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Comparison of horse and tractor traction using emergy analysis

Torbjörn Rydberg *, Jan Jansén

Department of Ecology and Crop Production Science, Swedish University of Agricultural Sciences, Box 7043, SE-750 07 Uppsala, Sweden

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Abstract

Horse traction in the context of Sweden 1927 and tractor traction in the context of Sweden 1996 were compared in terms of their resource requirements. Flows of energy, material and service from the environment and the economy were identified for the two traction-producing systems. The environmental work and human activity involved in generating necessary inputs for the systems were evaluated on a common basis, using emergy analysis. The main difference between the systems was found in their energy signature. Sixty percent of the horse inputs were renewable, compared with only 9% renewable inputs for the tractor. Ecological technology was replaced by mechanical technology. This represented a shift from a technology that was maintained and driven by mainly locally-generated qualities and driven on local flow-limited renewable sources to a technology controlled and supported by non-local processes and driven on non-renewable sources. A decrease in available fuels and minerals might cause a change in the choice of technology and ecological technology might then be reintroduced into our society as a whole and not only into the agricultural sector. Evaluating management strategies that consider direct and indirect requirements for natural resources from the economic system and 'free' natural resources from the environment currently requires a method able to integrate both. Emergy analysis provides that ability.

Keywords: Ecological technology; Emergy analysis; Animal power; Sustainability; Tractor traction

1. Introduction

A major question of natural resource management is how to integrate economic use activities with supporting ecosystems in order to achieve sustainable performance of the combined system of the environment and mankind (Hall et al., 1986; Daly and Cobb, 1989; Odum, 1993). Ecological economic methods with the ability to evaluate environmental services provided both by ecosystems and economic inputs are needed.

In the quest for sustainability, agriculture plays a central role as one of the main converters of sunlight energy into commodities and services re-

* Corresponding author. Address: Centre for Sustainable Agriculture, Swedish University of Agricultural Sciences, Box 7047, SE-750 07 Uppsala, Sweden. Tel.: + 46-18-67-29-11; fax: + 46-18-67-35-71.

E-mail address: torbjorn.rydberg@evp.slu.se (T. Rydberg).

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quired by the human economy. A study of farming systems practised at different times in Sweden in the 20th Century (Jansén, 2001) illustrates a massive change in dependency on external sources. An example is increased use of fossil fuel for food production during the conversion from the horse to motorised farming. In the past, farm production depended mainly on local resources and produced largely for subsistence and the local market. Currently, farming in Sweden is characterised by a more specialised division of production tasks and dependency on larger markets and energy and materials from non-renewable stores. While this development came about in the era of cheap and plentiful energy, it also led to a 13-fold increase in the external energy input. Total agricultural production in 1981, however, was only 2.4 times that in 1927 in the area studied (Jansén 2001). A major part of the increased dependence on external sources is due to the mounting dependence on combustion engines. Increased dependency on external inputs leaves the population at local and regional level vulnerable to shortages, market fluctuations and finite stocks, and means a loss of local control for people.

In response to increased concerns about the dependency on finite energy sources, numerous studies aimed at clarifying direct and indirect use of energy in agriculture have been made (Pimentel et al., 1973; Leach, 1976; Fluck, 1992; Uhlin, 1999). These studies mainly take into account the direct and indirect uses of fossil fuel, and use the heat value of the fuel as a common denominator for quantification and comparisons. Although some attempts have been made to deal with different kinds of fossil fuels (Cleveland, 1992), different energy forms are usually not recognised within the concept of energy analysis.

If only one form of energy is considered, the use of the conventional definition of energy gives meaningful results. For meaningful analyses of processes dealing with energy of different kinds, however, other methods are required. This is in part because energy of one kind is often not equivalent in its ability to do work to energy of other kinds (Odum, 1984). Energy analysis therefore has serious limitations for efforts to evaluate interactions between human society and nature, as this is much more than a question of fuel (Ulgiati et al., 1994). Since all different kinds of energies are capable of supporting very different types of work per unit of energy, evaluation cannot be based on heat values of the resources and processes. Human labour, information and expensive technological devices are examples of energies that have relatively small energy flows compared to environmental energies like sunlight, but very high flows of environmental energies are needed for their formation and maintenance. These types of energies are of a higher quality because they have a greater ability to feed back and amplify other flows (Odum, 1988). In energy and economic analyses, resources outside the monied economy are usually considered to be externalities and free, and are not quantified. Renewable energies like sun, wind, rain and tides are necessary in all economics and make up a significant portion in most products and processes (Brown et al., 1995). Emergy accounts for and measures the different forms of energy on a common basis by recognising that energy hierarchies develop as a result of the organisational structure of systems, where energy transformation processes are organised in 'webs' that converge and concentrate the energies into fewer and larger scale processes. Through the series of energy transformations, the final product carries less energy than the amount invested to generate it due to energy transformation losses. However, the high position in the hierarchy makes it more valuable due to the convergence of resources it took to support the process. Emergy analysis also measures both economic variables and ecological systems. Emergy is a quantitative measure of the resources required to develop a product, whether it is a mineral resource, a biological resource or a commercial product and it expresses the resources in units of one type of energy, usually, solar energy.

In this study we compared a mainly ecological technology with a mechanical technology. The shift from animal-powered traction to tractor traction was investigated, as an example of a shift from humans employing living systems to humans employing mechanical systems.

The horse is a living system that gets its support for maintenance and reproduction mainly from renewable local energy in plants and water. The traction that the horse produces is one of its functions, but, like other living systems, the horse is multifunctional. Using resources from the local environment it is self-recruiting, it produces manure, meat and hide, and through grazing it contributes to the maintenance of a multifunctional landscape. The additional needs for a horse to deliver useful traction, (e.g. tools, harness, and human care), are relatively limited.

The tractor is a mechanical device that is constructed outside the local ecosystem. The energy required for its use, production and maintenance is mostly of a non-renewable character. Different types of pollutants and waste are generated when the tractor is used, and negative environmental effects are also linked to the entire chain of production from mining of metals to use and reuse of metals and degraded wastes.

For a comprehensive comparison of essential sustainability parameters, a method that facilitates quantification of both environmental services provided by ecosystems and economic inputs was used. The aim of this comparison was to:

- Identify and quantify the amounts and qualities of energy needed directly and indirectly to produce traction, either by a typical horse in the context of Sweden 1927 or by a typical tractor in the context of Sweden 1996.
- Assess the ratio between the use of local renewable resources and purchased resources, and renewable resources embodied in purchases, in the same cases.
- Discuss implications for long-term sustainability between the choice of different technologies.

2. Materials and methods

2.1. Method

Emergy analysis, a quantitative evaluation technique that determines the value of nature's input to the human economy (Odum, 1988), was used. Emergy is a measure of direct and indirect supporting energy needed in different work processes supporting a product or a service, using a common unit. For a comprehensive description of the methodology we refer to Odum (1988, 1994, 1996). Brown and Herendeen (1996) also clarify the methodology through discussing differences and similarities between embodied energy analysis and emergy analysis. The basic unit of measurement used is usually solar joules; the accumulated amount of these used up in the chain behind a good or a service denotes its emergy value, and is counted as Solar Emergy Joules, abbreviated sej. The solar transformity for an item is the solar emergy per unit available energy (sej/J) or weight (sej/g). The ultimate system boundary of the analysis is the main energy sources behind all transformations in the geobiosphere, that is the sun, the tides and the deep heat from inside the earth. In emergy analysis, all processes are treated as nested to environmental processes outside the analytical window, so all definitions are therefore related to overriding energy systems networks.

