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Emergy evaluations of Denmark and Danish agriculture: Assessing the influence of changing resource availability on the organization of agriculture and society

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Abstract

This paper presents emergy evaluations of Denmark and Danish agriculture for the years 1936, 1970 and 1999. The evaluations highlight the changing relationship between agriculture and society over the time period studied. A large increase in total emergy supporting the Danish economy was observed, and the 379% rise from 1936 to 1999 in emergy use per capita, a biophysical measure of living standard, came from both imported sources and from the non-renewable storages of the biosphere. In 1936, Danish agriculture was largely based on the use of draft animals for traction and approximately 1,110,000,000 person-hours of direct labor were required for production, while in 1970 and 1999, all traction was mechanized and approximately 415,000,000 and 121,000,000 person-hours were required for production, respectively. Over the same period, the emergy supporting each person-hour of agricultural labor increased by 1600%. The driving forces for agricultural production shifted towards an increased reliance on commercial energy and indirect labor. Given the increase in emergy available to the Danish economy through extraction and use of domestic oil and gas and trade over the period studied, the shift in labor from agriculture to the service and manufacturing sectors represented a nation-wide re-organization for maximum empower. The evaluations also indicate that while agriculture remains an essential way for industrial economies to capture local renewable resources, given the limited net emergy yields of agricultural production, the magnitude of non-agricultural economic activity that agriculture systems can support appears limited in an economy with access to high-net-yield imported energy resources.
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1. Introduction

Agriculture is a primary activity by which human societies channel contemporary renewable energy flows into products that support societal welfare. For millennia, the agricultural systems of the world were run on locally available materials and renewable energy sources, and supported societies with complex, locally adapted economic, cultural and knowledge systems—albeit in a world with far fewer people than today (Odum, 1971; Pimentel and Pimentel, 1979). Over the past century, agricultural systems, agricultural technology and the socioeconomic structures to which they are coupled have undergone a dramatic transformation, and this transformation has been especially pronounced in the industrialized and newly industrializing regions of the planet (Cleveland, 1994; Conforti and Giampietro, 1997; Björklund et al., 1999). Salient among the observed trends during the era of rapid industrialization in agriculture has been a dramatic increase in commercial energy use in agricultural production, a no-less dramatic decrease in direct labor requirements, and a substantial increase in gross productivity per unit labor and per unit area. For these trends to be placed within their proper

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historical context, they must be understood as an outgrowth of the ability of human society to harness and utilize more concentrated, higher quality energy sources (Odum, 1971; Hall et al., 1986; Adams, 1988). In broad terms, this history represents a shift in the energetic resource base of society from solar energy, in the form of food and wood, to coal, and then oil, natural gas, hydroelectric and nuclear energy as the main driving forces behind economic growth and societal development. This long-term and relatively constant expansion and diversification of the 'energy signature' of industrial societies has strongly influenced the organization of their agricultural systems, and the relative abundance and diversity of energy sources available to the industrialized world continues to influence perceived options for the future direction for agriculture and rural development in industrialized nations.

Given that inexpensive petroleum energy resources will not be available indefinitely, at current rates of use and proved reserves (Campbell and Laherrère, 1998; Deffeyes, 2001), society will eventually be forced to make choices regarding how to invest what remains of this important commodity. Perhaps because it entails the investment of some high quality non-renewable energy to capture a lower quality yet more abundant quantity of renewable energy, the use of petroleum resources to increase agricultural productivity has heretofore seemed a 'wise-use' policy. However, dwindling fossil fuel availability will undoubtedly force all uses of petroleum and its derivatives to fall under increased scrutiny. Thus, the development of decision-making tools for energy resource allocation may become a central task for science in the coming decades. In this paper, we use emergy evaluations and energy systems theory to explore the potential of agricultural systems to support industrial society using the example of Denmark. By presenting emergy evaluations of Denmark and Danish agriculture for the years 1936, 1970 and 1999 we show how the organization of Denmark's agricultural system responded to changes in the emergy use of the national economy to which it is nested, and examine the changing role of agriculture in the Danish national economy, in emergy terms. We suggest that, during an era of declining non-renewable resource availability, a power maximizing strategy could entail holding constant the ratio of emergy contributions to agricultural production from human labor (both direct and indirect) and physical resource emergy. A hypothesis requiring further investigation.

1.1. Emergy evaluations of agricultural systems

Agricultural science has primarily been concerned with increasing crop yields and improving the economic efficiency of individual farming systems and farming regions. This process has been characterized by finding new uses for machinery and fossil energy and its derivatives in agricultural production, and by a continual decrease in the direct human labor requirements for agriculture (Hall et al., 1986; Mayumi, 1991; Cleveland, 1994; Giampietro and Pimentel, 1991). When the outcomes of this process are gauged against the performance indicators of gross yield and economic efficiency, agricultural science and engineering has been very successful, and food has become both cheaper and more plentiful in many parts of the world (Conway, 1997). However, economic and gross yield assessments of agricultural productivity have often overlooked important parallel developments. Central among these correlated trends are the decline of net-energy yields (often measured as the food energy produced to the commercial energy invested) of modern agricultural systems relative to earlier, pre-industrial systems (Odum, 1967; Martinez-Alier, 1987; Fluck, 1992). This fact has led many to question the validity of modern agriculture's claims to superior efficiency; a claim often supported by measurements of productivity per unit labor, and not based on analyses of energy return on energy invested (Odum, 1984; Hall et al., 1986; Fluck, 1992).

Emergy evaluations join the long history of energy analysis of agricultural systems (see Martinez-Alier, 1987). However, emergy analyses may offer a more complete picture of agriculture's role in the biosphere and human economies by calculating the total work contributed by both natural and economic systems to generate agricultural products, measured on a common basis and in one kind of energy. Emergy evaluations thus provide a more universal assessment of the total work requirements of agricultural production than other methods that focus solely on commercial energy inputs, or which omit environmental energies or societal energy support for labor (often called 'lifestyle energy') (see Fluck, 1992). From its origins in ecosystem science, emergy analysis has evolved into an environmental assessment tool grounded in the laws of thermodynamics that offers a biophysical alternative to economic analysis (Odum, 1996). A primary strength of emergy evaluations is that it allows for processes producing similar products, but through different means, to be compared on a common basis. For example, Brown and Ulgiati (2002) compared electricity production from coal, oil, hydro-electricity, geothermal and wind turbine technologies to assess their renewability, efficiency, net yield to society, and environmental load, using emergy as a common metric.

Although emergy analysis is still a relatively new field of science, it is based on a steady progression of scholarship initiated by Howard T. Odum and colleagues beginning in the 1960s. Initial research began with the measurement of the flow of energy in ecosystems. This yielded insights into the general energy principles underlying ecological-economic systems, which in turn fostered expanded application to include agroecosystems and economic systems (Odum, 1967, 1971, 1988, 1994, 1996; Hall, 1995). Having evolved from ecological energetics, emergy analysis applied to agriculture can identify those farming systems that are more efficient at capturing and utilizing sunlight energy and its derivatives (wind and rain), versus those that are simply conduits for fossil fuels, fertilizers, pesticides and machinery. Recent emergy evaluations of agricultural systems include analyses of a variety of different agricultural products, in diverse regional contexts (Ulgiati, 2001; Brandt-Williams, 2001; Rydberg and Jansen, 2002; Lefroy and Rydberg, 2003).

