

## **Phosphorus management and societal structure**

Hampered effluent accumulation processes (HEAP) in different areas of the  
Swedish society

## **Fosforhantering och samhällsstruktur**

Akkumulationseffekter i det svenska samhället

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### *Abstract:*

Some of the problems of phosphorus pollution and source exhaustion are identified to be time-dependent, structural problems. This is demonstrated to be the case in land independent animal production, in urban settlements and in the wastewater treatment — landfill cycle. A calculation indicates that saturation of the systems can take place in the time range of 20 - 100 years. After this time, inputs will be converted to leakage. It is maintained that structural problem must be solved with structural solutions. To avoid leakage problems, phosphorus circulation must be attained. A scenario analysis investigates the effort-result of some possible systems to attain phosphorus circulation. The results show that the cost/benefit efficiency of increasing attempts of phosphorus recycling will not increase considerably in spite of increased ambitions if the current habitation structure is kept. However, integration of the population with its supporting agriculture will increase this efficiency with about four orders of magnitude.

Key words: accumulation processes, balanced agriculture, energy efficiency, integrated habitats, nutrient recycling, phosphorus management, scenario analysis

### *Svensk sammanfattning*

En del av problemen med förorening och resursutarmning av fosfor har identifierats som tidsberoende, strukturella problem. Detta är fallet med såväl ackumuleringen och läckaget från djurproduktion där fodret producerats på annat håll, som de tätorter där fosfor renas ur avloppsvatten och läggs upp på tippor eller placeras på närbelägna jordbruk. En beräkning ger vid handen att mättnad av områdena kan uppnås inom 20 – 100 år. Därefter kommer läckaget att motsvara införseln av fosfor. I uppsatsen framhålls att strukturella problem av denna typ måste lösas med strukturella lösningar. För att undvika läckaget måste fosforcirkulation uppnås. En scenarioanalys utvärderar med hjälp av en cost-benefit analys olika metoder att uppnå fosforcirkulation från en stad av Stockholms storlek. Trots ökade ansträngningar för förbättrad fosforcirkulation ökar inte återvinningen per ansträngning nämnvärt vid den nuvarande bebyggelsestrukturen. En integration med jordbruk som tar hand om fosforrika restprodukter och levererar dem i form av mat ökar emellertid effektiviteten med tre till fyra tiopotenser.

## INTRODUCTION

Nutrients are elements that are, well known, to be necessary for biological life. Elements without important gaseous phases, e. g. like phosphorus are transported in solid or liquid forms, which makes them less mobile and more prone to local accumulation than other elements. Phosphorus is an important element in both animal and plant life. It is probably the element that is easiest to become limiting to living organisms because in biological structures it is needed in fairly large amounts. On the other hand, it is also an important pollutant in coastal and inland waters. The element could therefore be chosen as an excellent example of a pollutant as a resource in the wrong place. Ecosystem change during maturation tend to close nutrient cycles and minimise leakage (Odum, 1973, 1985; Schneider and Kay, 1993), since loss of nutrients diminish their capacity to use solar exergy. The regenerative cycle of ecosystems, coupling the increasing exergy consumption capacity of ecosystems with an increasing efficiency of nutrient cycling (Günther, 1994b), seems to be a universal principle for ecosystem development.

The demographic changes during industrialisation, with urbanisation and rural population reduction, have transformed the nutrient, and especially the phosphorus management system from a fairly circulating one to a mainly linear one (Günther, 1988; Günther, 1993; Günther, 1994a). This constitutes an accumulation of the nutrients to the most populated areas. To avoid pollution from phosphorus in local waters, advanced wastewater treatment systems with phosphorus precipitation was introduced in Sweden in the seventies. The sludge, containing the precipitated phosphorus is deposited rather close to the densely populated areas, either in landfills or in local agriculture.

The throughput of materials evolved as a standard in the industrial society has lead to more or less linear flows of phosphorus, resulting in pollution of inland and coastal waters with this nutrient. Together with the problems of source depletion, efforts to stop this pollution have lead to an accumulation and concentration of phosphorus in the urban area. A non-cyclic transport path of nutrients will therefore result in either a loss in the end of the line or an accumulation if the flow is hampered in the end. The hampering will lead to an accumulation that sooner or

later will induce a leakage that is equal to the inflow. Such processes are referred to as HEAP traps (Hampered Effluent Accumulation Processes) (Günther, 1997).

Studies regarding phosphorus leakage have often been concentrated on leakage due to wind and water processes in normal farmland (for example SNV 4731), but the type of nutrient management in the agriculture (e.g. accumulation or export agriculture) has seldom been taken into account.