The amount of indirect emergy inputs through service and labour is assessed via their monetary value, as money spent in the economy always purchases human service. The amount of emergy that supports each unit of money in circulation in a specific year is calculated from the national economy, as an emergy to money ratio.

To assess the emergy in the service component of purchased inputs and labour costs in our horse traction system, operating in the Swedish economy in 1927, we calculated the emergy to money (SEK) ratio for that year. From national statistics, we collected information about the environmental resources needed for the entire nation to produce wealth and converted those flows into solar emjoules for the year of interest. The emergy use was divided by the money circulating for that year (gross domestic product, GDP). The emergy–money ratio measures the average buying power of the money for that year and that country. A study by Lagerberg et al. (1999) of the emergy to money ratio for the Swedish economy in 1996 provided the corresponding figures for the tractor alternative. Our data sources, selected economic and agricultural statistics, calculations and estimates are specified as Notes to the analysis tables.

2.2. Objects studied

The evaluation concerned the emergy needed to generate traction, measured in joules at the hitch-point, that is where different types of farming equipment are attached. Data regarding farm production were taken from an earlier study (Jansén, 2001) of the farming in a specific rural area, Viksta parish in southern Sweden.

The working horse was assumed to be active in the context of a Swedish farm in 1927 and, like average horses in the area and time, to serve 8.4 ha. Its live weight was 700 kg, and allowance was made for its recruitment requirements. For 150 days hard work and 50 days light work, for maintenance and recruitment, it needed 3290 kg hay and 2100 kg oats. Emergy evaluation on hay and oat production in the context of Sweden 1927 was performed. With the yield levels of 1927 Viksta, this meant that to sustain a working horse 0.9 ha clover/grass crop for hay and grazing and 1.2 ha oats were required. The horse's draught power contribution was 0.7 kW, on average through 1200 h/yr. For feeding and care the horse required 60 man-days/yr, for work a driver (2 horses/driver) was needed for another 600 man-hours (computations are given in Table 5 footnotes).

As a reasonable representative for typical farm traction in Sweden 1996, we chose a 65 kW, 4000 kg tractor, at a cost of 360 000 SEK, serving 38 ha/yr. It was assumed to be completely depreciated in 15 years. Tractor fuel consumption was 80 l/ha. The tractor was used 300 h/yr, and additional 30 man-hours were needed for care and maintenance. It contributed, as drawbar traction under field conditions, on average 21 kW (computations are given in Table 6 footnotes).

3. Results

3.1. Sweden's natural resource base

Fig. 1 is a systems diagram of Sweden that summarises the annual resource flows and the GDP in 1927. Inflows of emergy that support the systems processes are drawn as solid lines, and currency flows are shown as dotted lines, drawn in the opposite direction to resource flow. The GDP was 8446 MSEK, and the renewable environmental resources were found to account for 54% of

Table 1
Summary of emergy and monetary flows for Sweden 1927 and 1996

Symbol in Fig. 1	Item	Units	1927[a]	1996[b]
R	Renewable resources used (*R*)	E+22 sej	4.5	4.8
N	Non-renewable indigenous sources (*N*) ($N = \mathrm{N1} + \mathrm{N2}$)	E+22 sej	2.5	5.8
N1	Concentrated use (N1)	E+22 sej	1.0	4.3
F	Imported fuels and minerals (*F*)	E+22 sej	0.9	7.9
G	Imported goods (*G*)	E+22 sej	0.3	7.0
I	SEK paid for imports (*I*)	E+09 SEK	1.6	447.6
P2I	Emergy value of imported service (P2I)	E+22 sej	1.6	12.0
	Total import ($F+G+\mathrm{P2I}$)	E+22 sej	2.8	26.9
U	Total emergy used ($R+\mathrm{N1}+F+G+\mathrm{P2I}$)	E+22 sej	8.4	36.0
N2	Exported without use (N2)	E+22 sej	1.5	1.5
E	SEK received for exports (E)	E+09 SEK	1.6	569.5
P1E	Emergy value of exported services (P1E)	E+22 sej	1.6	12.2
B	Emergy value of products transformed in Sweden (*B*)	E+22 sej	0.6	8.4
	Total export ($B+\mathrm{N2}+\mathrm{P1E}$)	E+22 sej	3.7	22.1
X	GDP	E+09 SEK	8.4	1678.4
P2	Emergy/money ratio used for imports (P2)	E+12 sej/SEK	10.0	0.3
P1	Emergy/money ratio used for Sweden and exports (P1)	E+12 sej/SEK	10.0	0.2

[a] Own calculations.
[b] Lagerberg et al. (1999).