1.2. The theoretical basis of emergy evaluations

Emergy is defined as the available energy of one kind previously used up directly and indirectly to make a service or product, usually quantified in solar energy equivalents (Odum, 1996). The unit used to express emergy values is the emjoule, and when using solar energy as gauge, the solar emjoule. The theoretical foundations of systems ecology and emergy analysis stem from the observation that both ecological systems and human social and economic systems are energetic systems, which exhibit characteristic designs that reinforce energy use (Odum et al., 2000; Odum, 1988, 1996). Because emergy evaluations are attended by considerable theory, we think that the theoretical basis of emergy evaluations, alternately energy systems theory, requires some introduction. Thus, we offer a brief description of emergy theory in the following text.

1.2.1. Energy quality, energy hierarchy and transformity

Over the years, scholars have assigned the concept of 'energy quality' different meanings. In energy systems theory (after Odum, 1994), the notion of energy quality refers to the observation that energies of different kinds vary in their ability to do useful work. Hall et al. (1986) offer a definition of energy quality based on the physical properties of various fuels and minerals, their economic value and their relative crustal abundance. Odum's more general definition of energy quality, which we subscribe to, is a function of the amount of previous energy of one kind required to produce a resource (Odum, 1996).

Odum (1971, 1994, 1996) uses the term 'energy hierarchy' to indicate that in all systems, a greater amount of low quality energy must be dissipated in order to produce a product containing less energy that is of a higher quality. Observing this process of energy transformations in systems of all types indicates that there is a self-organized order underlying how energies of differing qualities are grouped in natural and human-made systems. Agricultural products generally reside fairly low in the Earth's energy hierarchy, being two to three steps removed from the renewable emergy sources driving the processes of the biosphere. When the energy previously used up to make a product is divided by the energy remaining in the product one derives the transformity of that product, expressed as the ratio of solar emjoules per Joule (sej/J) or per gram (sej/g). Transformities are equated with energy quality in that they account for the convergence of global work processes required to produce something, expressed in energy units (Brown and Ulgiati, 1999). The more energy transformations there are contributing to a product, the higher the product's transformity, and the product therefore occupies a correspondingly higher position in the energy hierarchy (Odum, 1996). In this way, transformity can be used as energy scaling ratio to indicate energy quality and the hierarchical position of different energy sources in the universal energy hierarchy. Because the transformity concept is able to give an indication of the concentration of a system input with respect to the time, space and energy needed to form that input, it thereby allows for a fuller articulation of the forces driving the self-organizing processes underway in a given system.

1.2.2. Open systems analysis

Agricultural systems do not exist in isolation. Because they exchange matter and energy with surrounding their environment they are, by definition, open systems. Therefore, if an assessment methodology of the energetic dynamics of agricultural systems is to generate lasting insight, the systems being evaluated must be considered open, in a state of thermodynamic non-equilibrium and, symbiotically dependent on their surroundings (Odum, 1996). In this paper, agricultural systems are treated as open and contextually nested to the system(s) enveloping it. Specifically, we see that agricultural systems, at the national scale, are symbiotically nested to the entire surrounding national economy, which is in turn nested within higher order (global) economies and the biosphere. Whereas other systems analytical methods simplify systemic complexity by omitting those energy flows deemed unimportant, emergy evaluations include *all* energy flows, and opt to simplify complexity by aggregating resource flows of similar quality or transformity. This is based on the theory that all energy flows emanate from different levels of the universal energy hierarchy and may contribute considerable *emergy* to the system being evaluated, even if the magnitude of energy flow is not great (Odum, 1996). As modified ecosystems designed to produce socio-economically useful target products (Conway, 1987), agricultural systems are generally much more open to external exchanges than natural ecosystems. Specifically, agricultural systems require the import of concentrated materials and energy in the form of fuels, fertilizers, pesticides, machinery and high protein content feeds (Stanhill, 1984; Fluck, 1992). In addition, agricultural systems are often relied upon to provide a sink for the waste products of societal metabolism (Giampietro and Mayumi, 2000).

1.2.3. Self-organization and the maximum empower principle

Self-organization and the maximum empower principle are fundamental theoretical concepts underlying emergy analysis and must be elaborated upon if the results of a given analysis are to carry their full meaning. The concept of self-organization provides a framework for understanding how systems utilize incoming emergy sources to develop new organizational states over time. A nuanced conception of self-organization must be inclusive of systems' internal constraints, and must consider thermodynamic limits and their relation to the ability of a system to build and maintain structure, organization and distance from equilibrium (Müller and Nielsen, 2000). The maximum empower principle (MEP), after Lotka (1922a,b), Odum and Pinkerton (1955) and Odum (1996) state that 'prevailing systems are those whose designs maximize empower by reinforcing resource intake at the optimum efficiency' (Odum, 1996, p. 26). Another statement of the MEP is given by Brown and Ulgiati (1999): 'systems that self-organize to develop the most useful work with inflowing emergy sources, by reinforcing productive processes and overcoming limitations through system organization, will prevail in competition with others' (p. 488). Odum (1996) posits this principle to be the fourth law of thermodynamics.

It is important to state that while the concept of self-organization stems from the natural sciences, it does not entirely deny human agency and can be used to interpret systems that include socioeconomic aspects (Kay et al., 1999; Buenstorf, 2000). This fact is highlighted by Jantsch (1980) who indicates that a more refined view of self-organizing dynamics recognizes the degree of freedom available to a system for the self-determination of its own evolution, while at the same respecting energetic boundary conditions. Thus, while human decision-making is central to the evolution of ecological-economic systems, the laws of thermodynamics always apply, including possibly the MEP (or the fourth law). Many agricultural examples exist that illustrate how the MEP operates in the real world. For example, agricultural systems that undermine there own long-term productive capacity through soil erosion, soil compaction, overapplication of chemical fertilizers and biocides and other forms of mismanagement, although possibly displaying higher gross productivity in the short term, are less likely to remain productive in the long-term than agricultural systems based upon better management practices that include greater reliance on locally available energy sources, and greater nutrient cycling to maintain their productivity. Long-term sustainability requires an internal organization that use renewable resources in an effective way. Utilizing non-renewable sources to their greatest potential is also an example of the MEP. When the non-renewable sources are used up, changes have to be made to successfully return to lower energy inputs. In this paper, we consider both agricultural systems and the economy to which they are coupled to be self-organizing, dissipative systems governed by the maximum empower principle.

1.2.4. Empower, net emergy and work

The sun is the primary energy source powering the work processes of the biosphere, with other significant contributions from the gravitational force of the moon and deep earth heat. All other energy sources must be obtained from storages of the biosphere's previous work. Power is defined as useful energy flow per unit time, and empower is defined as the flow of emergy per unit time (Odum, 1996). Because work requires a source of useable energy to be performed, the amount of work that can be done by a system is governed by the amount of power, or useable energy per time, available to that system. Some systems are able to fuel work processes in excess of their own requirements and are thus considered to have a net yield of emergy. Those storages of previous environmental work, such as hydrocarbon fossil fuels, that are relatively easy to obtain and utilize, generally have a large net yield of emergy, and can therefore power a large amount of work processes in addition to the work performed in accessing the emergy storage itself (Odum, 1996). With regard to agriculture, and other production processes that run partially on contemporary sunlight and its derivatives, it must be noted that there are thermodynamic limits to the ability of these systems to provide empower in excess of the emergy invested in the production process itself. This is an important fact to bear in mind when attempting to understand the potential of ecological and agroecological systems to power economic processes.

