FOSSIL ENERGY AND FOOD SECURITY

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ABSTRACT

To fulfil the basic goal of delivering food for the tables of the citizens, modern Western agriculture is extremely dependent on supporting material flows, infrastructure, and fossil energy. According to several observers, fossil fuel production is about to peak, i.e., oil extraction is no longer capable of keeping pace with the increasing demand. This situation may trigger an unprecedented increase in fossil energy prices, which may make the current highly energy dependent food production-distribution system highly vulnerable. The paper starts with a survey of this vulnerability. Also, the supply of phosphorus, a key factor in agriculture, may be at stake under such circumstances. The paper analyses this situation and discusses settlement structures integrated with agriculture that might increase food security by reducing energy demands.
In the proposed ideal societal structure, agriculture is integrated with settlements and most of the food needed by the population is produced locally and the nutrients for food production are recycled from households and animals by means of biological processes demanding considerably less mechanical investment and fossil support energy than the conventional type of agriculture.
The vulnerability of this structure would therefore be considerably lower, than that of the current system.

Key words: agriculture, energy supply, energy efficiency, fossil energy, nutrients, settlement structure, vulnerability.

INTRODUCTION

Contemporary Swedish agriculture is one of the most technically advanced and successful in the world. The development of agricultural practice has led to a situation where a very small part of the population (1997: 0.72%, (SCB, 1999)) is employed in agriculture. However, this situation has been achieved only by a large amount of external support, (Giampietro, 1992). Agriculture has changed from a local activity to a throughput business (Goodland & al, 1992) that is dependent for support upon societal functions, energy sources and minerals derived from the wider world.
To survive and maintain food production for the population, current western European agriculture needs continuous support of the following:

- Reliable and cheap fuel production that can continue in the future.

- Availability of phosphorus ores that can be extracted to produce fertilisers.
- A distribution system for fertilisers, animal feed, fuels and agricultural products that function irrespective of disturbances in the society outside the agricultural system.
- A support infrastructure that can provide renewal and repair of machinery independent of the general industrial climate and future energy prices.

The agricultural system is heavily dependent on services that are often taken for granted, e.g. constantly low energy prices. Therefore, when discussing a sustainable agricultural system, it is important to include the necessary support systems for the entire chain.

The ultimate objective of agriculture must be the provision of food for the human population. However, some of the mentioned supports associated with this kind of agricultural production are so vital that any failure, such as an unexpected energy price increase, can turn the success of agriculture into disaster.

This perspective paints a gloomy picture of the sustainability of this highly productive agriculture and of any society that depends on it for its subsistence. The aim of this paper is to discuss the capacity and reliability of the support system as it is designed today in Sweden, and, in cases where this capacity and reliability appear doubtful, to discuss how problems might be alleviated.

THE DEPENDENCIES

Dependency on material and industrial energy support

Pre-industrial agriculture was a highly local activity. Most machinery was made locally, and agriculture was based mainly on different types of locally captured solar energy. Nutrients were collected by means of meadow plants and transported to the fields through harvesting of winter feed, or with manure from grazing animals brought home overnight. The necessary energy for these activities was exclusively derived from the sun, which therefore limited the energy use in these activities. Often, the energy used was considerably below this input, i.e. having high efficiency (Jansén, 2000).

The main energy input into modern agriculture is not solar energy but industrial energy of different types. Parallel with the need for constant input of other necessities, i.e., fertilisers, biocides, animal food, plastics for silage and drugs for treatment of animal diseases, it gives modern agriculture an operational structure similar to a throughput industry. The increased yields experienced by these methods are not due to increased ability of the crops to obtain more solar energy, but rather that some tasks formerly done by the crops (e.g., extracting nutrients and restraining diseases and herbivores) are done by the farmer using fossil energy, which accounts for the increased grain yield (Odum, 1971). Figure 1

This strategy is not limited to plant crop production, but can be found in most agricultural and food related activities, as animal husbandry, fish production and fishery. Thus, in order to boost the rate of output, a constant throughput of energy and materials are applied. This makes agriculture highly dependent on different types of industrial support for maintenance, and energy and nutrient requirements. Therefore, in this type of agriculture the energy input often equals or exceeds the output (Odum, 1971; Hall, 1992; Hoffman, 1995; Jansén, 2000).

To produce food, today's agriculture in developed countries is heavily dependent on fossil fuels. The input of fossil fuel energy often equals, or surpasses, the output of food energy for human consumption (Hall et al., 1992; Folke & Kautsky, 1992; Hoffman,1995), suggesting why industrial agriculture can be referred to as a black box for converting fossil fuel energy into edible food energy. The ratio of energy input/output of Swedish agriculture is about 0.96 including fodder for pet horses (Hoffman, 1995), which is in close concordance with this 'black box' description.

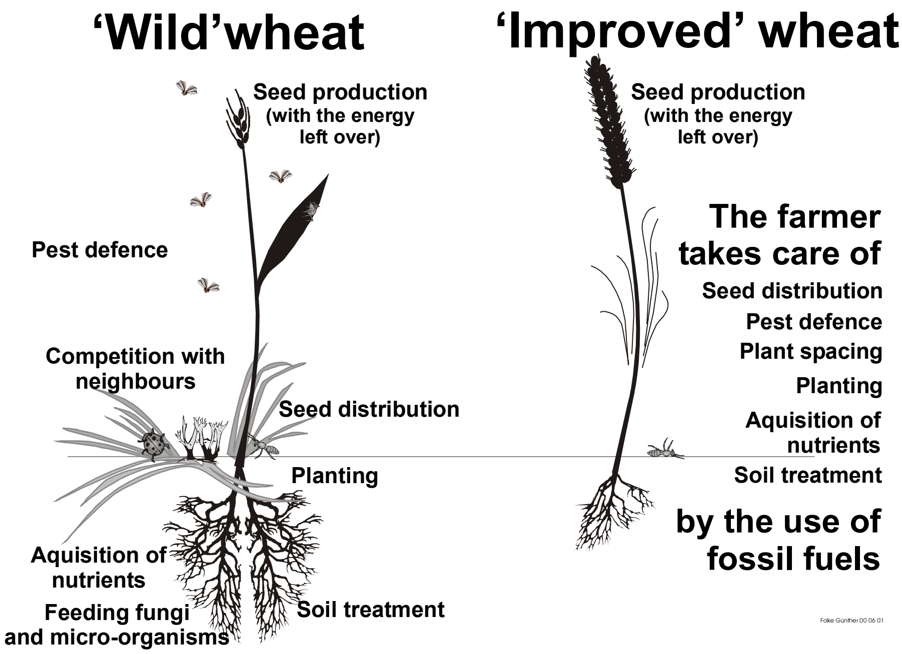

Figure 1. The improvement of domesticated plants and animals has often implied an increased dependency on fossil fuels.