The aim of this paper is to analyse and discuss where HEAP-traps may occur, indications for their occurrence and possible way to adjust flows in order to avoid them. This study also tries to estimate the size and the sites of the problems caused by linearisation of phosphorus transfer. Finally, some possible solutions to the problems will be evaluated through a scenario analysis discussing the effort needed in different societal structures if the aim is to maintain circulation of phosphorus.

## **Methods**

To analyse where HEAP-traps may occur in the society, data available in general statistics of Sweden 1990-1994 was used. Furthermore, published papers regarding agricultural practices, animal and human metabolism and phosphorus budgets were used. The attained data were used to study the hypothesis of the HEAP-trap (Günther, 1997) in different areas of the Swedish society.

To compare different solutions of the problem of attaining phosphorus recycling that is as inexpensive in energy terms as possible, a scenario analysis was performed. Four different scenarios were constructed with different levels of phosphorus cycling. The scenarios were chosen according to the four different strategies pointed out by Hill (1990), *Current method* (Scenario A), *efficiency* (Scenario B), *substitution* (Scenario C) and *rethinking* (Scenario D).

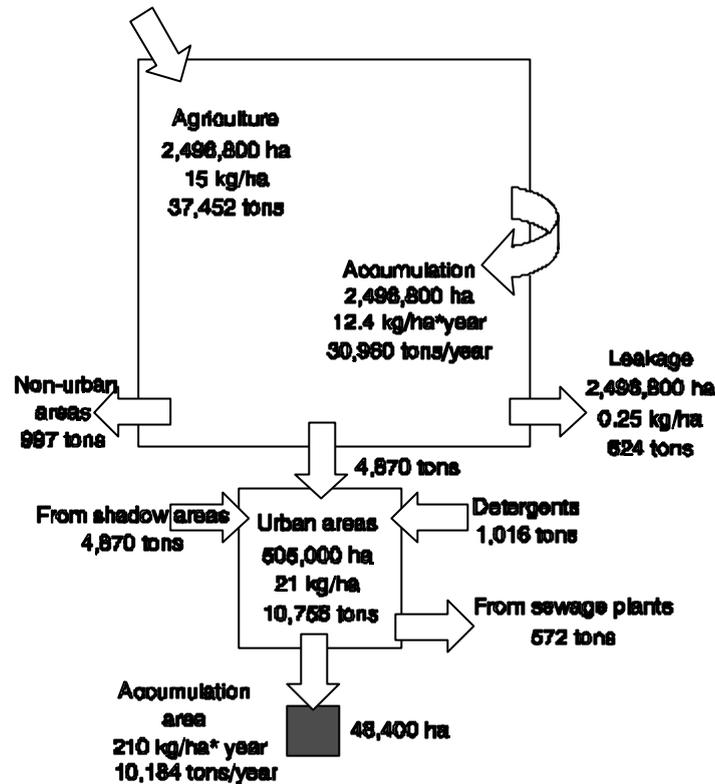
The scenario analyses regarding urban form are based on a study of the phosphorus budget of Stockholm (Forsberg and Rengefors, 1992) and the studies of Granstedt and Westberg (1993). Additional data was used from studies of the nutrition of the Stockholm population

made by nutritionist Eva Kallmer, Huddinge Hospital, Stockholm (1993) and studies of the nutrient intake by the Swedish population by Wulf Becker (1992). Data on the distribution of agricultural land near Stockholm was received from the Regional Planning Office of Stockholm County Council by the co-operation of Lars Österdal (1994). Additional data on transportation ranges, loads, fuel and other was amicably posed by Gunnar Thorsson (1993), director of transportation at RagnSells Agro Ltd., the company administrating the transportation of the sludge from the water treatment plants in the Stockholm area.

## **DIFFERENT ACCUMULATION SITES**

The society of today is often organised in a specialised way. This leads to a seclusion of different activities. In the modern urbanised society, a very large part of the population lives in a comparatively small part of the land. In Sweden, a sparsely populated country, with a population of about 8.6 millions, 7.1 millions, 83%, live in densely populated areas, occupying about 1.2% of the land area (SCB, 1993). The food is transported from a large area to a small one, which leads to a concentration of nutrients in the most populated areas. With modern communications, the food comes from almost the entire planet. This constitutes a linear transportation of phosphorus from mines via agriculture to cities, and from cities to deposition areas or directly into seas or lakes. Advanced wastewater treatment with phosphorus precipitation stops a large part of the phosphorus from being exported directly to nearby water systems (Balmér and Hultman, 1988; SCB, 1993). It has, however, been shown that efforts to hamper the point source effluents from the urban area will increase the accumulation of phosphorus in the total area where the element is deposited, i.e., in refuse dumps, suburban agriculture, golf links or other sub-urban storage (Forsberg and Rengefors, 1993). This process is described in Figure 1.