2. Materials and methods

2.1. Statistical sources

To understand how changes in the total emergy flow supporting the Danish national economy has influenced structural changes in Danish agriculture, the emergy supporting both systems was evaluated for the years 1936, 1970 and 1999, using data from national statistical compendiums and other sources (see www.cul.slu.se/information/publik/rydberg_haden.pdf). Denmark was chosen due to the fact that most of its land area is devoted to agriculture, as well as the fact that agriculture has been, for most of Denmark's history, a dominant economic activity (Ingemann, 1999). By performing analyses on two scales and at three intervals, an understanding was gained of the ecological and economic context within which Danish agriculture was and is nested. The analyses presented are somewhat aggregated, and are intended to serve as a historical background to the discussion of what society can expect agriculture to provide in the future if the energetic boundary conditions constraining the organizational state of their agricultural systems change.

2.2. Emergy evaluation procedure

Odum (1996) and Ulgiati and Brown (2001) give detailed explanations of the application of emergy accounting procedures for a variety of systems. What follows is a brief description of the methods used in performing the analyses specific to this paper. The first step is to define the boundary for the system under study. The choice of boundary dictates what is to be considered an indigenous resource, an inflowing emergy source or an export of emergy from the system. A systems diagram is drawn using the symbols of the energy language of systems ecology (Odum, 1994, 1996) to graphically represent system components, emergy sources and flows and the circulation of money through the system (see Figs. 1 and 2). The components and subsystems are connected with arrows that indicate energy, material and information flows (Odum, 1996). Emergy evaluations entail the tabulation and calculation of all energy, mass and macroeconomic monetary flows supporting the process or economy. To obtain emergy values for the supporting energy, material and monetary flows, the raw data is multiplied by transformities according to mass (sej/g), energy (sej/J), or a currency-specific emergy-to-money ratio (sej/\$). The boundaries of the system analyses presented subsequently are continental Denmark, including Denmark's continental shelf and territorial waters, and the Danish agricultural production subsystem. Aggregated diagrams indicating the variables used to calculate emergy indices and ratios for the national economy and agriculture are presented in Figs. 1 and 2, respectively. Land use in Denmark (total land area 43,070 km^2) is dominated by cultivated land, with up to 61–75% (2,644,000–3,250,000 ha) of total land area in agriculture over the years evaluated. Land use in 1999 was composed of approximately 61% cultivated land, 21% built up or otherwise developed lands, 12% forest and woodland, and 6% meadows and pastures (Statistics Denmark, 1999a).

Using nomenclature from Odum (1996), the variables shown in Fig. 1 represent the emergy flows supporting the Danish national economy including the subsystems of commerce, industry and services. In addition, emergy measures of the physical resource basis of national economies generates insight into their reliance on domestic versus external resources, the ‘‘standard of living’’ of the citizens, and the placement of individual countries within the global energy hierarchy of nations (Ulgiati et al., 1994; Odum, 1996). In Fig. 1, R represents the sum of the environmental emergy flows (rain, waves, tide); N the sum of non-renewable resources from within the system (national) boundary, including Denmark's territorial waters; N_0 represents the portion of N from non-concentrated rural sources (soil); N_1 the portion of N that is concentrated and for domestic use (fuels and minerals); N_2 the portion of N that is exported without use; F represents the emergy of all imported fuels and minerals; G represents the emergy of imported goods; I the total dollars paid for imports; P_2I represents the emergy in services that Denmark receives through trade; E represents the dollars received for exports; P_1E the emergy value of service in exports; B emergy of the exported products transformed (upgraded) within Denmark; x the gross domestic product of the nation in US\$, converted from Danish Kronor (DKK); P_2, world emergy/\$ ratio, and is used to value the emergy of services in imports; P_1 is the national emergy/\$ ratio in US\$. These aggregated variables are used to calculate indices that aid in the interpretation of results of the evaluation.

In order to understand the importance of agriculture, in emergy terms, to the economy of Denmark, the Danish agricultural system was evaluated as a whole for the years 1936, 1970 and 1999 using the same procedures as for the evaluations of the Danish economy. As a major subsystem of the Danish national economy, agriculture is also the primary activity through which the people of Denmark access the

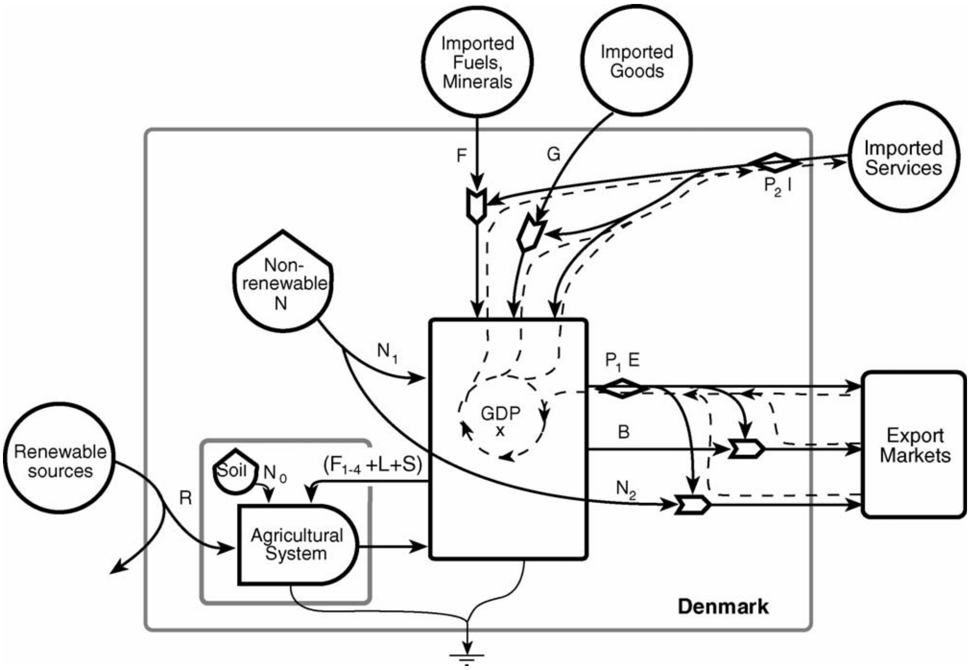

Fig. 1. Summary diagram of aggregated emergy flows for the Danish national economy. The letters next to each flow are variables used to calculate emergy indices. A system diagram of the corresponding agricultural subsystem analyses is given in Fig. 2.