This relation is further highlighted in a note by H.T. Odum in the Energy Resources list[1] in Sept. -2000:

> Because of its large content of environmental and fuel emergy, agriculture contributes much more than is paid for its products. At a time when agriculture was 7% of the Texas economy on a dollar basis it was 35% of the Texas energy budget. So-called agricultural subsidies are justified to sustain this bonanza.

Swedish agriculture uses over 110 litres of liquid petroleum per hectare per year (SCB, 1994). To this must be added the indirect use of fuel for production of pesticides, fertilisers, machinery etc., which can easily be 50% of what is directly used, and, on top of that, the requirements for electricity.

Is industrial energy cheap and will it continue to be so?

In this practice, the implicit assumption is that the prices of the supporting industrial energy and equipment will remain cheap enough, so that they will not increase the price of the food produced over what can be paid by the public. This assumption can, however, be questioned. Energy price is hard to calculate. The price ($/litre → $/kWh) for e.g., gasoline at the tank station changes very often, as does the salary ($/hour → $/second) for the person who buys it. Therefore, it is hard to say if the energy is 'cheap' or 'expensive'. Another way is to search for the 'availability' of energy. One way to do this is to calculate how long a person has to work in order to get a certain

[1] http://groups.yahoo.com/group/energyresources

amount of energy. By this, a new, price neutral denomination is attained, seconds/kWh, which reflects the availability of fossil energy. The result of such a calculation is demonstrated in figure 2.

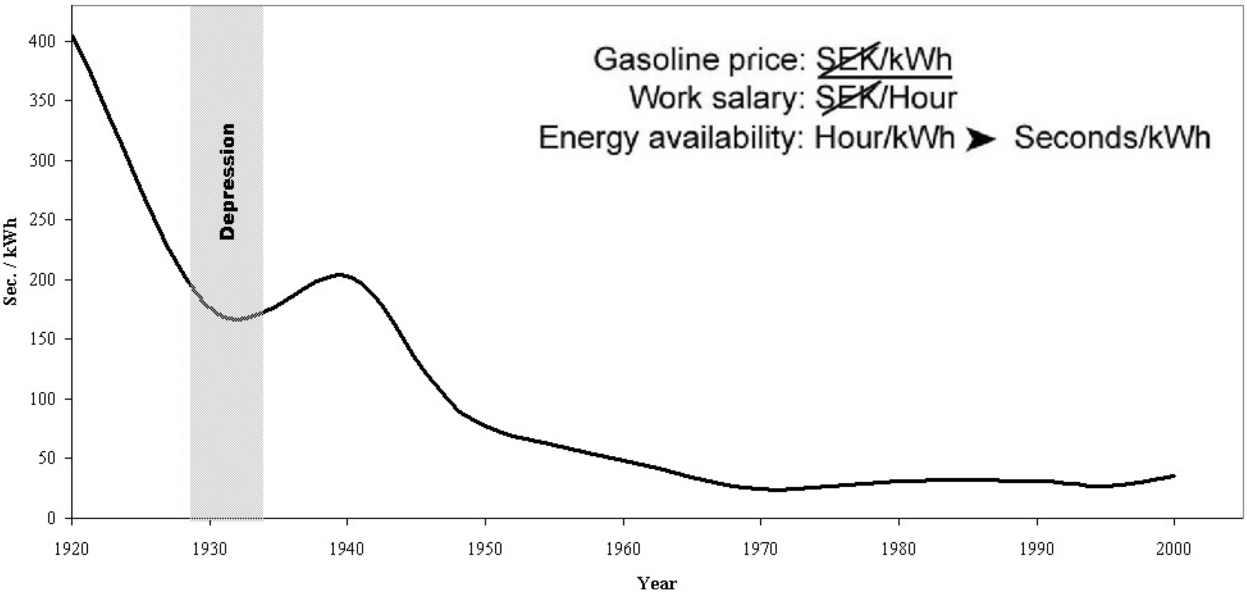

Figure 2. The working time needed to purchase one kWh of gasoline has diminshed to about 1/10 between 1920 and 1995. Note the increase during WW II. The 'energy crisis' during the 70-ies is barely noticeable.

In this graph, the price for gasoline in Sweden is divided by the salary of a 'general' worker in Sweden. The calculation makes is possible to estimate the availability of energy in the form of gasoline for the worker. The working time needed to purchase one kWh of gasoline in 1995 has diminished to about 0.1 of the time needed in about 1920, i.e., the availability has increased ten times.

The Hubbert curve

Calculations made from the verified amounts of crude oil reported by DOE, (1993) indicate that its availability is of a relatively short duration, 35 years, given the current rate of resource use today. Against this, it has been argued that new amounts found have always (i.e., lately) exceeded the used amounts; hence the total extractable resources have not diminished. This argument is not consistent with observations. Masters (1994) published a review of the global discoveries of oil this century that show a definite peak around 1960 and a definite decline in the discoveries thereafter, simply due to a more thorough knowledge of the subsurface globe. Ivanhoe (1995) referred to the weighted average of the global oil discoveries, a typical bell-shaped curve, as the 'Hubbert curve'. The extraction of discovered oil follows a similar curve, but with a lag of about 40 years. (Figure 3).
Since the peak of the 'use'-curve could be expected to occur around 2000, these curves has recently attracted considerable attention, however, more rather among geologists and engineers than economists. The Australian engineer Brian Fleay, associate of Murdoch University's