**Figure 1** Also in the vicinity of densely populated areas; there may be a serious accumulation of phosphorus, leading to future non-point-source pollution and losses of vital nutrients.

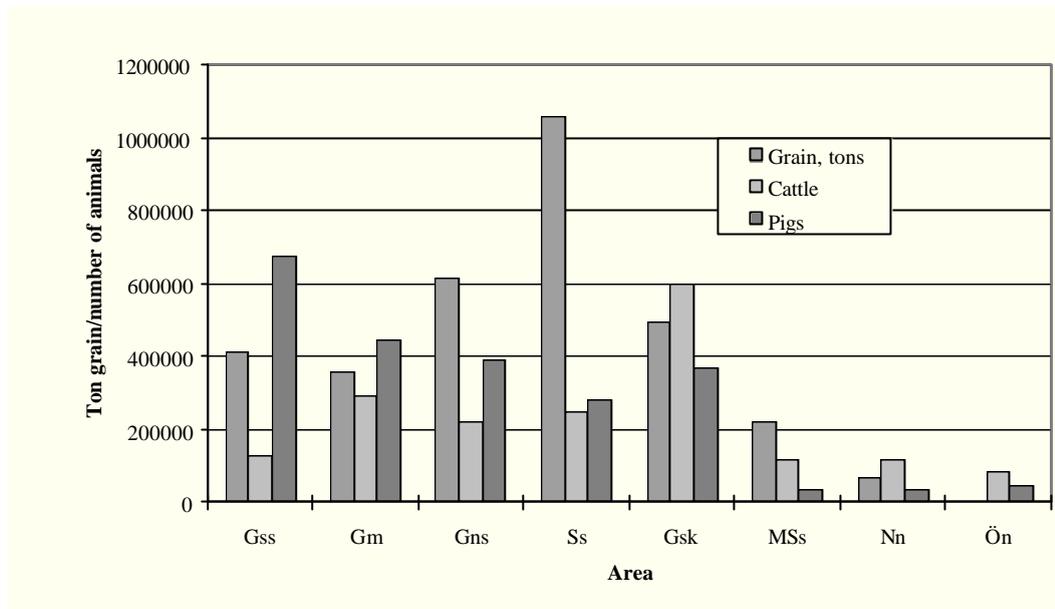


The figure regards the situation in Sweden in the first part of the 1990-ies. Raw data for calculations were taken from Forsberg and Rengefors (1992), Granstedt and Westberg (1993), KEMI (1994), SCB (1993) and SCB (1994).

### Agriculture

The practice to produce animal feed outside the area where manure from these animals can be recycled, separates the agriculture into two types: the *export* agriculture, where nutrients are imported as fertilisers and exported as food or animal feed (the type that is dominating in Svealands slättbygder, Ss, in Figure 2), and the *accumulation* agriculture where phosphorus sludge or manure are accumulated in excess (typical for Götalands södra slättbygder, Gss, in Figure 2). In many areas, these two types are intermixed, and there can also be an excess use of fertilisers where the nutrients contained in the sludge or manure is underestimated.

**Figure 2** Feed grain production and domestic animals in Sweden 1993.



The aim is to show the relation between the amount of feed grain production and the number of cattle and pigs in different agricultural areas in Sweden, (From South to North are these: Gss: Götalands södra slättbygder, Gm: Götalands mellanbygder, Gns: Götalands norra slättbygder, Ss: Svealands slättbygder, Gsk: Götalands skogsbygder, MSs: Mellersta Sveriges skogsbygder, Nn: Nedre Norrland, Ön: Övre Norrland) The difference between feed grain production and animal husbandry induces transportation of animal feed with an accumulation of food-related nutrients in areas with dominating animal production. Extremes are Gss (Götalands södra slättbygder) where animals dominate and Ss (Svealands slättbygder), where feed grain production dominates. (SCB, 1994)

If the amount of phosphorus in the imported feed regularly exceeds the amount exported as agricultural products; there will be an accumulation in the area. Such areas dominate in the watersheds of the rivers Lagan, Braån and Helge å in south Sweden, hence the pollution problems in the Laholmsbukten and Hanöbukten in Southwest and Southeast of Sweden.

The transport history constitutes a forked linear flow of phosphorus from mines to urban areas, with two accumulation areas: agriculture specialised for animal production with imported food and areas in the vicinity of densely populated areas, as cities and towns. There are Swedish regulations regarding the amount of animals that are allowed to be held per land unit (SJVFS 1991:128; SJVFS 1997:26).