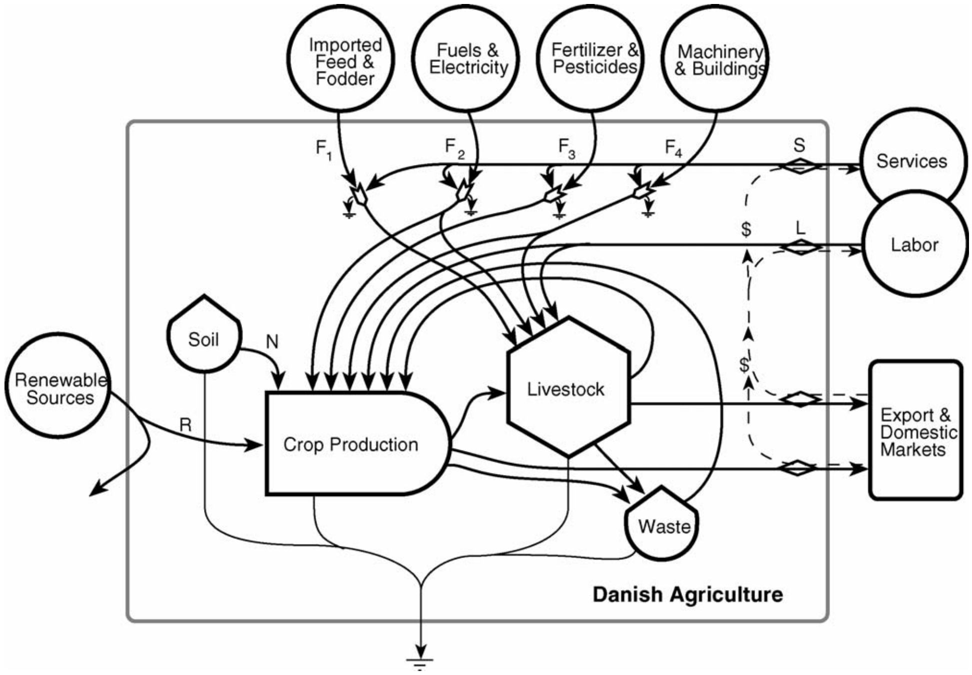

Fig. 2. Summary diagram of aggregated emergy flows for the Danish national agricultural system.

land-based, renewable emergy flows indigenous to their nation. By measuring the emergy flowing to agriculture, and from agriculture, to the surrounding society, an understanding of the role agriculture plays in the overall Danish economy was obtained and insight generated as to what can be expected from agricultural systems in a changing energy future.

Fig. 2 is a summary diagram of the national agricultural system of Denmark where; *R* is the largest of the renewable emergy flows from the global cycle supporting Danish agriculture (in this case rain); *N* the soil organic matter used up in crop production; F_1 the emergy of the digestible crude protein in imported feed concentrates and fodder supporting Danish livestock production (primarily pulses and cereals; bran; oil-cakes; bone, fish, milk and lucerne meals); F_2 the emergy of commercial energy sources used in agricultural production (diesel, gasoline, coal, natural gas and electricity); F_3 the emergy of commercial fertilizers and pesticides used in crop production, calculated as the amount of raw nutrient and active ingredient, respectively; F_4 the emergy of depreciating assets used in agricultural production (includes farm machinery, and an estimate of the depreciation of farm buildings based on the money spent for maintenance, multiplied by the emergy/$ ratio for each specific year); *L* the emergy supporting Danish agriculture in the form of direct labor calculated as labor costs multiplied by the emergy/$ ratio for each specific year; *S* is the contribution to agriculture from indirect human services purchased by agricultural operations from the wider economy. This is calculated as the gross income of Danish agriculture, minus labor costs, multiplied by the emergy/$ ratio for each specific year. This measurement provides an estimate of the degree of integration of farming operations to the wider economy by quantifying the portion of physical resources consumed by non-farm workers in support of agricultural operations. The energy output of each year was evaluated as the gross production of crops and livestock products converted into energy units (J). The spatial boundary of the system was limited to the area of land in agricultural production for each year.

3. Results

3.1. Emergy evaluations of the resource basis of the Danish economy 1936, 1970 and 1999

The emergy evaluations indicate that the most salient change observed over the period studied was a large increase in total emergy support for the Danish economy. The physical area of Denmark has not changed over the period studied. The major weather patterns that cross Denmark have been essentially unchanged over the studied period. Due to those two reasons no major changes in the renewable emergy flows (*R*) supporting the Danish economy could be registered. The calculated numbers was 158.54E+20 sej/yr for each year, using average data. Thus, any increase in the standards of living, in emergy terms, had to come from imported sources or from non-renewable storages. Over the period from 1936 to 1999, the Danish economy increased the overall throughput of both sources of emergy, and these flows have been responsible for the large increase in economic activity during the same period. Fig. 3 is a chart showing the magnitude of the emergy flows supporting the

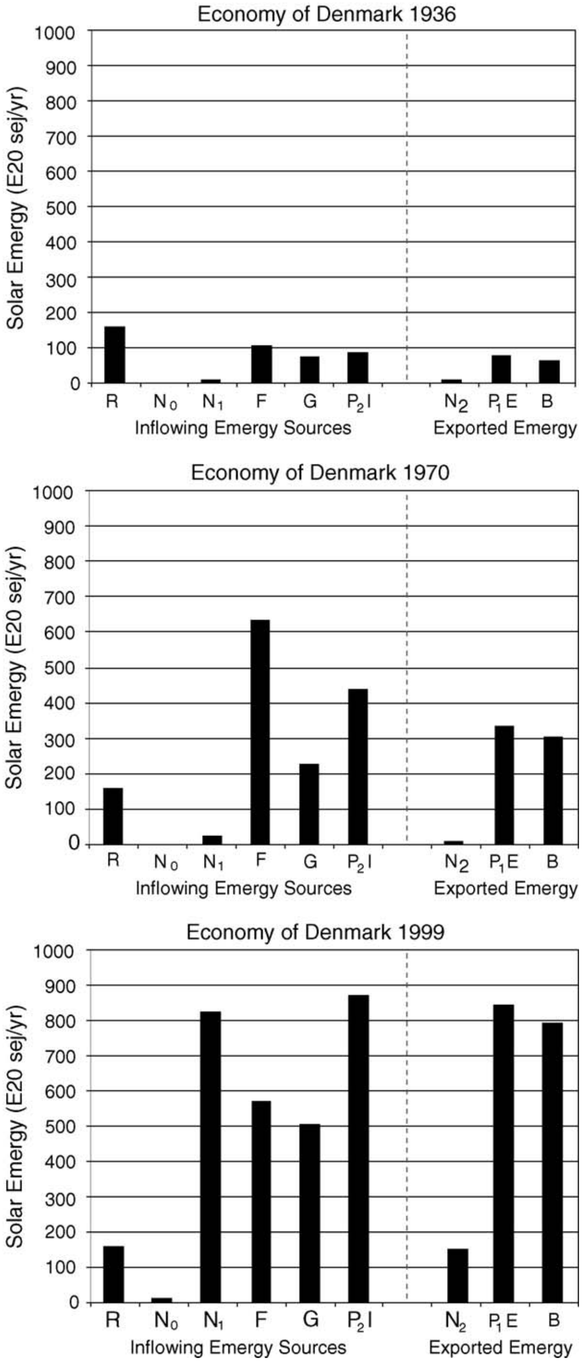

Fig. 3. Charts showing the magnitude of the emergy flows supporting the Danish economy in 1936, 1970 and 1999.

Danish economy during the period studied from both indigenous and imported sources. Table 1 shows both macroeconomic and emergy flows for the years studied and their percentage change (see www.cul.slu.se/information/publik/rydberg_haden.pdf for detailed calculations).