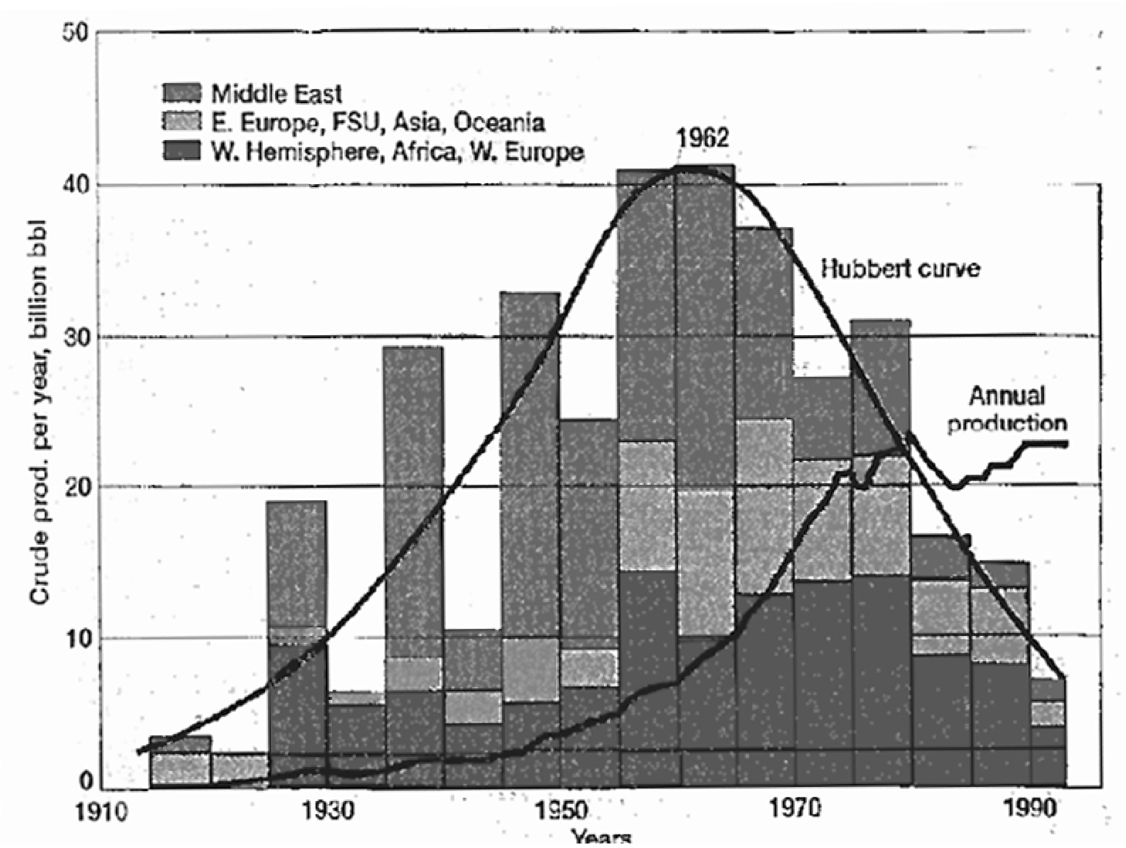

Figure 3. The 'Hubbert curve' displays the discoveries of crude oil during this century. They follow a bell-shaped figure with a peak around 1960. After that, no major fields are found. The total amount of extracted oil (the space under the curve 'Annual production') can never exceed the space under the Hubbert curve. If the time lag of the two curves hold, a peak production can be expected 2000 - 2005. (Adapted from Ivanhoe, 1995)

Institute of Science and Technology Policy, maintained on a net site[2] that the 'crunch' has come, i.e., that the oil extracting countries were not more able to keep pace with the demand. He pointed out that the oil market is very sensitive. The price of crude oil tripled over one year (1999-2000 from \$10 to \$30 per barrel) due to a 5 % decrease of the output, and have been rising constantly the last year, interrupted by some dips due to the release of strategic reserves in the USA and the market relief due to the resumed threats of cancelled production in Iraq. These energy price increases may be a factor for the recent economic slow-down in the USA. An increase or decrease in price does not, however, reflect the amount of crude oil available. This is constant and can be calculated by integration of the Hubbert curve (with some extrapolation at the end).

$$\text{Amount} = \int \text{'}\mathit{found}\text{'}(x)\,dx$$

This amount, minus the amount already used up, is the ultimate amount of oil that can ever be extracted. Oil as an energy resource for mankind is a 'one time shot', the duration of which can be calculated to be 150 -200 years. However, not speculating in the exact duration of the resource, another interesting characteristic of the curves can be deduced, namely that:

2 (http://www.hubbertpeak.com/fleay/crunch.htm 2000-03-13)

$$\int 'found'(x)_{dx} \geq \int 'used'(x)_{dx}$$

Or, to put it simply: 'You cannot use oil that is not found'. This means that the rest of the extraction curve can have three principally different shapes (Figure 4):

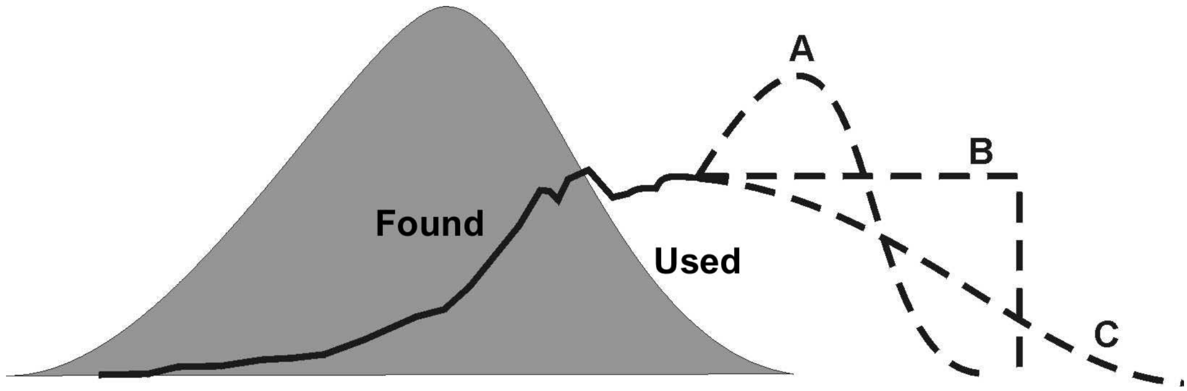

Figure 4. Since the area of the 'used' curve never can have a larger area the 'found' curve, three principally different extraction principles emerge

A. **An extraction increase, followed by a steep drop.** This curve doesn't seem realistic, due to the small amount of states (mainly Saudi Arabia, and to some extent Iran, Iraq, Kuwait, UAE, Venezuela and Nigeria) that actually have a potential to increase extraction, and these states have had an impeded modernisation of their fields due to low prices for crude oil.
B. **A constant extraction rate, followed by a production crash.** This curve is unrealistic due to the lowering YPE in ageing fields.
C. **A dwindling of production.** This type seems the most realistic. It should be pointed out, however, that after the peak of the extraction, a considerable price increase can be expected due to the discrepancy between extraction capacity and the demand from the world society, fuelled by oil. This change is referred to as 'the big rollover' by some authors (Magoon, 2000) when the seller, not the buyer, decides the price.

The increasing gap between the extraction of crude oil from the 'producer' countries and the demand from the consumer countries (notably USA and Japan) may trigger an unprecedented increase in fossil fuel price due to the overturn from an demand pricing market to a supplier price market. If the market base is in doubt, the investor's willingness to keep their money in the energy sector might also decrease. In such a scenario, the decimal point on the gasoline pumps may move to the right.