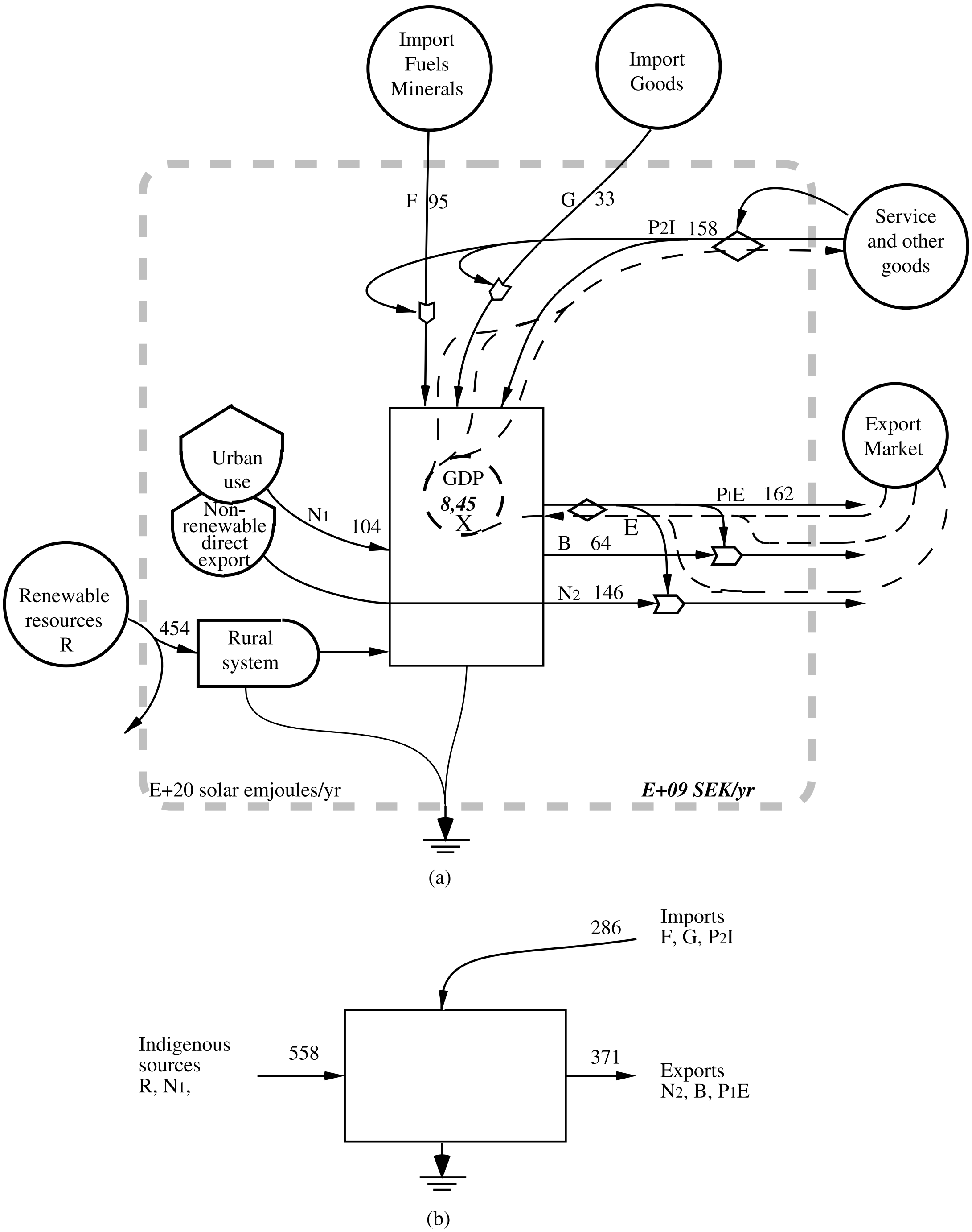

Fig. 1. Aggregated diagram of the Swedish economy 1927 showing a summary of its resource base, imports, exports and GDP. (a) Main flow of solar emergy and money. (b) Aggregated diagram showing indigenous sources, imports and export flow of emergy. Letters are explained in Table 1.

Table 2
Indices of resource use in Sweden, 1927 and 1996

Name of index	Expression	Units	1927[a]	1996[b]
Resource inputs:				
Indigenous renewable	R/U	%	54	13
Indigenous non-renewable	N1/U	%	12	12
Imported fuel and electricity	F/U	%	11	22
Imported goods	G/U	%	4	19
Imported services	P2I/U	%	19	33
Electricity used	electricity/U	%	1	18
Trade:				
Imports	$F+G+$P2I	E+22 sej/yr	2.9	26.9
Exports	N2+B+P1E	E+22 sej/yr	3.7	22.2
Ratio of imports to exports	($F+G+$P2I)/(N2+B+P1E)		0.8	1.2
Imports–exports	($F+G+$P2I)–(N2+B+P1E)	E+22 sej/yr	−0.9	4.7
Per capita:				
Population	pop	E+6 persons	6.1	8.8
Total resource use/person	U/pop	E+15 sej/capita	13.9	40.7
Fuel use/person	(F-uranium-electricity)/pop	E+15 sej/capita	1.2	7.6
Electricity use/person	(electricity)/pop	E+15 sej/capita	0.2	7.2
Renewable carrying capacity	(R/U)(pop)	E+6 people	3.3	1.2
Carrying capacity using local resources	($R+N$)/U)(pop)	E+6 people	5.1	2.6
GDP/person	GDP/pop	SEK	1387	198811
Resource-use indices:				
Imports to local resources	($F+G+$P2I)/($R+N$)		0.5	3.0
Environmental loading ratio	($F+G+$P2I$+N$)/R		1.2	6.9

[a] Own calculations.
[b] Lagerberg et al. (1999).

the annual emergy budget, Table 1 and Table 2. Of the non-renewable resources, fuels and minerals drawn from stocks within the country, some, N1, are processed and used in Sweden and some, N2, are exported without further processing. N1 accounted for 12% of the annual emergy flows. The export of emergy from Sweden is the sum of N2, processed products in Sweden (B) and the emergy embodied in service (P1E). Imports are aggregated into fuels (F), goods, (G) and services (P2I) and in 1927 contributed 11, 4 and 19% of the total, respectively.

A comparison of our results with those of Lagerberg et al. (1999) is given in Table 1 and Table 2. While the 1996 GDP, quantifying the annual production of goods and services in monetary terms, was almost 200 times that of 1927, the emergy budget of Sweden in 1996 was four times larger than in 1927. There was almost a 10-fold increase of emergy in the import of fuels, goods and service to the nation. The national use of non-renewable internal resources (N1) was 4 times larger in 1996 than in 1927, while the exports of unprocessed non-renewable resources (N2) was the same size in both years. Due to the increased import of natural resources, the locally renewable share dropped to 13% of the total emergy contribution in 1996, from 54% in 1927. The emergy to money ratio dropped from 9.99E + 12 sej/SEK 1927 to 0.2E + 12 sej/SEK 1996, an inflation with each unit of currency supported by less resource use.

A trade deficit in emergy terms of 0.85E + 22 sej in 1927 turned into a trade surplus of 4.7E + 22 sej in 1996. The population increased by 44% from 6.1 million to 8.8 million, and the resource use per capita by almost 300%, from 13.7E + 15 to 40.7E + 15 sej/person.

Both the renewable carrying capacity, i.e. the renewable emergy (R) in proportion to the total emergy (U) per capita, and the carrying capacity using local resources, i.e. renewable plus non-renewable emergy ($R+N$) in proportion to total emergy (U) per capita, decreased considerably from 1927 to 1996. Both the ratio of imports to local resources (($F+G+$P2I)/($R+N$) and the environmental loading ratio (the purchased emergy plus non-renewable use ($F+G+$P2I$+N$) in proportion to renewable resources used (R)), increased about 6-fold from 1927 to 1996.

3.2. Horse traction

The emergy evaluations on hay and oat production are presented in Table 3 and Table 4 and form the basis for the emergy analysis for the horse. The system producing horse traction is presented diagrammatically in Fig. 2, and the emergy evaluation is given in Table 5. The amount of emergy required for generation of traction, driver included, was found to be 1.87E+6 sej/J. Water, seed, wood and leather are considered as local renewable and they accounted for

Table 3
Emergy evaluation for 1 ha of oats in Viksta, Sweden 1927

Note, item, unit	Annual flow(raw units)	Transformity*(sej/unit)	Solar emergy × E+12
Renewable energy sources			
(1) Sunlight, J	2.72E+13	1.0E+0[a]	27.2
(2) Rain, chemical energy, J	1.56E+10	18.2E+3[a]	283.9
Goods			
(3) Seed, J	4.01E+09	12.7E+3[c]	51.0
(4) Machinery, steel, kg	8.70E+00	3.0E+12[f]	26.1
(5) Machinery, wood, J	2.87E+07	3.8E+3[b]	0.1
(6) Buildings, wood, J	1.49E+08	3.8E+3[b]	0.6
(7) Harness, leather, J	2.88E+07	4.5E+05[c]	12.9
Labour and service			
(8) Labour, SEK	5.09E+01	8.5E+12[c]	430.1
(9) Machinery, SEK	1.51E+01	8.5E+12[c]	127.6
(10) Buildings, SEK	2.10E−01	8.5E+12[c]	1.8
(11) Harness, SEK	3.49E+00	8.5E+12[c]	29.5
(12) Seed, SEK	4.20E+01	8.5E+12[c]	354.9
Output			
(13) Oats, J	2.95E+10	44.7E+3	1318.5