Imported emergy is, and has been, a major catalyst for the Danish economy, which is highly dependent upon external trade and fully embedded in the European and global economies. Table 2 presents a selection of emergy-based indices that examine the changes over time in the resource base supporting the Danish economy, the emergy balance of trade, and the relative carrying capacity of both Denmark, and the world at the Danish standard of living over the years studied. The renewable carrying capacity of a nation is measured by the amount of emergy person that could be met using only the renewable (*R*) emergy for that nation. The measure of world renewable carrying capacity is a measure of the number of people living at Danish standard of living that could be supported by the renewable emergy flow of the planet, as given by Brown and Ulgiati (1999). Between 1936 and 1970 imported emergy was the primary stimulus for increased economic activity, while between 1970 and 1999 Denmark began to exploit oil and natural gas reserves in the portion of the North Sea that falls within its territorial waters. This discovery, and subsequent exploitation, allowed Denmark to become self-sufficient with regard to fossil fuel production (Statistics Denmark, 1999a,b,c). Consequently, imported fuels and minerals (*F*) which totaled 102.82E+20 sej/yr in 1936, and expanded to 633.23E+20 sej/yr by 1970, dropped down to 569.73E+20 sej/yr in 1999 after discovery and utilization of domestic sources began to substitute for imports. Trade in goods more than doubled between each period studied. Exploitation of hydrocarbon resources resulted in an overall emergy self-sufficiency percentage, or the fraction of total emergy used from home sources, to fall from 39% to 12% between 1936 and 1970 and then to rise to 34% by 1999.

In terms of exports, the emergy exported from Denmark without further use (N_2) was limited in 1936 and 1970, at 7.89E+20 sej/yr and 7.35E+20 sej/yr, respectively, but grew to 149.28E+20 sej/yr in 1999, as Denmark began to export oil and natural gas. The exported products transformed within Denmark (*B*) – products that stimulate the Danish economy by adding value to both imported and local emergy sources before export – totaled 60.95E+20 sej/yr in 1936, 301.14E+20 sej/yr in 1970 and 790.89E+20 sej/yr in 1999. While both the GDP and the use of emergy expanded greatly from 1936 to 1999, they did not do so proportionately. During the period studied, the GDP of Denmark increased over 10,000% while the total emergy used, or the total entropy generated to support the economy, increased by 460%. While the total increase in emergy use was very large from 1936 to 1999, and the total increase in emergy use per capita was also large, rising approximately 290%, the emergy to money ratio – a measure of the real wealth purchasing power of a currency – declined by 95% during the same period.

3.2. Emergy evaluations of the resource basis of Danish agriculture 1936, 1970 and 1999

When the magnitude of the emergy flowing through the Danish economy increased, the agricultural subsystem of Denmark responded with distinct changes in its emergy signature. The total emergy support for agriculture increased from 1936 to 1970 but decreased from 1970 to 1999. Fig. 4 is

Table 1
Emergy and macroeconomic flows of the Danish economy, 1936, 1970, 1999 and their percentage

Variable	Item	Solar emergy ($\times 10^{20}$ sej/yr) (unless otherwise noted)			Percentage change	
		1936	1970	1999	1936–1970 (%)	1936–1999 (%)
R	Renewable sources (rain, tide, waves)	158.5	158.5	158.5	0	0
N	Non-renewable resources from within Denmark	15.7	30.5	974.2	95	6124
N_0	Dispersed rural source	1.4	1.7	3.1	25	127
N_1	Concentrated use	6.4	21.5	821.8	235	12726
N_2	Exported without use	7.9	7.3	149.3	−7	1793
F	Imported fuels and minerals	102.8	633.2	569.7	516	454
G	Imported goods	71.5	225.6	504.1	215	605
I	Dollar paid for imports (US$)	3.30E+08	4.38E+09	4.45E+10	1228	13388
P_2I	Emergy of services in imported goods & fuels	85.2	420.0	868.6	393	919
E	Dollars received for exports (US$)	2.95E+08	3.29E+09	4.95E+10	1016	16704
P_1E	Emergy value of goods and service exports	76.0	315.1	825.1	315	986
B	Exported products transformed within Denmark	60.9	301.1	790.9	394	1198
x	Gross national product (US$)	1.65E+09	1.52E+10	1.76E+11	823	10529
P_2	World emergy/$ ratio used in imports (sej/US$)	2.58E+13	9.58E+12	1.95E+12	−63	−92
P_1	Denmark emergy/US$ ratio (sej/US$)	2.58E+13	9.58E+12	1.67E+12	−63	−94

showing the magnitude of emergy flow supporting Danish agricultural production by category of emergy. Table 3 is a summary of emergy flows and their percentage change over the period studied.

In 1936, Danish agriculture was largely based on the use of draft animals for traction, but was nonetheless highly dependent upon outside imports and services to achieve its productivity. A 1936 falls within the time period that has been referred to as the classical period of agriculture in Denmark, as livestock cooperatives were strong and over 450,000 people were directly engaged in agricultural production (Ingemann, 1999; Statistics Denmark, 1937). Being oriented toward export markets, agricultural production was already functioning as a throughput industry and was a primary source of foreign exchange for Denmark at this time. In the first year evaluated, the Danish agricultural system relied on renewable emergy flows (R) slightly more than later years due to a larger land area in agriculture and a greater reliance on permanent pastures with correspondingly higher rates of evapotranspiration. Soil erosion was lowest in this year and was the locally available non-renewable storage (N) that was an input to production. While purchased inputs ($F_{1–4}$) were a major force driving productivity, the applied supplementary energy sources were relatively small at this time, with 2.72E+20 sej of electricity and fuel used in production. The use and depreciation of farm assets (F_4) contributed 5.29E+20 sej and, while draft animal power was the primary source of traction, there were over 5000 steam engine tractors in operation and hundreds of thousands of stationary and horse-drawn steel farm implements used in both crop and livestock production. The purchased goods specific to crop production were in the form of commercial

Table 2
Indices of Danish national carrying capacity and international trade

Name of index	Expression	1936	1970	1999	Percent change	
					1936–1970 (%)	1936–1999 (%)
Total emergy used, U (sej/yr)	$N_0 + N_1 + R + F + G + P_2I$	4.26E+22	1.46E+23	2.93E+23	243	587
Fraction emergy use derived from home sources	$(N_0 + N_1 + R)/U$	39%	12%	34%	−68	−14
Imports minus exports (sej/yr)	$(F + G + P_2I) - (N_2 + B + P_1E)$	1.15E+22	6.55E+22	1.77E+22	471	54
Ratio of imports to exports	$(F + G + P_2I)/(N_2 + B + P_1E)$	1.79	2.05	1.10	14	−39
Fraction used, locally renewable	R/U	37%	11%	5%	−71	−85
Use per person (sej/person year)	U/population	1.15E+16	2.96E+16	5.51E+16	157	379
Renewable carrying capacity at present living standard	(R/U) (population)	1379820	535980	287862	−61	−79
Ratio of use to GDP, emergy/dollar ratio (sej/US$)	$P_1 = U/GNP$	2.58E+13	9.58E+12	1.67E+12	−63	−94
World renewable carrying capacity at Danish living standard		2603123322	1011162576	543194876	−61	−79