Yield per effort

The extraction of fossil fuels is an energy intensive industry. To make the energy of fossil fuels available, a certain amount of energy is needed for prospecting, drilling, industrial frameworks etc. These activities are mainly powered by oil itself. When the quality of oilfields sink, a larger portion of the energy extracted need to be use in the extraction process, i.e. the net energy output will diminish even if the gross energy extraction remains constant. This factor is referred to as EROI (Energy Return On Investment) or, more generally, for any extraction process, YPE (Yield Per Effort) (Hall & al., 1992).New resources, requiring more extensive equipment (e.g. off-shore drilling towers and the like), can therefore be expected to have a lower energetic marginal return (YPE), than those already verified. This will change the 'perfect' bell-shape of the Hubbert curve to one with a steeper slope at the right (diminishing) side, i.e., the availability of the remaining resources will thus decline because of a decreasing YPE. This can also be observed by a close look at the curve.

The YPE of extracting efforts in fossil fuels have decreased globally during this century. In the lower 48 states of USA, it is expected to fall below 1:1 around 2005 (Hall & al., 1986; Cleveland, 1991). At this point, the oil cannot longer be considered an energy source, even if it could be extracted for other reasons. The large reserves of tar sand, which have been referred to as a future oil reserve (e.g., Odell, 1997) has an YPE of about 1.5, i.e. two energy units are necessary for the extraction of three.

Phosphorus ore availability?

To survive, the current (industrial and urban-supporting) agricultural system also needs a steady supply of nutrients, at least corresponding to the same amount of nutrients that are steadily exported with the produce. It is possible to obtain nitrogen from the atmosphere by means of leguminous plants, but potassium and phosphorus have no such gaseous phases and must be available in soil liquid. Potassium is quite a common element and scarcity is therefore rarely a problem. Phosphorus, however, exists in much lower concentration in the earth crust (about a tenth) than in biomass and is therefore often a limiting element for plant growth. This is why a constant supply of phosphorus is of vital importance for any agriculture exporting produce from which the nutrients are not recycled. This is often the case in prevailing industrial agriculture. Consequently, to be able to export food, nutrients must be imported, of which phosphorus is vital because its chemical behaviour is fundamentally different from nitrogen. It has no gaseous phases but must be transported.

Supplies of guano were used to substitute the deficits of phosphorus due to export of food products to urban areas in the 19th century, but this source was exhausted in about 30 years (Brundenius, 1972; Gutenberg, 1993). Today, the source of phosphorus is mainly rock P, which is extracted in a few places in the world. These resources are also limited. The estimations differ regarding the supply of phosphate ores that are worth working. In a literature survey, (Pierrou, 1976) estimates that the available amount of extractable phosphorus as being in the range of 3,140 - 9,000 Tg, with an extraction rate of 12.6 Tg/year. This gives the resource a lifetime of 249 - 714 years if the assumed rate of extraction is maintained. However, later estimates indicate lower values of supply and higher rates of extraction. Smil (1990) estimates the available ore to be about 20,000 Tg, containing of about 13% phosphorus, contrasted to 5% of Pierrou. Smil estimates the sources of pure phosphorus as about 2,600 Tg. Annual use of phosphorus from these resources is estimated to be about 20 Tg P. Calculating from Smil, the available phosphorus resources may have a life-time of about 130 years at current energy prices.

There is a large uncertainty both about the amount of extractable phosphorus ores and their average content of phosphorus. It is certain, however, that the extraction of phosphorus ore has a high energy demand.

Energy resource use in P mining depends of the end product (18-32 MJ/kg P, Smil, op.cit.). As in fossil fuel extraction, the YPE of phosphorus extracting diminishes (Hall & al., 1992). Given the finite availability of fossil fuels, this may lead to a resource trap, where phosphorus resources currently available may be unavailable in the future (Cleveland, 1991). The market price today is about 15 SEK/kg P, and the corresponding energy price for extraction 3.13 SEK. Assuming an annual energy price increase of 5% and the extraction energy needed to increase annually at 3%, the energy cost for extraction will exceed 400 SEK/kg within 75 years, an increase of two powers of ten.

Table 1. The energy price/YPE trap in the case of phosphorus mining, assuming 5% annual increase in petroleum prices

Year from now	0	25	50	75
Price for industrial energy, SEK/kWh	0,45	1,6	5,5	19
Price for the extraction of phosphorus, assuming a 3,00% annual decrease in YPE., SEK/kg	3,13	34	119	415

Thus, in a situation with increasing energy prices, and increased energy demand for extraction, recycling becomes necessary. However, with the settlement structure common in industrialised countries, where a very large part of the population inhabits a very small area and where farms are very specialised in crop or animal production, this is not an option (Günther, 1997). A clearly unsustainable situation may arise and is worth an analysis.

Transport dependent centralisation

With fossil fuel based industrialisation and its associated infrastructure development came the capacity for far-away production and cheap long-range transportation. This created the possibility of concentrating people in urbanised – industrialised areas. There seems to be a close connection between the availability of cheap energy and urbanisation. Without cheap energy, large cities cannot be sustained. The extraction, refinement and transport of necessary products would otherwise be too expensive, not to mention the recycling of nutrients necessary for sustainability (Günther, 1998).

A general principle of self-organising systems is to change in a direction that enables the system to degrade more available exergy (Schneider & Kay, 1993). This principle can explain the substitution of machinery for manual labour, or the transportation of food instead of local production. The availability of cheap energy can thus to a fair extent explain the growth of cities, just as it give clues to other types of centralisation, for example the specialisation of agriculture into large units. Low-cost energy development has lead to a situation where single households can be associated with large uses of cheap energy:

The house

In Sweden, a normal new-built house for a family of four, built according to the Swedish building standards of 1980 can be assumed to have a yearly energy use of about 17 000 kWh. However, by applying energy conservation it is possible to reduce this figure to below 10 000 kWh. The potential for increasing energy efficiency of the building is thus about 8 000 kWh/year for a family of four.

The car

Another large energy user of this four-person family is the car. Assuming an average use of the car to be 15 000 km/year, using 0.6 - 1 litre of gasoline per 10 km. A more energy-efficient car uses about 9 000 kWh of gasoline/year, a less efficient car about 15 000 kWh. Assuming the same indirect energy use in construction and maintenance, the difference is about 6 000 kWh/ year. Thus, the potential for increasing the energy efficiency of the car is about 6 000 kWh/year, i.e. in the same size range as for the house.

Food

The energy used in food transportation and handling is to a large extent an unacknowledged part of the total per capita usage of energy. In Sweden the use of direct energy for transport and handling of food is conservatively estimated to be about 10 % of the total annual energy use (Olsson, 1976). Nils Tiberg (Professor at Luleå Technical University, pers. comm.) estimates the figure for Sweden to be about 60 TWh, or 13 % of total energy use. Including the energy expenditure in agriculture which are in the region of 1:1, the total energy efficiency would have been about 8:1 in 1976. Considering the changes in society during the last 20 years, this figure would be worse today. A guess that it is more like the US in 1975, 1:10 (Hall & al, 1986), would not be in excess.