(1) Sunlight, average insolation 1961–1990 at Ultuna 943 kWh/m^2 (National Atlas of Sweden, 1995). Energy received on land/ha = 10 000 m^2/ha × 943 kWh/m^2 × 3.6E6 J/kWh × (1–20) (1-albedo) = 2.72448E13 J, (2) *Rain:* Average annual precipitation 1901–1930 at Uppsala 544 mm/yr. Evapotranspiration rate from spring sown crops, 58%. Energy in rain = area × evapotranspired rain (m) × weight (kg/m^3) × Gibbs free energy. 10 000 m^2 × 0.316 m × 1000 kg/m^3 × 4940 J/kg = 1.56E10 J/ha, (3) Seed, 200 kg/ha, 4790 kcal/kg, 4.19 kJ/kcal = 4.01E9 J, (4) Machinery, 8.7 kg steel/ha, (own calculations based on weight, hours in use/ha and durability of the machines), (5) Wood in implement and machinery 1.5 kg, (own calculations based on weight, hours in use/ha and durability of the machines), 19.1 MJ/kg = 28.7 MJ, (6) Wood building for two horses, 4 × 4 m^2 estimated to 7 m^3 of wood/horse. 525 kg dry matter/m^3 gives 3675 kg DM wood/horse. Depreciated in 50 years and 1200 hours horse use/yr gives 0.06 kg wood/horse and hour. 130 horse-hours/ha, 19.1 MJ/kg/DM gives 149 MJ, (7) *Harness:* Assumed, 20 kg harness, depreciated in 10 years and 1200 hours work/yr: 0.014 kg/hour. 130 horse-hours/ha gives 1.82 kg harness/ha. 15.8E6 J/kg gives 28.76E6 J. Transformity estimated to be one magnitude higher than oats in this study, (8) *Labour:* 120 h/ha/yr, Nannesson (1936) at 4.24 SEK/10/man-hour, Statistisk årsbok (1928), gives 50.9 SEK, (9) Machinery, depreciation cost, 15.1 SEK/ha/yr, (own calculations based on price, hours in use/ha and durability of the machines), (10) Building, depreciation cost, 7.8 kg, see Note 6. Price for lumber (Sveriges Officiella Statistik, 1929) 27.4 SEK/ton = 0.21 SEK, (11) Harness, depreciation cost, 1.82 kg/ha, see note 7. Leather price 1.92 SEK/kg (Sveriges Officiella Statistik, 1929) = 3.49 SEK/ha, (12) Seed cost, assumed same price as wheat grain (Sveriges Officiella Statistik, 1927), 0.21 SEK/kg × 200 kg/ha = 42 SEK/ha, (13) Yield of oats 1.73 ton/ha, at 85% DM and 4790 kcal/kg/DM, 4.19 kJ/kcal gives 29.5 GJ.

* Transformity from: [a]Odum (1996); [b]Doherty (1995); [c]this study; [f]Odum et al. (1983).

Table 4
Emergy evaluation for 1 ha of hay in Viksta, Sweden 1927

Note, item, unit	Annual flow (raw units)	Transformity* (sej/unit)	Solar emergy × E+12
Renewable energy sources			
(1) Sunlight, J	2.72E+13	1.0E+0[a]	27.2
(2) Rain, chemical energy, J	2.12E+10	18.2E+3[a]	385.8
Goods			
(3) Seed, J	5.32E+05	27.0E+3[c]	0.0
(4) Machinery, steel, kg	6.20E+00	3.0E+12[f]	18.7
(5) Machinery, wood, J	4.01E+07	3.8E+3[b]	0.2
(6) Buildings, wood, J	6.88E+07	3.8E+3[b]	0.3
(7) Harness, leather, J	1.33E+07	4.7E+05[c]	6.3
Labour and service			
(8) Labour, SEK	2.83E+01	8.5E+12[c]	239.1
(9) Machinery, SEK	1.08E+01	8.5E+12[c]	91.3
(10) Buildings, SEK	1.00E−01	8.5E+12[c]	0.8
(11) Harness, SEK	1.61E+00	8.5E+12[c]	13.6
(12) Seed, SEK	1.47E+00	8.5E+12[c]	12.4
Output			
(13) Hay, J	5.67E+10	13.6E+3	768.5

(1) Sunlight, average insolation 1961–1990 at Ultuna 943 kWh/m^2 (National Atlas of Sweden, 1995). Energy received on land/ha = 10 000 m^2/ha × 943 kWh/m^2 × 3.6E6 J/kWh × (1-20) (1-albedo) = 2.72448E13 J, (2) *Rain:* Average annual precipitation 1901–1930 at Uppsala 544 mm/yr. Evapotranspiration rate from clover grass 79%. Energy in rain = area × evapotranspired rain (m) × weight (kg/m^3) × Gibbs free energy. 10 000 m^2 × 0.544 m × 1000 kg/m^3 × 4940 J/kg = 2.69E10 J/ha, (3) *Seed:* 21 kg/ha, 3 year hay gives 7 kg/ha/yr, energy content of seed 4327 kcal/kg, 4.19 kJ/kcal gives 7 × 4327 × 4.19 = 5.32E+5 J, (4) Machinery, 6.2 kg steel/ha/yr, (own calculations based on weight, hours in use/ha and durability of the machines). Transformity, Odum et al. (1983) service excluded, (5) Wood for machinery, (own calculations based on weight, hours in use/ha and durability of the machines). 2.1 kg wood/ha/yr × 19.1 MJ/kg = 40.1 MJ, (6) Wood building for two horses, 4 × 4 m^2 estimated to 7 m^3 of wood/horse. 525 kg dry matter/m^3 gives 3675 kg DM wood/horse. Depreciated in 50 years and 1200 hours horse use/yr gives 0.06 kg wood/horse and hour. 60 horse-hours/ha, 19.1 MJ/kg/DM gives 68.8 MJ, (7) *Harness:* Assumed, 20 kg harness, depreciated in 10 years and 1200 hours work/yr: 0.014 kg/h. 60 horse-hours/ha gives 0.84 kg harness/ha. 15.8E6 J/kg gives 13.27E6 J. Transformity estimated to be one magnitude higher than oats in this study, (8) *Labour:* 60 h/ha/yr, Nannesson (1936) at 4.72 SEK/10 man-hour, (Sveriges Officiella Statistik, 1929), gives 28.3 SEK, (9) Depreciation cost of machinery, 10.8 SEK/ha, (own calculations based on price, hours in use/ha and durability of the machines), (10) Depreciation cost of building, 3.6 kg see Note 6. Price for lumber (Sveriges Officiella Statistik, 1929) 27.4 SEK/ton = 0.10 SEK, (11) Depreciation of harness, 0.84 kg/ha, see note 7. Leather price 1.92 SEK/kg (Sveriges Officiella Statistik, 1929) = 1.61 SEK/ha, (12) Seed cost, assumed same price as wheat grain in (Sveriges Officiella Statistik, 1927), 0.21 SEK/kg × 7 kg/ha = 1.47 SEK/ha, (13) Yield of hay 3.63 ton/ha, at 85% DM and 4385 kcal/kg/DM, 4.19 J/cal gives 3630 kg × 0.85 × 4385 kcal/kg × 4.19 kJ/kcal = 5.669E+10 J.