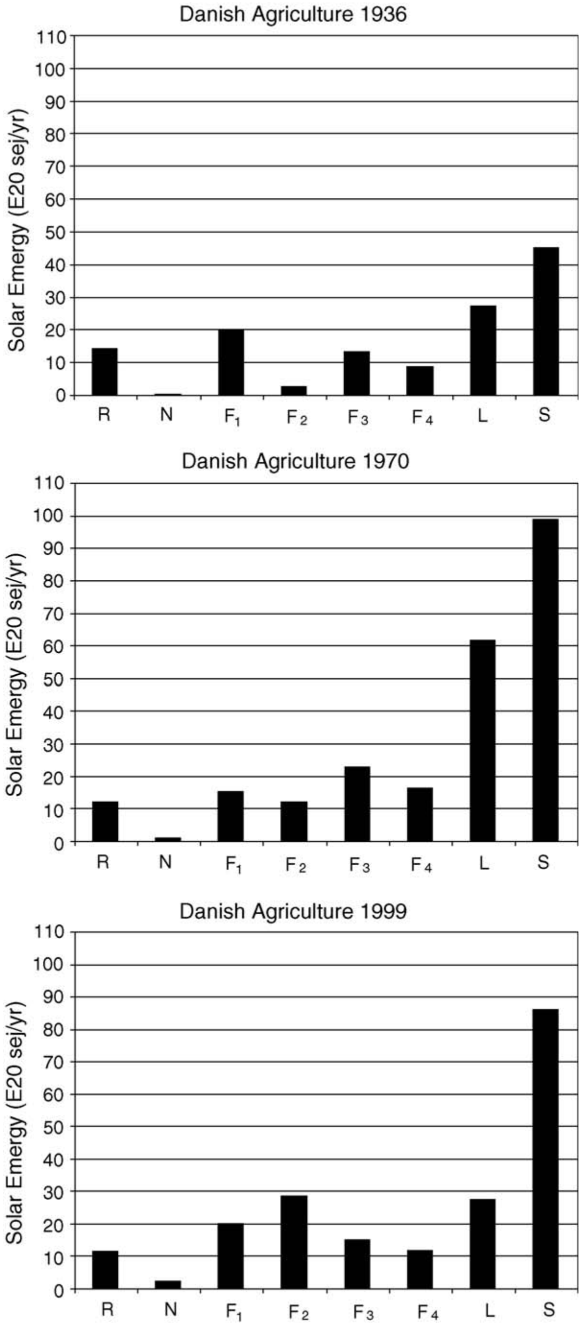

Fig. 4. Charts showing the emergy flows supporting Danish agriculture in 1936, 1970 and 1999.

fertilizers and represent a major stimulus, in emergy terms, to agricultural production in this year. Imported cereals and high protein feed concentrates for livestock production were also a major driving force for total productivity in 1936.

In 1970, the amount of locally available renewable and non-renewable emergy sources (*R*) supporting Danish agriculture decreased from 1936, and the system received 11.98E+20 sej, with evapotranspired rain again being the dominant emergy source. The amount of local non-renewable emergy (*N*) that contributed to production in 1970, in the form of soil erosion and used organic matter increased 86% from 1936. The increase is assumed to be due to changes in cropping patterns towards winter crops, which are more prone to erosion (Schjønning, 1995). In 1970, Danish agriculture was fully mechanized. No draft horses were used in production and all traction was provided by tractors and most harvesting done by combined harvesters (Statistics Denmark, 1971a,b; Schroll, 1994). Consequently, there was an increase in the quantity of purchased inputs ($F_{2,4}$) that needed to be imported from outside the system. A large increase in non-renewable emergy use stemmed from the increased use of fuel and electricity, which increased 690% from 1936 to 1970. Other large increases where from the contribution of farm assets (buildings and machinery) which expanded by 154% over the period from 1936 to 1970, inputs of fertilizer, and the introduction of pesticides which increased the total amount of emergy in purchased goods flowing to crop production by 72% from 1936. Goods purchased for livestock production declined by 24% during the same period, most likely due to increased domestic grain production.

By 1999 the agricultural system employed fewer machines than 1970. Furthermore, it employed relatively few people compared to the previous years. The renewable emergy (*R*) flowing to agriculture in 1999 was approximately the same as 1970. The estimated loss of topsoil (*N*) contributing to production increased by 164% from 1970, and was due to the large increase in winter grain farming. The commercial energy inputs to Danish agriculture was the largest increase, and in 1999, the mix of fuels used in agriculture was quite diversified with diesel, coal, gasoline, natural gas and electricity all contributing to production. The decrease in the use of farm assets (buildings and machinery) was due to a decrease in the number of tractors in use and a decrease in the number of working farms that required building maintenance.

3.3. Direct and indirect human labor in Danish agriculture

Human labor, both direct on-farm labor (*L*) and indirect labor in the form of services (*S*) represents the largest single input to all the years studied. Because emergy analysis employs a network perspective and considers that all the resources supporting human labor are a component of the production process, the emergy flowing to farm families and laborers, and from those who work in the industries that provide goods and services to the agricultural sector, are all considered to contribute to agricultural productivity and must be included in evaluations. The service and labor emergy is measured by multiplying the monetary cost of labor and services by the emergy to money ratio for each specific year. For instance, in 1936, the total value of agricultural production totaled US$ 402,000,000. By multiplying this amount by an emergy/$ ratio for the 1936 Danish economy of 1.80E+13 sej/US$, the total emergy contribution from human service was calculated

Table 3
Summary of emergy flows and their percentage change for Danish agriculture, 1936, 1970 and 1999 ($\times 10^{20}$ sej/yr)

Item	1936	1970	1999	Percent change	
				1936–1970 (%)	1936–1999 (%)
Local renewable sources (R)	14.2	12.0	11.4	−16	−20
Local non-renewable sources (N)	0.5	0.9	2.4	86	391
Goods for livestock production (F_1)	20.1	15.3	20.1	24	0
Applied energy (F_2)	2.7	21.5	28.5	689	946
Goods for crop production (F_3)	13.2	22.7	15.0	72	14
Farm assets (F_4)	5.3	13.4	4.1	154	−22
Labor (L)	27.2	61.7	27.6	127	2
Services (S)	45.2	98.7	86.0	118	90
Yield (Y)	128.4	246.2	195.1	92	52

to be 72.41E+20 sej. The emergy/\$ ratio was modified so that the emergy yielded to the economy from agriculture was subtracted from the total emergy/\$ ratio of the Danish economy at this time, to avoid double counting when services from the Danish economy is feeding back into the agricultural sector.

In 1936, a large human workforce in agriculture was coupled to an economy that was supported by much less emergy in comparison to later years. Thus, the labor of each person employed was of lower transformity. Consequently, the total emergy contribution of human service in 1936 was less than in later years, even though twice to four times as many people were directly engaged in agriculture. In 1999, each person employed in agriculture was embedded in an economy in which the magnitude of emergy support per person was much greater than previous years. Therefore, the total emergy contribution of human services in this year was greater than 1936, even with only 11% of the workforce directly employed in agriculture. In 1970, Danish agriculture was both highly mechanized in comparison to 1936, and employed a relatively large labor force when compared to 1999. Therefore, Danish agriculture in 1970 exhibited less efficiency than either 1936 or 1999 in terms total emergy per unit output (see www.cul.slu.se/information/publik/rydberg_haden.pdf for transformity calculations of Danish crop and livestock production).

The direct human labor required for agricultural production decreased from 1109 million person-hours in 1936 to 415 million person-hours in 1970, and further to 121 million person hours in 1999 (see Table 4). Over the same time period, the monetary cost of labor increased over 1000%, while the emergy/\$ ratio of the money paid to agricultural labor decreased 91%. Additionally, the emergy support for each person-hour of direct labor on-farm went up 830%. Moreover, the indirect labor support to agriculture via services increased over 1600%. In relative terms, the ratio of indirect labor emergy (S) to direct labor emergy (L) was little changed between 1936 and 1970 at 1.6–1.7, but nearly doubled from 1970 to 1999 to 3.1. This indicates a greater reliance on the labor of humans outside the agricultural system who provide information, goods and services to those directly employed in agriculture. Likewise, the ratio of the emergy of commercial energy (F_2) to direct labor emergy (L), which increased 929% over the period studied, also indicates a much greater reliance on exogenous emergy sources.