It can thus be estimated that the YPE in food production, transport and handling is about 0.1. This implies that about ten energy units are spent for each energy unit delivered to the dinner table. The average food energy needed for a person is about 1000 kWh per year. A conclusion of this is that for a family of four, about 40 000 kWh/yr is needed for food. This is clearly the largest single energy use.

Assuming a Swedish agricultural system similar to the one today, but with more local handling and managing of food, the energy expenditures for the production of food necessary for feeding this family would be about 4000 kWh in agriculture itself and an equal amount of energy for a 'local' supply system. In this case, the potential for efficiency increase would be about 32000 kWh (Figure 5).

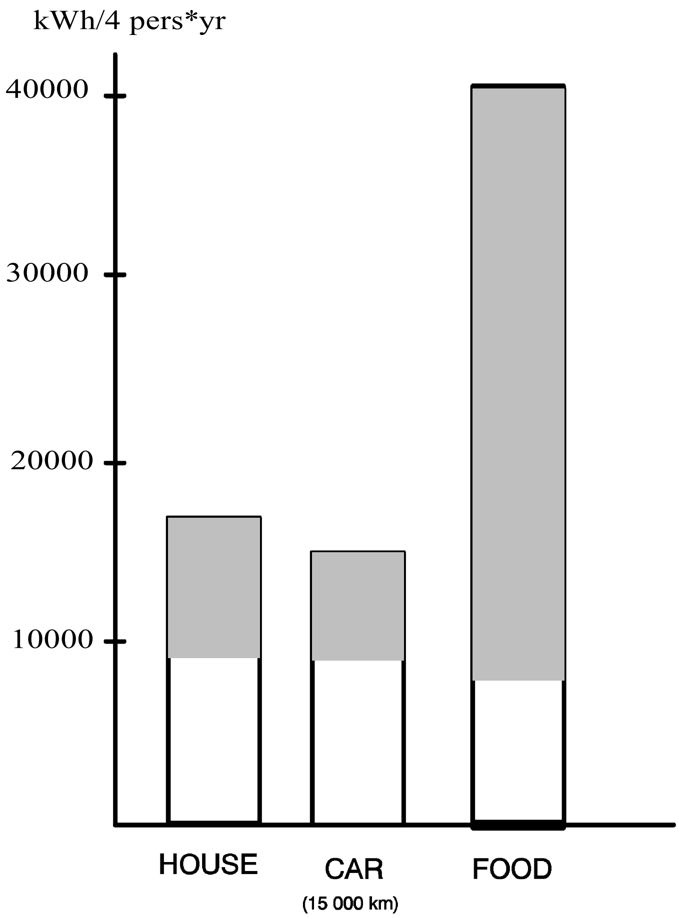

Figure 5. The energy use of a family of four in Sweden, roughly calculated. The single largest energy user is the food system. Here is also the largest potential for increased energy efficiency (grey part of the bars) to be found.

Agriculture and vulnerability

Industrialised agriculture is as dependent on the general services of wider society as any other industrial activity. In order to meet the need for increased economic efficiency of these services, the tendency during recent decades has been to increase the size of the industrial units delivering the services. This is especially true of the reduction in the number of dairies and slaughterhouses in Sweden. The total number of dairies has declined from about 200 to 51 during the 33-year period 1968-1998 (SCB, 1999) (Figure 6).

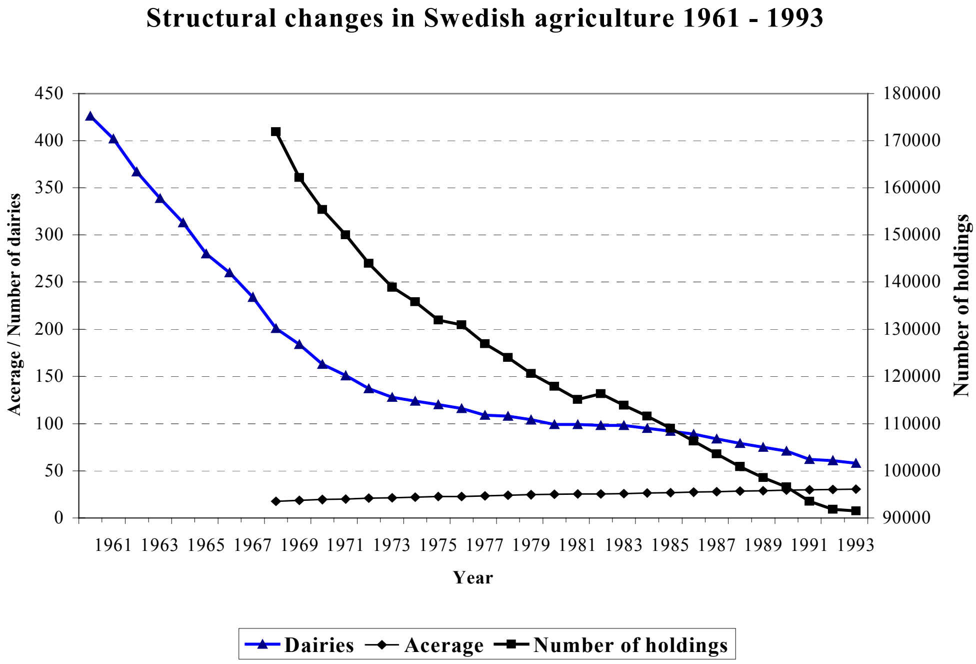

Figure 6 An increase in vulnerability can be expected with a specialisation of the agricultural units. At the same time as the size of the units have increased, the number of service elements (here: dairies), have diminished.

The same problems are associated with the system for delivering supplementary inputs into agricultural production, e.g., animal feed, fertilisers, seed grain, spare parts for machinery, and frozen sperm for insemination. Today over 90 % of the cows in Sweden are artificially inseminated (SCB, 1999). About 80% of the Swedish milling capacity is situated in the far southeast part of Sweden (Jordbruksverket, 1991).

Besides the effects of increased transport, to be discussed later, all this leads to an increasingly vulnerable structure. A permanent or temporary malfunction of one unit, e.g., the outbreak of disease, malfunction of the electricity delivery system, some problem in the delivery system for packages, or any other civil or military crisis will, by its increasing share of total production, have a far more severe effect on food delivery for the population than if a smaller unit had been eliminated. This whole case exemplifies a reduction in the general resilience of a system. (Holling, 1973)

To these problems of vulnerability, a further one may be added: With the decrease in number of production and support units, the importance of the distribution system will increase and the supply lines will lengthen. The need for the safe and constant delivery of cheap energy and a well-functioning transportation infrastructure thus increases, as will the need for accurate and precise distribution. Compared to a system with shorter supply lines and a higher grade of self-sufficiency, effects of failures in this kind of system will be more severe. This tendency is general for all sectors of the mature industrial society, of which agriculture is a part.