* Transformity from: [a]Odum (1996); [b]Doherty (1995); [c]this study; [f]Odum et al. (1983).

15% of the total emergy inputs to the horse. We are able to estimate the portion of renewable emergy supporting labour and service from the emergy evaluation made on Sweden 1927. On this scale, 54% (Table 2) of the emergy was local renewable. Since the emergy for labour and services for the horse was responsible for 83% of the total emergy, 54% of this could also be considered renewable. This made altogether a fraction of 60% renewable emergy for the horse.

A horse does not only generate traction. In addition to its ability to repair and regenerate, it has the ability to learn and build up experiences useful in different kinds of farm work and it also produces meat, leather and manure. Manure is a feedback to the feed crops and to avoid double counting it was not counted. Leather is also a co-product of the system and cannot therefore be added as a source. Thus only the service involved in processing hides to leather products was accounted. The transformity for the horsemeat, a by-product to traction, was 6.7E + 6 sej/J.

3.3. Tractor traction

The tractor traction is presented in a systems diagram in Fig. 3 and the emergy evaluation is given in Table 6. The emergy support for traction, under the conditions assumed as representative for Sweden 1996, was found to be 1.2E + 6 sej/J, driver included. There were no local renewable sources used to produce tractor traction. Emergy in fuel and lubricant accounted for 27% of the total emergy and the emergy support for services associated with fuel and lubricants accounted for an additional 11%. Emergy for all services and labour accounted for 68% of total emergy, 26% of which represented the driver's salary. The tractor has no direct renewable energies, but there was only a portion of indirect renewable energies. The emergy analysis for Sweden 1996 shows that the renewable emergy sources accounted for 13% of the total emergy for Sweden. Therefore 13% of the emergy for labour and services for tractor traction, which was 68%, could be considered as indirect renewable emergy. That makes 9% of the total emergy input for tractor traction.

3.4. Comparison

Comparing the two different ways to generate traction, Table 7, shows that the total amount of emergy required behind a unit of traction energy was somewhat larger for the horse than for the tractor system. However, since the traction energy input/ha in typical 1996 farming was 67% larger than in 1927, more emergy was required per ha in the tractor case.

The major difference between the two systems is identified in the emergy signature for the different strategies presented in Fig. 4. Most energies supporting the horse have lower transformities and are more locally generated than the energies supporting the tractor. Through aggregating emergy inputs and considering direct and indirect emergy flows, we found the horse traction system to be supported by 60% from renewable emergy sources, the tractor traction system by only 9% from renewable sources.

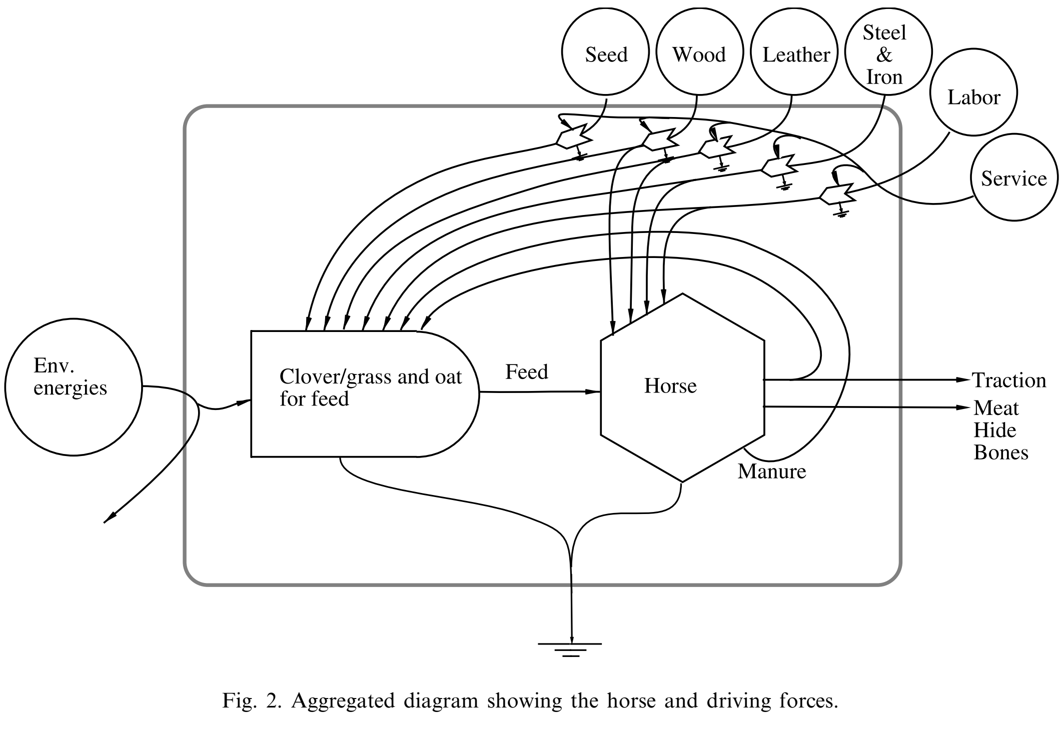

Fig. 2. Aggregated diagram showing the horse and driving forces.

Table 5
Emergy evaluation for one horse including recruitment serving 8.4 ha

Note, item, unit	Annual flow (raw units)	Transformity * (sej/unit)	Solar emergy (E+13 sej)
Renewable energy sources			
(1) Sunlight via feed, J	5.8E+13	1[a]	6
(2) Water, chemical energy, J	3.8E+10	1.8E+04[a]	70
Goods			
(3) Wood, J	1.5E+09	3.8E+03[b]	1
(4) Seeds, J	5.0E+09	1.3E+04[c]	6
(5) Leather, J	4.7E+07	4.7E+05[c]	2
(6) Steel and iron, J	2.0E+07	5.9E+06[d]	12
Labour and service			
(7) Wood, SEK	2.10	8.45E+12[c]	2
(8) Seeds, SEK	52.10	8.45E+12[c]	44
(9) Leather, SEK	6.60	8.45E+12[c]	6
(10) Steel and iron, SEK	37.90	8.45E+12[c]	32
(11) Farm labour, SEK	201.00	8.45E+12[c]	170
(12) Veterinary care, SEK	2.10	8.45E+12[c]	2
(13) Driver, SEK	254.00	8.45E+12[c]	215
Outputs			
(14) Traction, J	3.02E+09	1.85E+06	558
(15) Meat, carcass, J	8.48E+08	6.58E+06	558