Although the intensity of agriculture has fluctuated over the years studied, the ratio of the emergy of all direct and indirect labor ($L + S$) to the total emergy invested in agriculture (Y), has fluctuated little (remaining between 0.56 and 0.65). In other words, between 56% and 65% of the total emergy invested in agriculture stemmed from the management activities of human beings, regardless of the energetic boundary conditions within which the agricultural system was nested.

3.4. Relative empower of Danish agriculture and economy

Fig. 5 is a chart showing the total emergy per year, or empower, supporting both the economy and agricultural

Table 4
A selection of flows and indices related to labor and service emergy in Danish agriculture

Item	1936	1970	1999	Percent change	
				1936–1970 (%)	1936–1999 (%)
Person-hours direct labor in agricultural production	1109577600	415480800	121270008	−63	−89
Gross economic product for agriculture (US\$)	402277778	2014997548	7281714286	401	1710
Monetary cost of direct agricultural labor (US\$)	150944444	774546547	1770454757	413	1073
Emergy/\$ ratio for agriculture (sej/US\$)	1.80E+13	7.96E+12	1.56E+12	−56	−91
Labor (L)/person-hour of direct labor (sej/h)	2.45E+12	1.48E+13	2.28E+13	506	830
Services (S)/person-hour of direct labor (sej/h)	4.08E+12	2.38E+13	7.09E+13	483	1639
Service (S)/labor (L) (or emergy of indirect to direct labor)	1.67	1.60	3.11	−4	87
Commerical energy (F_2)/labor (L)	0.10	0.35	1.03	248	929
Service and labor ($S + L$)/yield (Y)	0.56	0.65	0.58	16	3

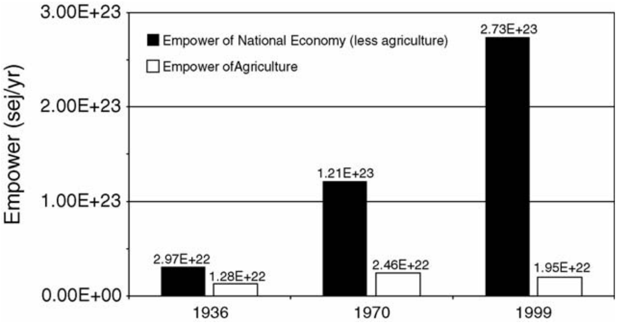

Fig. 5. Comparison of the empower of the Danish national economy (with agriculture subtracted) and Danish agricultural system for 1936, 1970 and 1999.

system of Denmark for the years studied. The figure indicates how the economy has increasingly become dependent on other emergy sources, in addition to agriculture, to run the national economy. In 1936, 30% of the total national emergy budget was invested in agricultural production, however this dropped to 17% in 1970 and then 7% in 1999. This figure gives an indication of what can be expected from agriculture as a source of emergy for the national economy, both now, and if a lower-energy future should come to pass.

4. Discussion

4.1. Emergy signature

Emergy evaluations quantify the energy and resource flow to and within a system, and thus articulate the driving forces that influence the organization of the system in question. This spectrum of energy and resource flows interacting to organize a system can be thought of as representing the ‘‘emergy signature’’ of that system (Campbell, 2000). In Denmark, the national emergy signature, represented in Fig. 1, underwent a constant expansion from year 1937 to 1999. However, the emergy signature of Danish agriculture, represented in Fig. 2, saw both expansion and contraction, as well as a redistribution of emergy throughout the signature. Over the same period, there was a commensurate change in the employment structure of Denmark, with a pronounced shift towards public service sector employment, and away from the primary industries of agriculture, forestry and fishing (Statistics Denmark, 1937, 1971a,b, 1999a,b,c). This decrease in primary sector employment indicates the changing role of agriculture for the Danish economy to one of providing less relative empower (emergy per unit time) for the Danish economy as shown in Fig. 5. This development was made possible by an increased import of goods and services and by extraction and use of local non-renewable resources. The primary sectors are restricted in their production capacity by flow-limited environmental sources. In a shorter time perspective this does not restrain the expansion of the public service sector.

The shift in societal structure from rural to urban employment and lifestyle, parallels Denmark's transition from an agricultural society, more dependent on flow-limited renewable emergy sources, to a modern industrial society primarily organized around flows from non-renewable sources. Schneider and Kay (1994) posit that evolving ecosystems develop in such a manner that they build more and more capacity to degrade incoming available energy and use that energy to build increasingly complex structures that enhance the ability of the ecosystem to ingest and degrade more energy. Odum (1994) proposes that this pattern is a general one observed in both ecological and societal systems. Indeed, in many respects, this pattern is an accurate characterization of the growth of the Danish economy over the past century.

4.2. Nation-wide reorganization for maximum empower

One reason given for the large shift of people out of agriculture and into urban areas and occupations was the shortage of labor in the urban activities. Besides this, the Danish agricultural societies fought to ensure that farmers received a monetary income that was equal to that earned by those employed in urban sectors. This was done in order for Danish farmers to enjoy the same quality of life as urban dwellers, with full access to the fossil fueled economy and its associated consumer goods. This policy placed economic pressure on the agricultural sector as a whole to rationalize labor costs, which forced many farmers out of production (Ingemann, 1999). Interpreted through the lens of emergy and the MEP, which stipulates that all systems are under evolutionary pressure to reach an optimum efficiency to maximize useful energy processing (Odum, 1996), the same phenomenon can be interpreted as process of self-organization for maximum emergy use, at the national level. It could be questioned if the income goal for the farmers increased the MEP for the society or not. But since labor was needed in the urbanization process, more labors become available through this attitude and thereby more energies could be transformed in the society.

We consider the changes in agriculture to partially stem from the nation-wide adoption of new farm technology, which we see as an emergent property of the interactions between social goals, scientific/technological advancement and the level of emergy available to the ecological-economic system within which an agricultural system is nested. Our analysis indicates that direct fossil energy inputs, its derivatives in the form of chemical fertilizers and pesticides, as well as electricity (mainly from coal, natural gas, oil), were primary driving forces behind the development of Denmark's highly industrialized agricultural system (see also Schroll, 1994). However, we also see that the shift to greater reliance on indirect labor in the form of purchased services was also very important. While causal relationships between economic pressure and political will are a valid way to explain this shift to industrialization, complex systems such as ecosystems and economic systems are constrained by energy availability and defy explanation in terms of linear causality. Implying non-linearity, the metaphor of the agricultural treadmill (Cochrane, 1993) provides insight into the processes that evolve to entrain a certain level of resource use in agricultural systems. As individual farmers adopt successively more advanced technologies that are more efficient at utilizing available emergy sources, they can produce a given product at a lower economic cost and thus out-compete their fellow farmers by undercutting them in competitive commodities markets. This process sets a new level of minimum efficiency that must be met for the average farmer to remain in production. Those farmers that cannot meet this standard often seek employment in other sectors and sell or lease out their land to those who remain in agricultural production, a process which occurred in Denmark over the period studied (Ingemann, 1999; Kristensen, 1999). This is a well know trend going on in many countries besides Denmark.

