy. This points at the great importance of concentrating on reduction of fossil fuel in favour of more renewable fuels use for heating. Lower transformity fuels will lower the transformity of the yield, while the greater renewable fraction will decrease the environmental stress and increase the sustainability. Wood powder from logging residue would be a reasonable alternative provided that there is no competition for this resource. Several domestic renewable fuels may also be feasible for heating greenhouses. To determine the long-term ecological effects of their use, emergy analyses would be useful as a complement to short term economic analysis.

The emergy analyses in this study shows similar results regarding the importance of the harvest level as the study by Nienhuis and de Vreede (1994) does. Their life cycle assessment of different tomato production systems shows that the environmental impact, although greater per m^2, may be less for non-organic systems when weighted per kg harvested tomatoes. Thus it is imperative to raise the yields in organic systems.

Toxic effects of chemical substances, e.g. pesticides, are not accounted for by the emergy analysis, because of limitations to the present pesticide transformities. However, this did not affect the comparison between the organic and conventional tomato production systems in this study. In general, very small amounts of pesticides, if any, are used in conventional Swedish tomato production. In the systems compared in this study, only biological control was used. When comparing systems using chemical pesticides, the effects of these would have to be addressed with other methods than the present version of emergy analysis.

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References

Brown, M. T. and Arding, J. (1991). *Transformities. Working paper.* Center for Wetlands, University of Florida, Gainesville, USA.

Brown, M. T. and Mc Clanahan. (1992). *Emergy analysis perspectives of Thailand and Mekong river dam proposals. Report to the Cousteau Society. Research studies conducted under contract no. 89092601.* Center for Wetlands and Water Resources, University of Florida, Gainesville, USA.

Brown, M. T. and Ulgiati, S. (1997). Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. *Ecological Engineering* **9**, 51-69.

Doherty, S. J. (1995). *Emergy evaluation of and limits to forest production.* A dissertation presented to the graduate school of the University of Florida in partial fullfillment of the requirements for the degree of doctor of philosophy. Department of Environmental Engineering Sciences, University of Florida, Gainesville, USA.

Fluck, R. C. (ed.). (1992). *Energy in farm production. Energy in world agriculture, volume 6.* Elsevier, Amsterdam.

Gäredal, L. and Lundegårdh, B. (1998). Ecological cultivation of greenhouse tomatoes (*Lycopericon esculentum* Mill.) in limited beds fertilized with locally produced mulches: effects on growth and yield. *Biological Agriculture and Horticulture* **16**, 173-189.

Haukoos, D. S. (1994). *An Emergy analysis of various construction materials. ENV 6905.* Department of Environmental Engineering Sciences, University of Florida, Gainesville, USA.

Lagerberg, C. and Brown, M. T. (1999). Improving agricultural sustainability: the case of Swedish greenhouse tomatoes. *Journal of Cleaner Production.* (in press)

Lagerberg, C. Doherty, S. J. and Nilsson, P. O. (1999). *Evaluation of the resource efficiency and sustainability of the Swedish economy using emergy based indices.* (manuscript)

Mc Graw-Hill Encyclopedia of Science & Technology. (1992). p. 499.

Nienhuis, J. and de Vreede, P. (1994). *Milieugerichte levenscyclusanalyse in de glastuinbouw: bruikbaarheid.* Research Station for Floriculture and Glasshouse Vegetables, Naaldwijk, Netherlands.

Odum, H. T. (1987). Living with complexity. In: *The Craaford Prize in the Biosciences. Craaford Lectures.* The Royal Swedish Academy of Sciences, 19-85.

Odum, H. T. (1988). Self-organization, transformity and information. *Science* **242**, 1132-1139.

Odum, H. T. (1996). *Environmental accounting. Emergy and environmental decision making.* Wiley, New York.

Odum, H. T. and Odum, E. C. (1983). *Energy analysis overview of nations. Working paper WP-83-82.* International Institute of Applied Systems Analysis, Laxenburg, Austria.

Odum, H. T. Odum, E. C. and Brown, M. T. (1998). *Environment and society in Florida.* Lewis Publishers, Boca Raton.

Scienceman, D. M. (1987). Energy and emergy. In: Pillet, G. and Murota, T. (Eds.). *Environmental economics — the analysis of a major interface.* Rolland Leimgruber, Geneva, 257-276.

SMHI. (1996). *Väder och Vatten. En tidning från SMHI. Väderåret 1995.* p. 4.

Statens Livsmedelsverk. (1988). *Livsmedelstabeller. Energi och näringsämnen*. p. 22.

Tillman, A.-M. (1994). *Godstransporter i livscykelanalys. Schablonvärden för energianvändning och emissioner. Rapport 1994:1*. Chalmers tekniska högskola, avd. f. teknisk miljöplanering.

Ulgiati, S. and Brown, M. T. (1998). Monitoring patterns of sustainability in natural and man-made ecosystems. *Ecological Modelling* **108**, 23-36.

Appendix. Footnotes to Table 1.

1. The normal value 1961-1990 of the global insolation in Lund (SMHI, 1996) = 972.9 kWh/m^2. Consequently, the insolation on 9000 m^2 would be area x insolation x (1-albedo) = 9000[m^2]x972.9[kWh/m^2]x3.6E6[J/kWh]x0.60[assumed transmission of light into the greenhouse] = 1.8913E13 J/year.
   The remaining 4500 m^2 outside areas receive 500[m^2]x972.9[kWh/m^2]x3.6E6[J/kWh] x(1-0.37) = 9.9294E12 J/year.
   Sum: 1.8913E13+9.9294E12 = 2.884E13 J/year.
   Transformity from Odum (1996)..