The increase in specialisation of agricultural units themselves has had the same effect of decreasing their diversity. Half a century ago, it was commonplace that farms not only grew a large part of the fodder for the animals, but also exhibited a large diversity in animals and plants on the farm. Commonly, cows, pigs, horses, geese, and chicken could be found on the same farm,

together with a variety of crops and enhancement procedures. Today, this situation is very rare. By their dependency on increasingly expensive inputs and the decreasing price for their outputs, farmers are forced by to specialise in products that can be produced in large quantities to a low cost per unit. The general economic paradigm has transformed the relation between the farmer and his farm from managing the land to running a company. Various governmental subsidies have intensified this process, together with the entrainment of firms into a new infrastructure (Rosser & al., 1993). Increase in specialisation has lead to a decrease in diversity, reduced resilience and, consequently, to an increase in the vulnerability of the food delivery system as a whole.
The infrastructure of contemporary agriculture was created to deal with well-known problems , e.g., local demands and malfunctions. However, the feedbacks in the system are slow or non-existent for problems arising on a higher level or on a longer temporal scale, i.e., ecological problems or dependencies on future energy access (Allen and Starr, 1982).

DISCUSSION

The question has been raised whether the importance of liquid fuels has not been over-stressed in this article, and whether increased energy efficiency not could do.
Consider Figure 5. Here, the energy use of a family is broken down into the general components: house, car and food. The grey parts of the bars are estimated decrease due to increased efficiencies. In the first bar, the house, a large part of the total energy use could come from biomass, solar collectors, photovoltaics and the like. Together with an increase in the efficiency in the construction of the house, an increase in the price of fossil fuels doesn't seem to be detrimental for the possibilities of providing energy for housing.
The car, however, seems to be more vulnerable. Most of the cars today are propelled by means of *liquid* fuels. Attempts have been made to propel them with electric batteries, fuel cells and the like. Since these not are fuel *sources*, but only fuel *carriers*, this changes the question into how to find power to load these carriers, whether with solar energy or other, fossil, sources submitted to the same problems as mentioned for petroleum in this paper. Providing personal transportation in the same scale as today with renewables and solids seems to be difficult, but not completely impossible. The energy use for personal transportation might however be diminished by decreasing the *need* for transportation, such as distance working, decentralisation of working places and the like.
The food production and transportation, however, is the largest single energy demand, today nearly entirely dependent on liquid fuels and, to a lesser part, electricity. To this comes the problem of recycling the nutrients, which is necessary for long-time survival. It is hard to imagine a transport system that would accomplish this with a considerably lower energy demand. In this case, increased energy efficiency seems to be the only solution. This is what the last part of this paper is about.

Potential solutions

In this part of the paper I will suggest some measures that could be taken in order to alleviate the problems of high risk and potential instability of the food supply system. Some benign side effects that can be expected from the alleviation measures will also be pointed out. I will not discuss measures taken within the agricultural system itself, such as, for example, organic farming or agroecology, since such measures have been discussed extensively in the literature (e.g., Altieri, 1987; Pimentel, 1989). Instead, I will focus on the alleviation of the problems that have arisen as effects of access to cheap fossil energy.

1. Minimising energy use in transportation

The heavy dependence on transportation in current food production system can be ascribed to two or three infrastructure modes:

- Fertilisers and other support material for the agriculture are externally produced, often very distantly.
- Agricultural sites and end-user of food are separated, often spatially very separated.
- Animal fodder is commonly produced in a different part of the country to where it is needed.

These transportation dependencies could be diminished radically by a closer spatial, and social, integration of agriculture and settlements, together with a re-introduction of a balance between animal husbandry and plant production on individual farms (Granstedt and Westberg, 1993). The discussion in the first part of this paper indicated that today about 10 000 $kWh*p^{-1}*yr^{-1}$ is used for food delivery. However, it is possible to imagine a decrease of this figure to 2 000 kWh through the closer integration of agriculture and settlements, combined with a strategy for local food production. If this were possible for 50% of the Swedish population, the amount of energy saved is about 40 TWh annually, which equals to the electricity production of eight nuclear powered reactors.
Energy use can of course also be diminished by different intra-farm technological changes to diminish energy investments in agriculture, which is currently of the same order as energy input in food. Increased efficiency of intra-farm energy use can, however, not be expected to lessen the total energy use more than by a small part of the industrial energy subsidies used in agriculture, which is about 18 TWh in Sweden (Hoffman, 1995).

2. Increasing nutrient circulation

In modern agriculture, the nutrients lost via export are replaced by new ones, supplied from mineral ores (P, K), or from industrial processes (N). However, this increases the vulnerability of the food system due to the connection with the mining and processing industry and the earlier mentioned problems of materials and YPE.

Natural biological systems, e.g., ecosystems, offset the problem of source deprivation of essential nutrients. They respond in two ways: For elements that have volatile phases (e.g., C, N, O, S and H) supply is by atmospheric transport. For elements that in practice have no volatile phases, repeated cycling solves the problem. Advanced ecosystems are able to nearly eliminate leakage through export of nutrients (Stark and Jordan, 1978; Odum, 1973, 1985; Kay, 1994). Therefore, in order to augment sustainability, it seems appropriate to imitate the strategies of long-time sustainable self-organising systems. One of the most important of those strategies appears to be 'cyclic charging - discharging process' of simple elements, the regenerative cycle (Günther and Folke, 1993; Günther, 1998). In ecosystems, such elements are volatile (N, C, S, O, H) and non-volatile (P, K and trace metals). The limiting ones, such as nitric oxides and phosphorus, are carefully recycled in such systems (Stark and Jordan, 1978; Odum 1973, 1985; Kay 1994). To attain ecosystem mimicking (ecomimetic) nutrient circulation, two changes are needed in current agricultural practice.

- Animal feed has to be produced on the same farm, or in the vicinity, allowing the manure to be returned to the land where the feed is produced. By this practice, 60-90% of the nutrients, at least the non-volatile ones, can be circulated (Granstedt and Westberg, 1993). Nutrients with volatile phases, e.g. nitrogen, can be conserved by anaerobic storage, effective mixing into the soil or other means.
- Nutrients actually exported as human food should be returned as uncontaminated as possible, preferably as human urine and (composted) faecal matter. With the use of source-separating toilets, which do not mix urine with faeces, the urine, containing most of the phosphorus and the nitrogen excreted (Günther, 1997), can be easily reclaimed. The faeces can be composted out of reach of flies for six months to a year in order to eliminate pathogens before returning it to the fields (Figure 7).