The correlation coefficient of feed grain production and number of animals in Figure 2 can be calculated. A high correlation coefficient indicates a high self-sufficiency of feed grain. In this case, the coefficient feed grain production and number of pigs is 0,46, and the correlation

between feed grain production and number of cattle is 0,39. This means that there is a large transportation volume from areas of feed grain production to areas of animal production. To this, a large extent of imported animal feed is added based largely on soymeal (60,000 tonnes 1993) and fish (24,000 tonnes) (SCB, 1994). Dry soybeans contain about 0,55% of their weight as phosphorus. The import of soymeal 1993 therefore corresponded to a net import of phosphorus of over 332 tonnes, about 1,7% of the 19,000 tonnes imported as fertilisers. The same figure for fishmeal is about 3,8%. The primary agriculture does not allow for extensive accumulation since these areas are primarily fertilised to compensation of the losses of nutrients in the harvest.

An example of the HEAP effect can be found in the local pollution by dense agricultural units. Today a large part of the pig meat production in Sweden comes from "pig-towns", large factories often situated in south Sweden, while the food for the pigs to a large extent is grown in central Sweden (SCB, 1994). The net import of pig-feed into the area, and the fact that most of the food used by the pigs is converted into pig manure and the ambitions to spread the pig manure over large areas will therefore induce a local HEAP-effect, which may cause leakage and environmental problems. This situation is brought about by unbalance between pigs and pig-feed production, and will occur even if all the pigs originated in the area are exported.

Importing fodder to animals always implies an accumulation of nutrients in the area because of the metabolism of the growing animal. Illustrated by the following example from pig production (Simonsson, 1990):

P in fodder for 100 kg pig (mainly imported)	1,60 Kg
P/ 100 kg pig (exported)	0,46 Kg
P as excrements (accumulated)	1,14 Kg

Since the manure is spread over a comparatively small area, such areas are at risk of over-fertilisation. To avoid this problem, at least 70% of the feed for the pig need to be grown from crops fertilised with pig manure. From statistical figures regarding the amount of cows and pigs and manured areas (SCB, 1994) combined with the knowledge of annual phosphorus in cow

and pig excrements, a rough estimate of the amount of phosphorus on pig manured areas was calculated.

**Table 1** The amount of phosphorus on pig-manured area in South Sweden (Gss and Gm in Figure 2) based on a calculation from the amount of manured areas and the amount on pigs/cows in the area.

<b>Kg P per hectare fertilised with pig manure</b>	
Hallands län	84
Kristianstads län	96
Malmöhus län	62
	79 (avg)

The input data in this calculation are taken from SCB , 1994 and SLU, 1987

The calculation indicates that areas fertilised with pig manure on the average get more than four times more phosphorus than areas fertilised according to the general advice from the Swedish agricultural authorities (15 kg/ha).

#### *Balanced agriculture*

In balanced agriculture, animal food is produced in the same area as the animals are raised. This reduces both output and input of nutrients in the agricultural system extensively. To be perfect in this way, such a system should also include methods to regain nutrients exported as food and as leakage. From figures of Granstedt and Westberg (1993) and (Brink, 1979; SNV 4730, 1997; SNV 4425, 1995), a balance for an ideal balanced agriculture regarding the phosphorus can be calculated.

A calculation of the phosphorus circulation capacity with different production — consumption capacities:

	Kg P/ha
Circulation between animals and plants	15
Export as food (high figure)	4
Leakage from agricultural land	0,25
Annual P turnover in one person	0,7
Total amount of P in active transport	19,25

#### *Circulation capacity:*

If nutrients are circulated between animals and feed	78%
If nutrients are returned from food produced for humans	99%
If measures are taken to stop leakage	100%

To avoid the direct threat of a HEAP-trap (Günther, 1997), the feed for the animals must be grown in the vicinity and fertilised with the manure from the animals. This attains about 80% circulation of nutrients. If waste products from food export and human urine and faeces from about 5 persons/ha are returned to the agriculture, about 99% circulation is attained. The last percent can be returned if plants are grown close to the ditches from the agriculture (Mander and Muring, 1994), harvested, and in some form returned to agricultural land.