(1) Average insulation 1961–1990 at Ultuna 943 kWh/m^2 (National Atlas of Sweden, 1995). Energy received on land/ha = 10 000 m^2/ha × 943 kWh/m^2 × 3.6E6 J/kWh × 0.20 (1-albedo) = 2.72E13 J/ha. (0.91 ha hay 1.21 ha oats) × 2.72E13 J/ha = 5.77E13 J, (2) *Water: Rain:* Average annual precipitation 1901–1930 at Uppsala 0.544 m/yr × 10 000 m^2/ha × 1000 kg/m^3 × evapotranspiration rate from hay 79% × energy in rain (Gibbs free energy) 4940 J/kg = 2.12E10 J/ha hay, × 0.91 = 1.92E10 J. Plus, for oats with an evaporation rate of 58%, 58/100 × 2.12E10 J/ha = 1.56E10 J/ha oats × 1.21 ha = 1.89E10 J. Total 3.81E+10 J, (3) *Wood:* Building for two horses, 4 × 4 m^2, estimated to 7 m^3 of wood/horse × 525 kg dry matter/m^3, depreciated in 50 years, makes 7 × 525/50 = 73.5 kg wood/horse and year. Plus wood in tools for 0.91 ha hay, (Table 4) 2.1 kg/ha/yr, makes 1.9 kg. Plus wood in tools for 1.21 ha oats (Table 3), 1.5 kg/ha/yr, makes 1.8 kg. Total 77.2 kg wood, 19.1E6 J/kg wood makes 1.48E9 J, (4) *Seeds:* Hay 21 kg/ha, 3 year hay gives 7 kg/ha/yr × 0.91 ha = 6.4 kg. Oats 200 kg seed grain/ha × 1.21 ha = 242 kg. Energy content of 248 kg seeds × 4790 kcal/kg × 4.19E+03 J/kcal = 4.98E+09 J, (5) *Leather:* Harness, assumed 20 kg depreciated in 10 years = 2 kg/yr, plus 1 kg for maintenance. 15.8E6 J/kg gives 47.4E6 J. Transformity for cattle estimated to be one magnitude of order higher than transformity for oats this study. Leather is considered a product generated from the horse and therefore not added as an emergy source to avoid double counting, (6) *Steel and iron:* Shoes, assumed 4 sets at 3 kg = 12 kg/yr. Plus 6 kg in harness discounted in 6 years = 1 kg. Plus steel in machinery for 0.91 ha hay (Table 4) at 6.2 kg/ha/yr = 5.6 kg. Plus steel in machinery for 1.21 ha oats (Table 3) at 8.7 kg/ha/yr = 10.5 kg. Total 29.1 kg/yr. Energy in steel and iron 694.9 J/g (Buranakarn 1998) gives 2.02E+07 J, (7) *Wood:* 77.2 kg wood (note 4) × 0.027 SEK/kg (Sveriges Officiella Statistik, 1929) = 2.1 SEK. Transformity from this study, (8) *Seed cost:* 248 kg (note 3) × 0.21 SEK/kg (Wheat price 1927, (Statistisk årsbok, 1928)) = 52.1 SEK, (9) *Leather:* 3 kg (note 6) × 2.19 SEK/kg (exported leather, (Sveriges Officiella Statistik, 1929)) = 6.6 SEK, (10) *Steel and iron:* 13 kg (shoes, harness, note 5) × 0.76 SEK/kg (Sveriges Officiella Statistik, 1929) + (5.6 + 10.5 kg) (tools note 5) × 1.74 SEK/kg (own calculations) = 37.9 SEK, (11) *Farm labour:* For care and maintenance, training, etc. assumed 0.75 h/day and working horse × 365 = 274 h. Plus for hay 0.91 ha × 60 h/ha/yr (Nannesson, 1936) = 55 h. Plus for oats 1.21 ha × 120 h/ha/yr (Nannesson, 1936) = 145 h. Total 474 h, at 4.24 SEK 10/h/man-day, (Statistisk årsbok, 1928) = 201 SEK, (12) Veterinary care assumed 1 h working/horse/yrs, at 5 times cost of ordinary labour 0.424 SEK/h (Statistisk årsbok, 1928) = 2.1 SEK, (13) Driver payment for 600 h, 0.424 SEK/h. 600 h × 0.424 SEK/h = 254 SEK, (14) Assumed 1200 working h/working horse and year (Nannesson, 1936), average pull 10% of body weight, speed 1 m/s = 0.7 kW (Crossley and Killgour, 1983): 1200 h × 0.7 kW × 3.6E+06 J/kWh = 3.02E+09 J, (15) After 12 years of work the horse is slaughtered, which, per year, makes 1/12 × 700 kg = 58 kg live weight, 5.8 kWh/kg (Hoffman and Uhlin 1997) × 3.6E+06 J/kWh = 1211E+06 J in live weight, 70% of this = 848E+06 J in carcass.

* Transformity from: [a]Odum (1996); [b]Doherty (1995); [c]this study; [d]Buranakarn (1998).

4. Discussion

In general there was an increase in energy and emergy support to the Swedish economy and to agriculture with the mechanised system. Fewer hectares were needed for food production due to increased yields. In 1927, there were 3.7 million ha of arable land in Sweden, while in 1996 the corresponding figure was 2.8 million ha. The population increased during those years from 6.1 million to 8.8 million. Horse traction in the context of Sweden 1927 was to a large extent based on local resource use, and to 60% driven from renewable sources. Tractor traction in the context of Sweden 1996 had a signature based on non-renewable sources, 91%, and more linked to non-local economy and ecology. Marginal improvements in systems performance would not greatly alter the dependence on renewable versus non-renewable energies. Evaluation methods that are unable to regard both resources that flow directly from the environment and indirectly through the economic system, and that do not consider energy qualities, can be misleading. The emergy analysis shows that the surrounding context is of overriding importance and must be regarded in any analysis that aims at a comprehensive understanding of resource dependency.

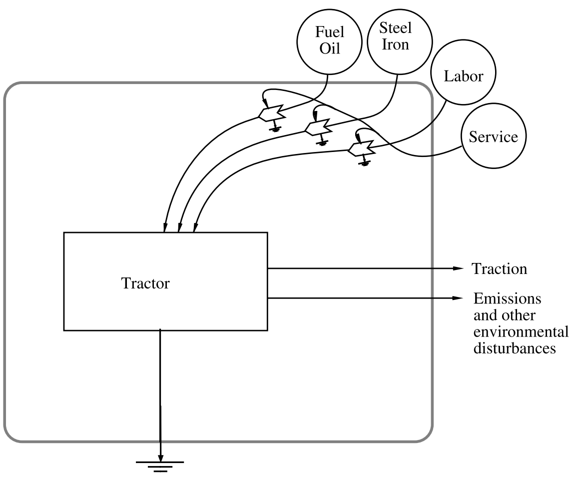

Fig. 3. Aggregated diagram showing the tractor and its main driving forces.

As long as the two systems are compared only in terms of the total emergy requirements of traction energy, the tractor in its 1996 setting is more efficient. While this could be interpreted as a success of target-orientated and large-scale technology, such a conclusion is incomplete. When the background of the emergy inputs is accounted for, other perspectives become important. The tractor system is supported by 9% renewable sources, compared to 60% for horse traction. This demonstrates an advantage of the horse system in situations where efficient utilisation of renewable and limited resources is prioritised.

A comparison of this type is also incomplete if only traction is considered as the output, and if the effects of by-products are neglected. Thus the horse, as a living system, is locally self-reproducing, multifunctional, and integrated with and scaled to its surrounding systems. The tractor, with its large dependency on non-renewable resources, drains finite stocks and generates downstream effects with negative potential for both humans and environment. For example, emissions of CO_2, oil spills, soil compaction, harmful emissions from tractor manufacturing and from disposal of old tractors are important effects not considered in our evaluation.