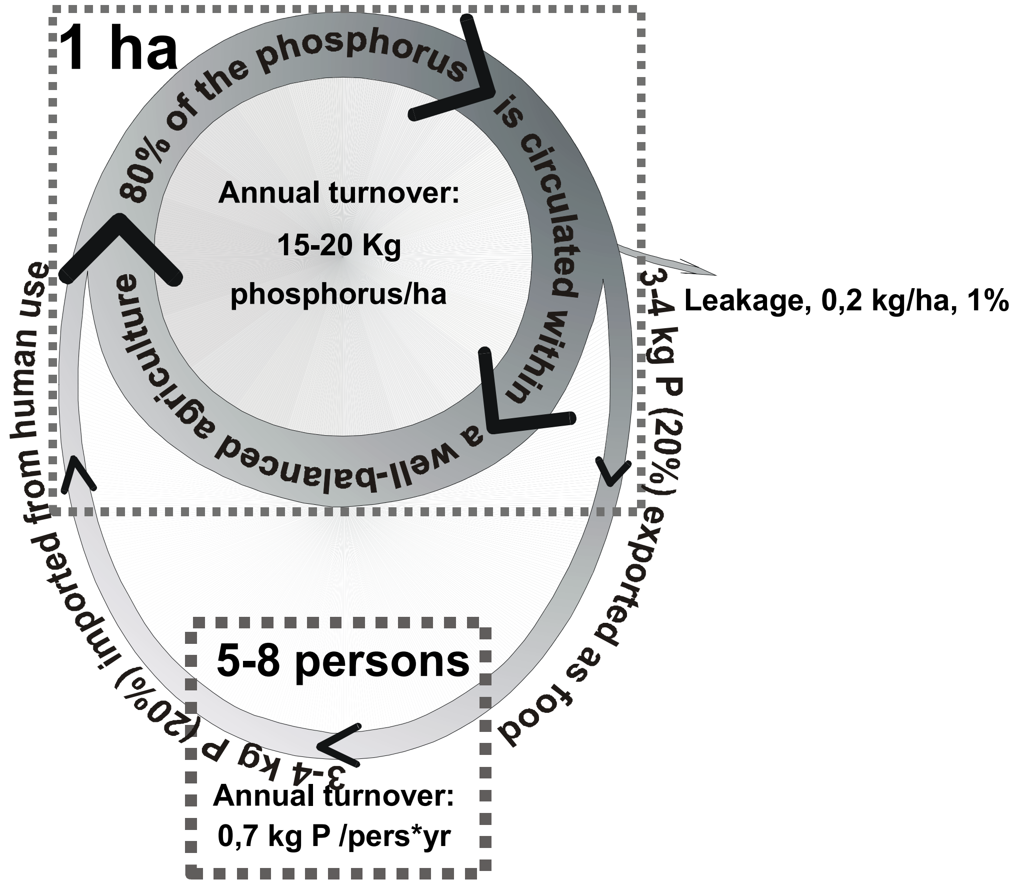

Figure 7. The phosphorus export from a hectare of balanced agriculture (i.e., one producing food for its animals) equals the phosphorus content of the excrements from 5-7 persons. This means that one person needs about 0.2 hectares of balanced agriculture for the production of the annual food needs.

Integration of agriculture and settlements

Most of the problems pointed out in the first part of this paper can be ascribed to the unintentional separation of agriculture and settlements, that developed as a side-effect of 'the industrial revolution' over the last hundred years. Re-integration of agriculture with settlements would be one way of solving the problems of increased vulnerability and decreased sustainability of the food system. Many of the environmental problems experienced today might also be alleviated by this strategy. Such a restructuring would also increase the ecological qualities of the society.

Alleviating the problems at different scale-levels: Micro-scale

It is also necessary to study different hierarchical levels (Allen & Starr, 1982). I will first try to outline an example of how some of the identified problems can be solved on the scale of a single agricultural unit and a simple small settlement (around 200 people).

Elimination of dependency for feed and nutrients

Assume an agricultural unit that produces both animal and vegetable products. Suppose further, that all the feed for the animals is produced locally. This will reduce the need for the import of nutrients by 60 - 90 % (Granstedt and Westberg, 1993). However, the export of essential nutrients in food will still amount to 3-4 kg $P*ha^{-1}*yr^{-1}$. For long-term survival of the system, this amount must be recycled. A human generates 0.6 - 0.7 kg P/year in urine and faeces. This means that the phosphorus content of the excrement from 5-7 people equals the losses of phosphorus in food from one hectare of a balanced agriculture (Figure 7).

From these figures, the area of balanced agriculture needed to support one person is obtained. This area is between 0.23 and 0.15 hectares, which is in agreement with the figure of 0.2 hectare per person calculated from the need of food for a person and a controlled production capacity of an average Swedish farm (Günther, 1989). A 40-hectare farm can thus support about 200 people for a majority of their food needs.

Thus, to diminish the acute dependence on outside support of nutrients, integration is needed between the production of animal fodder and the use of animal manure, and local settlements with the agriculture as a food producing system. This integration also implies diversification of agriculture because of the diversity of products needed by a population of consumers.

Elimination of leakage

The direct leakage of phosphorus, which in this article is chosen as a 'standard' nutrient from an agricultural unit, is within the range of 0.2 - 0.4 $kg*ha^{-1}*yr^{-1}$ (Brink & al., 1979). By the opening water courses and re-planting of buffer-strips, a large part of this leakage can be captured (Mander & al., 1991, 1994). Examples of reclaiming methods for the nutrients contained in the biomass would be compost, biogas sludge or ash. Such buffer strips also have other functions than the capturing of nutrients. In windy conditions, they also have a wind shielding function, increasing the yield 15 - 30 % within 15 meters from the vegetation strip. Other benefits of such vegetation are the increased occurrence of predators against insect pests (Andersson, 1990) and bumble bees for pollination (Hasselrot, 1960).

Economy

Another problem already noted above is the low and decreasing income of farmers. The extensive handling and transportation system between the producer and consumer is not only energy intensive, but also appropriates a large part of the price for food paid by the end-user, more than 75% (calculated from the figures in LES, 1991, 1993a, b). Furthermore, the income received by the farmer largely covers the cost for financial and material inputs paid by the farmer, which is about 85% calculated from the figures of Augustsson and Johansson (1995) (Figure 8).