### **Urban vicinities**

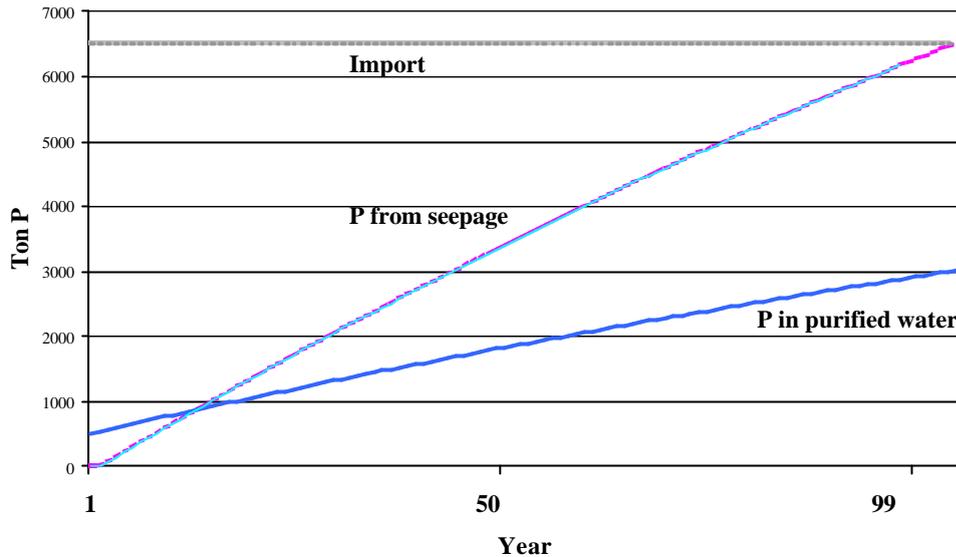
Although there is a large leakage on the way, the end of the transport routes for phosphorus is the densely populated area, since the phosphorus principally follows the food chain: primary agriculture (feed production)  $\Rightarrow$  secondary agriculture (animal production)  $\Rightarrow$  urban area. Earlier this flux gave rise to large pollution problems in the lakes in urban areas, since human faeces and urine was exported from the waste water pipes into nearby waters as point source pollutants. After the introduction of advanced wastewater treatment plants with phosphorus precipitation in the seventies, the point source discharges were largely diminished.

The sludge containing phosphorus was disposed of in either landfills, nearby agriculture or as plant pot soil, further discussed in (Günther, 1988; Forsberg and Rengefors, 1992; Günther, 1993, 1994a, 1997). As a result of a boycott from the farmer's union 1989-1993, the part of the sludge deposited on agricultural land diminished to about 20% 1992 (SCB, 1994b) from an earlier share of about 50% (SCB, 1990). In 1996, the share of the sludge deposited on agriculture had recovered somewhat, to about 30% (SCB, 1997). During the last decade, about 4000 - 4500 ton phosphorus is annually put in landfills. From landfills there is an annual leakage due to rain percolation. A part of this water is returned to waste water plants for purification and the remainder sinks to the ground water for later transport into lakes and seas.

There will be an accumulation of phosphorus if a large part of the sludge is conveyed to landfills, hence leading to an increased leakage and an increased amount of phosphorus coming with the leakage water for purification in the waste water plants. Since the efficiency in these

plants seldom exceeds 92%, with increased amounts processed, the 8% remaining will increase in absolute amounts, thus leading to an increased leakage.

To accommodate the model to the Swedish reality, it was adjusted to the amount of phosphorus in sludge from municipal purification plants in 1995, which was 6,000 tons (SCB, 1997). With the normal purification efficiency, this means that about 6,550 tonnes entered the wastewater system, to be purified. This implicates a connection of roughly 8 million persons to the municipal system. Assuming 1%, of the stored phosphorus is leaking from the landfills and taken to municipal waste water plants for purification, and that nothing was stored there before 1996, both very conservative assumptions, an increasing amount of phosphorus will be trapped in the circuit. This leads to a situation where an increasing part of the input will exit the circuit as leakage. After a short time, 10-20 years, the leakage from the landfills taken care of in the sewage system will be of the same size as the amount of phosphorus that is not caught by the waste water plants. In this situation, it can be said that there is a throughput of phosphorus from the landfills to lakes and seas. As can be seen in Figure 3, the situation aggravates thereafter, and an increasing amount of the handled phosphorus will appear as seepage. After a century, the amount of phosphorus in the seepage will be of the same size as the import to the system. The system urban area — wastewater plant — landfill will then be leaking about half the import to the system, which can be seen as a collapse of the wastewater purification system. In practice, however, also a part of the sludge is put on the agriculture, and some of the seepage from landfills will not be taken care of. The amount leaking in this way will aggravate the situation depicted in Figure 3.



**Figure 3.** Output of the landfill — wastewater plant circuit model.

This calculation uses the assumptions discussed in the text above. It shows the increasing leakage due to the accumulation process emanating from an *efficiently* working wastewater management system.

### SCENARIO ANALYSIS

In order to attain a scenario analysis, the phosphorus flow of Stockholm city, Sweden was studied. Calculations are done to estimate the energy needed in different levels of ambition for nutrient recycling. These calculations are used to estimate effort and efficiency indexes for the handling of the phosphorus used by the urban population.