In order to understand this shift in energetic terms, we turn to Lotka (1922a,b), who offered a thermodynamic interpretation of Darwinian natural selection that posits competition for available energy as a selection pressure constraining the development of natural systems—restated by Odum as the maximum empower principle (Odum, 1996). Applying this perspective to economic change, Buenstorf (2000) indicates that the Lotka–Odum principle opens two viable strategies, efficiency and innovative specialization for competing organisms, as well as economic organizations. Further, Buenstorf suggests that ‘organisms are favored which can utilize forms of energy flows for which no competition exists because other species are not capable of exploiting them’ (Buenstorf, 2000, p. 121) and that ‘selection favors organisms which can use contested energy flows more efficiently than their competitors for the preservation of the species’ (Buenstorf, 2000, p. 121). If we assume the metaphor of farm as organism, there is evidence that the two strategies of competing organisms – efficiency and innovative specialization – describe the survival strategies of modern farms quite well. Djurfeldt and Waldenström (1999), in their research on survival strategies of Swedish farm households, identify three basic survival strategies: pluriactivity (the development of multiple income streams, a form of innovation), intensification of production (towards specialization), or the adoption of new technology (generally to increase efficiency). A parallel process seems to have occurred in Denmark (Ingemann, 1999; Porter and Petersen, 1997), and we suggest this process is more a general process in which the agricultural sector has adjusted to changing boundary conditions with respect to available emergy.

Because most non-renewable emergy sources fueling industrial economies have high net emergy yields, and have not been valued in monetary terms at a level commensurate with their emergy contribution (Odum, 1996), they have been cheaply available. Farmers that organized their operations to draw on high yield emergy sources were able to displace their fellow farmers who continued to organize their farming systems around local renewable emergy flows to greater degree—a process observed in Denmark as a fairly rapid shift from horse-powered farming to fully mechanized farming. As stated by Odum: ‘As greater energies become available through trade for fuels or for goods and services based on fuels, agriculture becomes based increasingly on inputs from sales of crops and less on the environmental energies of sun, wind, rain and soil. Cash crops begin to replace diverse farms’ (Odum, 1994, p. 519). This was the observed trend in Denmark as well as many other industrialized nations.

By converting their operations to draw on non-renewable energy sources that contribute much greater emergy than could be generated through local on-farm sources, the Danish farmers that mechanized first were able to out-compete their counterparts relying mainly on horse and human energy. The displacement of horse-drawn agriculture by mechanized agriculture is partially represented by the ratio of commercial energy (F_2) to direct labor (L), which between 1936 and 1999 increased from 0.10 to 1.03; a 929% increase. In 1970, when the majority of Danish farmers were reliant on non-renewable imported emergy, the efficiency selection principle became operative—i.e. the efficient use of imported emergy sources became a factor in the ongoing survival of the species (the farm). This process is evidenced by the decrease in the number of farms, the decrease in the number of farmers, and the increase in the size of farms in Danish agriculture (Statistics Denmark, 1999b). As this process unfolded during the period studied, those farmers who were displaced from agriculture and who subsequently relocated to urban areas often took jobs in the energy-intensive manufacturing and service sectors. Urban service jobs reside higher in the energy transformation hierarchy of society than agricultural labor (Odum, 1996), and thus require larger emergy support for each job held, and allow for more emergy to be drawn into the national economy through trade with the global economy. Odum (1996) suggests that the maximum empower principle (MEP) will tend towards self-organization in ecological-economic systems such that they will maximize their use of available emergy. When considered as coupled systems, the mechanization of Danish agriculture and the shift in employment towards the urban sector was a reorganization for maximum empower on a national scale that allowed Denmark to achieve much higher levels of emergy use than could be supported from domestic resources alone.

4.3. Looking forward

Many neoclassical economists argue that market forces will never allow the world to run out of the fossil energy upon which industrial society and its forms of agriculture are based. However, some petroleum geologists suggest that we may be nearing the peak of world petroleum production (Campbell and Laherrère, 1998; Deffeyes, 2001). After the world petroleum production peak, society will be forced to seek new, less energy demanding patterns of economic organization as the total amount of energy available to fuel to the economy declines (Odum and Odum, 2001). Based on our analysis, we suggest that agriculture can never be a primary emergy source for an industrialized nation. Therefore, we suggest that the current relative abundance of energy for societal needs including agriculture, may have inspired overly optimistic plans calling for modern agricultural systems to provide such things as transportation fuels in addition to food and fiber (Berndes et al., 2001; Hall and Scrase, 1998). While we concur that the future of society will include an expanded role for agriculture, our interpretation of energy systems theory (Odum, 1994, 1996) indicates that considering agriculture to be a multifunctional livelihood system for human beings with human food its primary output, and tailoring policy with this in mind, may be the strategy that maximizes empower for society in the long-term. We do not mean to imply that lower energy availability will necessarily lead society and agriculture to revert to historical patterns, i.e. horse farming, but rather that the resource use trends observed in Danish agriculture over the studied period may not continue in the face of declining access to high-emergy-yield energy sources, and new patterns of farming are likely to emerge that will fit somewhere between the agriculture of today and previous eras. Addressing energy resources and the policy domain, Odum and Odum (2001) offer a blueprint for a ‘‘prosperous way down’’, a primary component of which is an increase in rural employment for those not employed in useful urban work, based on assumptions of long-term nonrenewable resource shortages. This suggests a future in which the countryside regains salience in the minds of the urban majority, and agricultural and forestry may once again be perceived as a source of cultural sustenance, not simply consumer products.

5. Conclusions

Based on the results of the emergy analyses of Denmark and Danish agriculture 1936, 1970, and 1999, we find that agriculture remains an essential way for industrial economies to harness local renewable resources. Furthermore, the relationship of agriculture to non-agricultural sectors is mutually supportive, evidenced by the amount of off-farm services that agriculture requires; a fact not adequately represented by direct on-farm labor requirements. Emergy evaluations include all human services purchased through off-farm trade that support agricultural production, because not doing so might allow the conclusion to be drawn that the farmer is the sole source of labor responsible for agricultural productivity. Today, farmers often work alone in the field, but there is a diverse service network of people and industries providing necessary support to each farmer. Furthermore, we see that in the Danish context, there has been a relatively constant relationship between the amount of human labor (both direct and indirect) and the physical resources invested in the agricultural sector. Since this relationship was observed over a 63-year time scale, it may reflect the maximum empower principle, and be thermodynamically constrained.

Given the limited net emergy yields of agricultural production, the magnitude of non-agricultural economic activity that agricultural systems can support appears limited in an economy with access to high-net-yield imported energy resources. The emergy evaluations suggest that agricultural systems cannot be a primary emergy source to an economy with access to sources of cheap fossil fuels. However, agriculture is the primary means by which humans access the ecological systems they inhabit, and being that food is a qualitatively unique resource, it will always be grown, and will continue to be a source of biological, cultural and economic sustenance for nations. Moreover, a thriving agricultural sector, with a large proportion of a national population engaged in the growing of food, is possible when accessibility to sources of high net-yield fossil energy is limited. If societal access to high yielding emergy sources should decrease, agriculture, as the most time-tested means of capturing and channeling renewable energy for societal use, can once again be the primary domicile of a nation's economy and culture.

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