With an increased integration of agricultural units and settlements, direct trading between the farmer and the consumer becomes possible. If the farmers were given half the price for food that is paid by the consumer today, this could increase his income five to six times. The consumer could also reduce the cost for the food produced by the farmer by about half, both figures assuming that the product price to the farmer is 25 % of the consumer price (a figure that is somewhat high).

Today, the farmer's earnings are 15 % of his income (Augustsson and Johansson, 1995), which represents not more than 3.6 % of the market price in the shop. Assuming that the production cost would increase by 30 % because of the increased diversity in agriculture, a fifty-fifty agreement between a farmer and a local settlement would still increase the payment to the farmer from 3.7 % of the shop price to 22 %, or about six times

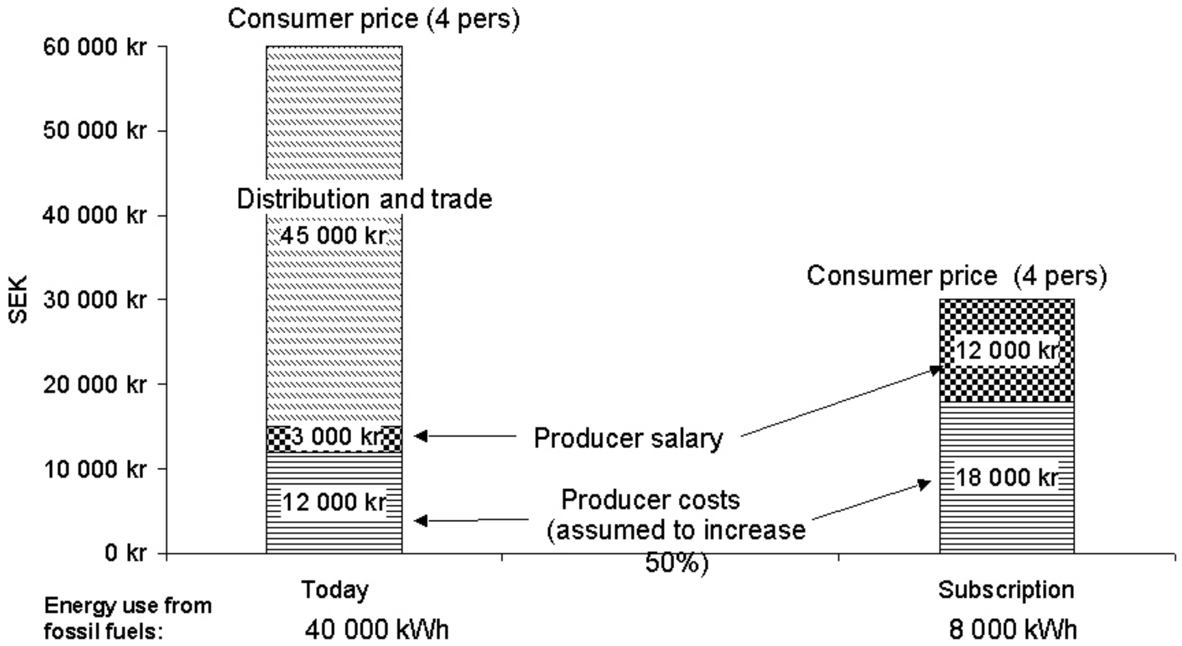

Figure 8. A direct co-operation between an agricultural unit and a local settlement would be economically favourable, not only for the consumers, but also for the farmer, even if the production costs would increase with 50%.

A rise in farmer income of that magnitude can be expected to enforce even large changes in agricultural practice.

Medium scale

The implementation of the above-proposed solutions is compatible with intermediate size settlements. Three or four settlements with their associated farms can form groups of 800 - 1,200 persons and an associated agricultural area of 160 - 240 hectares. If areas also are used for the improvement of local ecosystems, 170 - 260 hectares can be expected to support these people. This population size is large enough for the establishment of a common social infrastructure, such as primary schools and small service business. However, it could be argued that this size of settlement is not enough for non-agricultural production, such as cultural needs and service provisions, and that this may generate an increased need for transportation. For the sake of discussion, however, imagine an area where such settlement types cover the land. In such an area, not regarding the incidence of lakes, mountains etc., there would be a population density close to 500 p/km^2, which might be enough for a diversity of direct social interactions, although not the amount we are accustomed to in high density urban areas.

Large-scale implementation of the proposed solutions: Ruralisation

Nutrient circulation becomes increasingly expensive with increasing spatial distribution ranges (Günther, 1998). The energy requirements for distribution of food also tend to increase in quantum leaps when the distribution pathways require extensive packaging and preservation of the products. As pointed out earlier, solving these energy requirements by means of fossil fuels increases the vulnerability of the society above the level needed if only basic provisions are made for human and environmental security. The only solution left, if the goal were this security, would be to maintain basic energy flows from renewable sources, i.e. solar, and reduce the external energy requirements for all sectors to the lowest level possible.

The means of providing agriculture with its ‘ultimate’ raw material, phosphorus, would also need change. A system of linear flux of phosphorus through society over a prolonged time is both wasteful and insecure. Therefore, to attain nutrient circulation and at the same time reduce energy support requirements in large societies, a different strategy of societal structure should be chosen: The current trend towards increasing agricultural specialisation combined with urbanisation should be replaced by a closer integration of farms and settlements.

A name for such a strategy is *ruralisation*, as opposed to urbanisation. This development strategy implies a successive replacement of houses in need of extensive restoration or rebuilding. Instead of building new houses in existing urban areas, small settlements integrated with agriculture as outlined above would be created in the hinterland of the urban areas. Many of the problems outlined could be alleviated by this strategy.

CONCLUSIONS

In this overview, I argue that agriculture is afflicted with a lot of structural problems that cannot be alleviated by further rationalisations of agriculture along current lines, for food system problems reflect general structural changes of society. They must be resolved by new structural solutions as outlined.

The problems include:

- dependency on industrial energy support
- constant input of nutrients and other materials
- inescapable loss of nutrients, which is an effect from
- linearity of the nutrient handling system

They are aggravated by the following factors:

- ongoing specialisation of agricultural units
- decreasing population working with agriculture

- urbanisation
- a dependency on cheap energy
- a probable increase in fossil fuel prices

I have argued that these problems, as well as others, could be alleviated by a gradual transformation of settlement systems called 'ruralisation' and a closer integration of agriculture and residential settlements, this would:

- minimise dependency on industrial energy
- increase nutrient circulation
- increase integration between agriculture and other social activities
- increase and support ecosystem services received

The economic and sound benefits of such systems may well seem to be considerable, especially given the anticipated price rises and vulnerability of modern industrial agriculture. If one reflects more deeply on recent information on future access to fossil fuels, it is hard to conceive of a sustainable society that is not principally powered by solar energy.

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