Forsberg and Rengefors (1992) studied the budget of phosphorus in the city of Stockholm. The city has a registered population of 920,000 in the city area and an annual turnover of about 1,000 tonnes of phosphorus. An analysis of this study shows that the phosphorus imported to the urban area is deposited on a land area of about 1/60 of the area for food production. This includes a heavy deposit on waste disposal plants (744 tonnes, 82% of the phosphorus imported to the urban area) and a high farmland deposit. The average deposit, 33 kgs/year, deposited once per five years as an application of 166 kgs/hectare, is considerably higher than the normal agricultural practice of 10-15 kgs/hectare\*yr (Jordbruksverket, 1997).

The problem of circulating nutrients from a city of the size of Stockholm turns out to be two-fold: to avoid the accumulation in the area and to diminish the efforts invested in recycling. Increasing the ambitions of nutrient recycling extends the area needed to receive the nutrients, which also increases the transport demand. An increasing transport demand increases the amount of energy needed, which could be unsustainable in a future. To simplify the computations, only phosphorus is calculated for. However, in two of the scenarios, nitrogen as nitrate or urea is also recycled in considerable amounts, on behalf of its coincidence with phosphorus in the urine.

### *Indexes*

The calculations compare the *efforts* needed for recycling of phosphorus. Bases for these are the transportation cost of waste of different types. To evaluate different methods of attaining recycling of phosphorus, the fuel cost of returning the phosphorus to agriculture and the achievement of recycling is estimated in the four different scenarios. This cost is set at the current cost per tonne-kilometre, SEK 0.08. However, as this cost is considered the same in all the four scenarios, its actual value is not essential. Rather, the comparative cost in the different scenarios is of importance. In this analysis, the fuel cost is taken as an *index* of the total societal effort needed for the redistribution of phosphorus, not as an estimate of the actual total cost. The cost for producing and maintaining lorries, salary charges, cost for building, persevering and operating the sewage system, the waste water treatment and waste deposition plants are thus *not* included. Nor are the investments for collection and distribution of the nutrients, neither the economical benefits received by the diminished wastewater treatment work and the substitution of urine and composted solid waste for fertilisers.

This comparative cost, called the *effort index*, is set to 1 in scenario D. It should be as low as possible to avoid vulnerability in a situation with rising absolute energy prices. This effort index is then compared with the accomplishment of the goal: *to redistribute the nutrients to an area equal to that needed for a sustainable production of food for the population*. Since a large effort in some of the scenarios does not result in a corresponding redistribution, the effort index is then multiplied with the concentration of phosphorus in the area to illustrate the achievements due to the investments in phosphorus recycling.

Four different scenarios were investigated:

*Scenario A. Current practice*

The conditions as reported in (Forsberg and Rengefors, 1992). The phosphorus handling method used 1991, as studied, with a ratio of accumulation of phosphorus 60 times in the suburban area compared to the food producing area. Here, 1.7 % of the phosphorus and only a small part of the nitrogen can theoretically be recycled (provided the area where phosphorus is deposited really produces food that is used in the city, which is not always the case). 0.02% of the area surrounding the city within the maximum transportation range (125 km) is used for deposition of phosphorus on agricultural land.

In the computations a total annual input of 998 tonnes of phosphorus is accounted for (Forsberg and Rengefors, 1992), of these 832 tonnes appear in the water entering the sewage treatment plants and about 166 tonnes in the organic part of the solid waste. The wastewater treatment plants produce a sludge containing 761 tonnes of phosphorus. In the current situation, 744 tonnes (82%) of the phosphorus entering the urban area is deposited in waste deposition plants, and 183 tonnes are transported to 1,100 hectares of agriculture (once every fifth year, the actual area involved is thus 5,500 hectares) situated at the furthest 125 km from the city. The remaining, about 71 tonnes follow the purified wastewater into the Baltic sea.

In the phosphorus budget by Forsberg and Rengefors , 140 tonnes of phosphorus enter the waste water treatment plants that could not be accounted for by the 0.92 millions registered to live in Stockholm municipality. A possible explanation of this is that a part of the population using the water treatment system of Stockholm during the day, lives outside the border of the city municipality. Besides this extra input, a quantity of phosphorus enters the city as detergents, via industries and communication and as rainfall. In the study this amount is calculated to 126 tonnes. This means that the population of Stockholm (or any other city) actually uses more phosphorus than its input as food. For simplicity of calculations, all the phosphorus is considered, as it was 'food' phosphorus used by a 'virtual' population.

To calculate a 'virtual' population, the total amount of phosphorus imported to the Stockholm area is divided with the annual per capita excretion of phosphorus, 0.61 kgs. The "virtual" population of Stockholm is about 1.63 millions and is used to calculate a "virtual" food area

(332,533 ha), onto which the phosphorus need to be circulated if concentration should be avoided. The theoretical recycling of phosphorus is then found by dividing the virtual food area with the area actually used for redistributing phosphorus (1,100 ha). In this case, the theoretical maximum recycling is about 1.7 %, and the concentration of phosphorus is 60 times compared to the agricultural area (0.2 hectares/person) needed to produce the food. The amount redistributed to agricultural areas is limited by economy, not by the land available (Öster, 1993, pers. comm.).