In monetary terms (SEK) the 1996 wage for a farm worker was 257 times the 1927 wage, while wages in terms of emergy increased approximately 6-fold. This illustrates the drastic increase in what Giampietro (1997) terms socioeconomic pressure. Increased productivity of labour is both a prerequisite for and a consequence of such a development, both in a Swedish rural area (Jansén, 2001) and globally (Giampietro, 1997). In emergy terms the input of manpower required for production of traction was more than twice as great in the 1927 horse case as in the 1997 tractor situation, in spite of the 1927 worker receiving, as emergy, only 1/6 of the 1996 remuneration for his work. This can be seen as an illustration of how modern technologies, supported by fossil energy and imports, in the 20th Century were successful in increasing the productivity of human labour when only a single or few target products were manufactured. To be competitive, the horse alternative requires evaluation and fair consideration of all by-products and of effects on the supporting ecosystem.

Table 6
Emergy evaluation for one tractor (65 kw) serving 38 ha/yr

Note, item, unit	Annual flow (raw units)	Transformity* (sej/unit)	Solar emergy × E+13
Fuels and goods			
(1) Fuel, J	1.07E+11	6.60E+04[a]	706
(2) Oils, J	2.20E+09	6.60E+04[a]	15
(3) Tractor, J	1.86E+08	5.90E+06[d]	109
(4) Spare parts, J	5.84E+06	5.90E+06[d]	3
(5) Garage, J	4.17E+07	5.90E+06[d]	25
Labour and service			
(6) Fuel, SEK	12 160	2.15E+11[e]	261
(7) Oils, SEK	1260	2.15E+11[e]	27
(8) Tractor, SEK	24 000	2.15E+11[e]	516
(9) Service and spares, SEK	10 800	2.15E+11[e]	232
(10) Garage, SEK	1600	2.15E+11[e]	34
(11) Tax and insurance, SEK	1080	2.15E+11[e]	23
(12) Labour for maintenance, SEK	3240	2.15E+11[e]	70
(13) Driver, SEK	32 400	2.15E+11[e]	697
Output			
(14) Traction, J	2.26E+10	1.20E+06	2719

(1) *Fuel:* 80 l diesel/ha (SLU, 1996) × 38 ha (cultivated area) = 3040 l. Diesel weight/volume, 0.84 kg gives 2550 kg/yr (SMP, 1984). Energy content 4.19E7 J/kg gives 107E9 J/yr, (2) *Oils:* 2 oil changes at 12 l/yr + consumption 15 l, + gearbox oil 0.5 × 48 l (recommendations for Valmet 705-4, (SMP, 1984)), total 63 l/yr. 63 l × 0.84/kg × 4.19E+07 J/kg = 2.2E+09 J/yr, (3) Weight of tractor, 4000 kg (65 kW). Depreciation time, 15 years. 4000 kg (15/yr) = 267 kg/yr. Energy in steel and iron 694.9 J/g (Buranakarn, 1998) gives 1.855E+08 J. Typical amount of tractor power 1.7 kW/ha (SLU, 1996), therefore calculation regards a 65 kW tractor serving 38 ha. Typical price 360 000 SEK, typical weight 4000 kg (Lantmannen, 1998). Depreciated to 0 in 15 years (Hoffman and Uhlin, 1997), (4) Spares. Cost for maintenance and service is 3% of tractor price, 7% of the service is estimated to be paid for spare parts (Svensson, 1987). Assumed that the percentage paid for spare parts equals the percentage of material needed for spare parts. 4000 kg × 0.03 × 0.07 = 8.4 kg. Energy in steel and iron 694.9 J/g (Buranakarn, 1998) gives 5.84E+06 J, (5) Garage 4 × 2 m^2, assumed to contain 3000 kg steel products (own estimate), depreciated in 50 years, makes 60 kg/yr. Energy in steel and iron 694.9 J/g (Buranakarn, 1998) gives 4.17E+07 J, (6) Fuel 4.0 SEK/l (SLU, 1996) × 3040 l (note 3) = 12 160 SEK, (7) Oils and lubricants: 63 l (note 4) × 20 SEK/l = 1260 SEK, (8) Price tractor 360 000 SEK, depreciated in 15 years. 360 000 SEK 15/yr = 24 000 SEK/yr, (9) Service and spares, 3% of tractor price per year (Svensson, 1987). 360 000 SEK × 0.03 = 10 800 SEK, (10) Garage 4 × 2 m^2 at annual cost 200 SEK/m^2 (SLU, 1996) = 1600 SEK/yr, (11) Traffic tax and insurance 0.3% × 360 000 = 1080 SEK (SLU, 1996). (12) *Labour for maintenance:* assumed 10% of 300 tractor h, at 108 SEK/h. (13) Driver, 300 h × 108 SEK = 32 400 SEK, (14) Average fuel consumption for 40 tested tractors was 306 g/kWh = 85 g/MJ (SMP, 1994) In field work losses in rolling resistance, slip and transmission are up to 37% of engine power (Crossley and Killgour, 1983), here assumed an average of 25% loss, which gives 113 g/MJ. With 2550 kg oil/yr this means the tractor delivers 22.6E9 J of traction per year.

* Transformity from: [a]Odum (1996); [d]Buranakarn (1998): Lagerberg et al. (1999).

Traction is one of several necessary inputs to agricultural production. It is probably used in quantities necessary to manage the farm and till the soil. The 1996 tractor farmer used two thirds more traction energy/ha than the horse traction farmer, according to our calculations. Johansson et al. (1993) estimate that due to a quality reduction of the soil structure one could expect an increased fuel requirement of 15–20%. We also know that the tilling depth had increased from 19 to 24 cm. A reduction of tillage depth from 24 to 19 cm reduces the power requirement by 30% according SMP (1984). Other important factors that significantly increase the demand for traction energy requirement are an increased tillage speed and a later date of primary tillage (Arvidsson, 2001). It requires more energy to accelerate the soil at higher speed. When ploughing is done later than normal, soil water content usually increases and more energy is required for tillage operations. These factors together explain to a great extend why the tractor needs more energy/ha than the horse.

Table 7
Comparison of resource use for horse and tractor traction

Index	Unit	Horse	Tractor	% of horse
Flows				
(1) Traction input	MJ/ha	357	595	167
(2) Emergy/man-hour	E+12 sej/h	3.6	23.2	644
(3) Emergy use/generated J traction	E+06 sej/J	1.87	1.20	64
(4) Emergy use/J traction exclusive driver	E+06 sej/J	1.15	0.89	77
(5) Emergy use for driver/J generated traction	E+06 sej/J	0.72	0.31	43
(6) Emergy use/ha	E+14 sej/ha	6.7	7.2	107
(7) Emergy use exclusive driver/ha	E+14 sej/ha	4.2	5.3	126
(8) Emergy use for driver/ha	E+14 sej/ha	2.5	1.9	76
Indices				
(9) Local renewable component[a]	%	15	0	
(10) Indirect renewable component[b]	%	45	9	
(11) Total renewable component	%	60	9	

[a] Items 2, 3, 4 and 5 in Table 3.
[b] 54% of the emergy for service and labour to the horse is added as renewable emergy and 13% of the emergy for service and labour to the tractor is added as renewable emergy, as found in respective national analyses.