2. Water uptake by the plants amounts to 75 % of the total water consumption. The transpired water from the 8000 m^2 plant area is then given by 75 % of total water consumption - water in harvest[harvest x water contents] - water in plant tissue = 0.75x4500[m^3]x0.9982E3[kg/m^3, at 20 °C]-185600[kg]x0.95[%]-0.1E-3[m^3/plant] x0.9982E3[kg/m^3]x2.5[plants/m^2]x8000[m^2]x20[weeks, assumed incorporation may-decapitation] ≈ 3.153E6 kg of water.
   This water would raise the humidity in the greenhouse to approximately 100 %, if there was no ventilation. Optimum humidity in the greenhouse is 75-80 %. The humidity of the outside air is 65-75 % and 85-90 % during the summer and winter respectively in the Malmö region. The 5.004E6 kg of water has to be moved out of the greenhouse in order to decrease the RH from 100 % to an assumed seasonal average of 75 %.

   Air of 100 % RH [1 kPa, 21 °C] can hold 15.14 g of water per kg dry air whereas air of 75 % RH can hold about 83[grains/pound]x1/7[g/kg per grain/pound]≈11.86 g of water per kg dry air (Mc Graw-Hill, 1992). ⇒ 1 kg of 75 % air can remove 15.14 - 11.86 = 3.28 g of water. To remove 3.153E6 kg = 3.153E9 g of water we thus need 3.153E9/3.28 ≈ 9.61E8 kg of 75 % air. The kinetic energy required to move this air mass is given by KE = $mv^2/2$ ⇒ 3.153E9/3.28x5.5^2[m/s, wind speed estimated from data from the Swedish Meterological and Hydrological Institute]/2 ≈ 1.45E10 J.

   Wind contribution on remaining area = kinetic energy = (air mass)x(windspeed absorbed; 40 % of windspeed at 1000 m)^2/2 = 4500[m^2]x1000[m, boundary layer]x1000[kg/m^3, density of air]x(0.4x5.5[m/s]/0.6)^2/2 = 3.025E10 J.

   Sum: 1.454E10+3.025E10 = 4.48E10 J. Transformity from Odum (1996).

3. The normal value of precipitation in Lund 1961-1990 (SMHI, 1996) = 658 mm = 0.658 m. 25 % of the total rainfall was considered to be evapotranspired. Free energy of rainfall = (area)*(evapotranspired rain) *(density of water)*(Gibbs free energy) = 13500[m^2]*0.658[m]*0.25[25 %]*1000[kg/m^3]*4.94E3[J/kg] = 1.097E10 J. Transformity from Odum (1996).

4. The mean transformity of granitic rock (Odum, 1996) and metamorphic rock (Odum, 1996) was used.

5.-8. Transformities from Haukoos (1994).

Appendix cont.

9. Transformity from Lagerberg and Brown (in press).

10. Transformity from Brown and Arding (1991).

11. Services associated with the greenhouse building, major components (incl. artificial light) and maintenance. Emergy to currency ratio from Lagerberg et al. (manuscript).

12. Transformity from Brown and Arding (1991).

13. Brass, cupper and unknown metals. Transformity from Odum (1996).

14. Transformity from Doherty (1995).

15. Emergy weighted from the transformity of clay and organic matter (Odum, 1996).

16. 111[m^3]x350[kg/m^3]x3.27E9[J/m^3]/300[kg/m^3] = 4.23E11 J. Transformity from Odum et al. (1998).

17.-22. Transformities calculated in this study.

17. 39% of transformity, derived from the emergy contribution of rain to barley cultivation, was considered to be locally renewable.

18. 20% of transformity, derived from the emergy required to run a nearby dairy farm where the direct environmental inputs (rain dominating) and environmental input of fodder purchased locally, was considered locally renewable.

20. 43% of transformity, derived from direct environmental inputs (rain dominating) and locally produced seed (less than 1% of the clover mulch transformity).

24. The energy contents of lauric acid (the predominant fatty acid of soap) is 8.816 kcal/g (Odum and Odum, 1983). Assuming that soft soap contains about 0.5 kg soap per dm^3, gives an energy contents of 130 dm^3]x0.5[kg/dm^3] x8.816E3[kcal/kg]x4186[J/kcal] = 2.40E9 J in 130 dm^3 soft soap.
Transformity from Odum and Odum (1983).

28. Water used for irrigation = 4500[m^3]x4.94E6[J/m^3]= 2.22E10 J. Transformity from Brown and Mc Clanahan (1992).

29. Including tax.

30. Incl. costs for remaining materials, insurance, interest on loans and costs for amortization on remaining materials.

31. Oil used for heating is more refined than the oil for transportation. Therefore the transformity of refined fuels was used (calculated from sedimentary coal in Odum, 1996).

Appendix cont.

33. Mean transformity of world average (Odum, 1996) and Swedish hydroelectric power (Doherty, 1995) = (1.74E5+8.02E4)/2 = 1.28E5 sej/J.

35.-39. The transportation of inputs was evaluated by the inputs of fuels and electricity.

40. Items 1, 2, and 3 are byproducts of the same solar emergy flow. To avoid double counting, only the largest of these components (rain) are used when summing the emergy inputs to the system. (Odum, 1996)

42. 95 % water contents.

43. 1.68E7 J/kg dry matter calculated from tables of protein, fat and carbohydrate contents of fresh tomatoes (Statens Livsmedelsverk, 1988). Energy contents of protein, fat and carbohydrates (Fluck, 1992).

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