**Scenario B.** *Efficiency, recycling of all phosphorus in the sludge*

The same city as A, but in a state where all the phosphorus in the sludge is deposited in agricultural land in appropriate amounts, i.e., it is assumed that animal food is produced in the same area as the animals are raised, in order to avoid accumulation and steady state leakage of the type discussed earlier.

Redistribution of all the sludge from waste water treatment plants to accomplish an annual load of phosphorus on the agricultural area of 3 kg, which is considered the net export from a balanced agriculture with food production for the animals and recycling of manure (Granstedt and Westberg, 1993; Günther, 1993). This improves the possible recycling of phosphorus to 76%. The solid waste, however, is placed in waste deposition plants as usual. Some legal or political formal statement is assumed in this case and the next, leading to an increase of the area for sludge deposition by a factor of 50. Thus, 1% of the area surrounding the city within the maximum transportation range (extended to 127 km to attain area enough) is used for deposition of phosphorus on agricultural land. Therefore, the average transportation length is not considerably increased, only the rate of transportation.

In this case, the same figures are used as in the study described under scenario A, but all the sludge from the waste water treatment plants is supposed to be redistributed to agricultural land in appropriate amounts, that is, what is supposed to be the net export from a balanced agriculture according to the Granstedt and Westberg study (1993), about 3 kgs per hectare. Actually, since this figure is used in all the scenarios, its size does not change the indexes in the results. The term '*balanced agriculture*' here means an agriculture with both animals and plants, producing the food for the animals at the agriculture and using the manure to fertilise the

plants. The only export of phosphorus from agriculture of this type would be that in the food produced for human consumption. Here, about 76% of the phosphorus entering the urban area is circulated. As the phosphorus in the solid waste is deposited on waste deposition plants, this gives a concentration of 1.31 in the urban area compared to the virtual food area. The term 'urban area' in this article means the *total* area, both the one used for residence and the one used for redistribution of phosphorus.

**Scenario C.** *Substitution: Recycling of all available phosphorus*

A case where all the phosphorus entering the city is carefully redistributed to agricultural land in appropriate amounts. This scenario considers recycling of most of the phosphorus (96 %) imported to the urban area and redistributing it to a food producing area of a size needed for the population of Stockholm. This is accomplished for example by collection of urine with its content of nitrogen, phosphorus and other nutrients by means of source-separating toilets. Redistribution also includes the phosphorus in the organic part of the solid waste. Faeces, detergents and other sources of phosphorus are supposed to follow the wastewater to treatment plants with 91% efficiency in phosphorus precipitation. The sludge from this treatment is then distributed on agricultural land, but 7% of the phosphorus imported to the area follows the purified water to the sea. All the available phosphorus is then circulated in adequate amounts. There is no concentration in the area, but as some of the phosphorus is lost in wastewater treatment, why the theoretical recycling is only 96 %. Also here, 1 % of the area surrounding the city within the maximum transportation range (this time 140 km) is supposed to be used for deposition of residues containing phosphorus.

In this scenario, the ambitions are set to total recycling, regardless the cost. The urine from the population is collected by means of source-separating toilets. Faeces and other sources of phosphorus are in this scenario transported to waste water treatment plants with the ordinary treatment pattern, resulting in sludge that is transported in adequate amounts to agricultural land. The solid waste is imagined to be separated into a non-organic and an organic part, the latter part is composted and returned to agricultural land. This combined conduct is supposed to return all phosphorus but a minor part (the one expelled by the wastewater treatment plants after the purification of the water) to agricultural land. In this case also a large part of the nitrogen, that in the urine, is returned to the agriculture.

**Scenario D.** *Rethinking: Changed settlement structure*

A case where the population of Stockholm is hypothetically thought to be divided into small communities, with elementary population units of about 200 inhabitants, each one surrounded by an appropriate amount of supporting balanced agriculture as described in the *ruralised town* scenario (Günther, 1993b; 1994a). Here, after the food is consumed, all the nutrients are returned to agricultural land in the same rate as they are taken away. The nutrients are re-distributed to the agriculture with the same load and cost per tonne-kilometre transported as the above scenarios. In this case, 80% of the area surrounding the village within the maximum transportation range (0.54 km) is used for deposition of phosphorus on agricultural land.