It has been shown that there is a strong relationship between economic growth in many sectors and the consumption of energy (Odum, 1971; Hall et al., 1986). The increased productivity in agriculture is also a result of an increased input of fossil energy and other natural resources of a non-renewable character, e.g. metals and other minerals. This was possible much due to the development of machines that allowed their use by extracting, refining, conversion and transportation. With help of the machines, more energy could be converted to useful energy outside human bodies. Machinery technology made humans more powerful. Human activity was no longer restricted by human power, nor by the restriction that comes from renewable energy sources. Each farmer could manage a larger agricultural area. More machines, fertilisers, pesticides and information were used to increase the output from agriculture. There is no doubt that the increased productivity from agriculture was a result of an increased input of non-renewable resources. Tractor traction quickly supplanted the horse with cheap energy in a concentrated and powerful quality. This type of agricultural activity is possible only in situations of access to concentrated stocks of natural resources. When such stocks are used up, or if environmental disturbances from their use restricts the use of them, we will have to organise our agriculture and other societal activities to the flow of limited renewable resources. Animal traction is only one example of a renewable biological technology more appropriate in low energy situations. With the rising cost of purchased inputs, more of the work falls on the environment and less on purchased resources. This production will be flow limited since the renewable driving sources are flow limited. The total activity in the society has to slow down and be organised in a new way. The transition to a future with less available net yielding energy sources will require greater changes in those societies that today are organised and strongly dependent on fossil fuels. In agriculture, nutrients will have to be recycled on farm by integration of crops and animals. Nitrogen will have to be fixed by bacteria in symbiosis with clover and other leguminous crops. Food and other crop products that leave the farm will to a great extent have to be brought back to the fields after their use, to recycle the nutrients and the organic matter. Farmers and consumers will have to live closer to each other to lower the cost of transportation, storage and retailing. Crops and crop rotations will have to be chosen and organised in such a way that they will generate a useful output, maintain soil fertility and protect crops from pests.

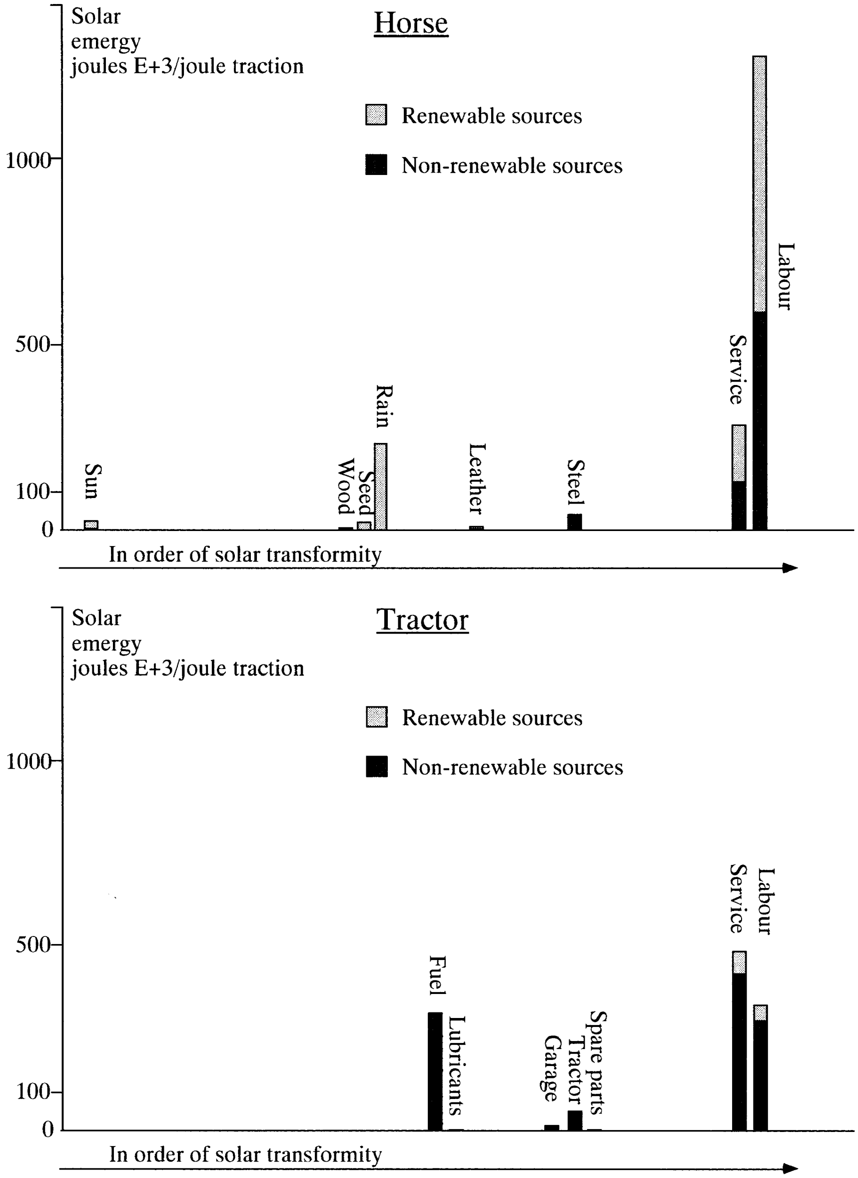

Fig. 4. Emergy signature of traction, generated by horse in Sweden 1927 and tractor in Sweden 1996.

It is interesting to note the interdependency between the choice of technology and the context in which it is operating. The use of horses in the context of 1996 would increase the emergy use dramatically. Due to our lifestyle, the emergy support for labour is greater today than in the past, so horse traction in 1996 would require more emergy if the horse driver were to have the same standard of living as our tractor driver. Resource demand, however, could be radically different when sustainability challenges, or other social, economic or ecological forces, lead to lower material living standards and remuneration demands of farmers and communities.

It can be concluded that when ecological technology, in this study represented by the horse, was replaced by mechanical technology, the tractor, it meant a shift from a technology integrated in local environmentally processes to a system with less degree of integration. Several of the driving forces for the horse are generated in the local environment e.g. grass, oats, water and wood for equipment and housing. The horse generates several useful outputs of importance for humans, not only traction but also meat, leather, horsehair and friendship. The waste products from the horse are necessary feedback for maintenance of soil fertility and growth of crops as well as the consumed and worn out products. The information needed for maintenance, renewing and for reproducing is all embedded in the horse. The horse has the ability to learn and develop its skills together with the farmer. The farmer is in control of the information needed for the management of the horse. The tractor is nested to another type of environment and without the abilities typical for a living system. No direct driving forces can be found in the local environment. Most driving forces for the tractor are generated in the industrial technological part of society. The driving forces for the industry, infrastructure and knowledge necessary for the production and maintenance of the tractor are of a non-renewable character. Most of the information is outside the farm and the local environment. Emergy analysis has the ability to deal with all of these different resource qualities by valuing their different position in the energy hierarchy. Since the method treats the system of interest as an open system and uses a strategy of aggregation of driving forces instead of exclusion of driving forces, it gives us a possibility to understand the dependence of the next large scale.

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