In this scenario, instead of redistributing phosphorus in a series of elaborate ways, the population is thought to be distributed over the agricultural area that produces food for the population. The integration between population and agriculture is thought to be so thorough that every group of 200 persons are surrounded by a balanced agriculture producing the food and receiving all the nutrients in the waste and the excreta. In this scenario, all the phosphorus, and most of the nitrogen (everything that is not lost in gaseous form during the management process) is returned to the agriculture. Thus recycling of phosphorus is 100% and concentration is 1.00, somewhat better than scenario C above, where some phosphorus was lost to coastal waters during the purification process. The redistribution of other substances, as nitrogen and potassium, is also more efficient than that of scenario C. The nutrients are distributed to agricultural land in adequate amounts every year instead of five times the adequate amounts every fifth year. This conduct is more energy intensive than the above used, but is considered more ecologically adequate (Ivarsson, 1989). For the purpose of comparison, the energy cost per km transported weight in returning the nutrients to the agriculture is assumed to be the same as in the other scenarios. The figures from the "villages" are then multiplied to equal the population of Stockholm.

The different scenarios are summarised in Table 1 and Table 2, The results, indicate that there is a considerable difference in the effort necessary for the achievement of phosphorus recycling between scenarios A, B, C (centralised city) and D (distributed population integrated with agriculture) respectively. The differences are three to four orders of magnitude.

**Table 2 Summary of the four different scenarios for phosphorus recycling**

Scenario	Food producing area (ha)	Nutrient receiving area					Max. circulation / Concentration in the settlement area	Direct to lakes and seas, ton
		Agriculture		Landfill		Excess area		
		ha	ton	ha	ton			
<b>Current method (A)</b>	188,500	5,500	183	50	744	-183,000	1,7% / 60	71
<b>Efficiency (B)</b>	188,500	253,883	761	50	166	65,383	76% / 1,3	71
<b>Substitution (C)</b>	188,500	319,194	958	0	0	130,694	96% / 1	28
<b>Rethinking (D)</b>	188,500	188,500	986	0	0	0	100% / 1	0

These figures are calculated from the initial figures in the phosphorus budget by Forsberg and Rengefors (1992), with the modification indicated in the text.

**Table 3** Calculated Cost/benefit index.

Scenario	Population	Total fuel cost for P transportation, (MSEK)	Fuel cost, (SEK per capita)	Effort index	Cost/benefit index
<b>A</b>	920000*1	3.64	3.96	154	9248
<b>B</b>	920000*1	5.54	6.02	235	307
<b>C</b>	920000*1	7.52	8.17	319	319
<b>D</b>	200*4600	0.024	0.03	1	1

The effort index is calculated by dividing the effort cost in Scenario A, B and C by the effort cost in Scenario D. The efforts in the different scenarios lead to different accomplishments, from which a *cost/benefit index* is calculated by dividing the cost for circulation with the effort index. This index should be as low as possible, indicating high circulation by a low effort.

## DISCUSSION

The examples in this study serve to demonstrate that hampered linear flows of non-gaseous elements lead to accumulation and ultimately to large leakage (the HEAP trap), and that is an actual threat to societies that have a tendency to separate activities as food and feed production from the human and animal populations. This can be seen in the tables 1-3. The calculations indicate that the process of saturation is quite fast, from 20 -100 years with current flows. This situation is unsustainable. To avoid it, cycling of phosphorus is necessary. The study also indicates that if the ambitions for recycling of phosphorus are substantially increased over the current level, the efforts needed will increase at least two to three times. However, if aims are set to zero accumulation in the area and a high level of recycling, the increased efforts will not pay substantially despite high investments in recycling.

Changing the structure of the population toward a settlement type with increased integration with agriculture seems however to be rewarding. In the situation of a dispersed population, a certain investment (in a broad sense) in efforts for recycling rewards about four orders of magnitude more than the investments for phosphorus recycling used in the current situation with a centralised city. The calculations in the study also point out the increasing energy dependency in the recycling of nutrients if a settlement grows and concentrates from its support area, an issue seldom discussed in literature.

To ascertain the constant supply of phosphorus necessary for any sustainable human population, phosphorus must be circulated between the population (of humans in this case, but it is naturally also necessary for other animals) and the food producing area. To rely on a diminishing and fossil energy demanding supply from mines is not compatible with sustainability. To be able to plan for a society that is able to maintain the nutrient cycle in a variety of situations regarding energy availability, transportation difficulties and the like, knowledge of structural limitations is of importance. The problems pointed out in this study are not due to malfunctions of technical systems, but rather to structural fallacies. Therefore, the solutions might be found in structural changes, not in refinement of the technical solutions.

Taken together, this seems to point out that, to diminish vulnerability and energy dependency in urban planning, the goal should be to integrate the urban population with the supporting agricultural ecosystem rather than to concentrate it in small areas separate from its support systems.

Although the figures are rough and various simplifications have been introduced, the differences between the specific cases are large enough to invite further investigations and calculations in this field.

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