Wastewater Management Integrated with Farming

An Environmental Systems Analysis of the Model City Surahammar

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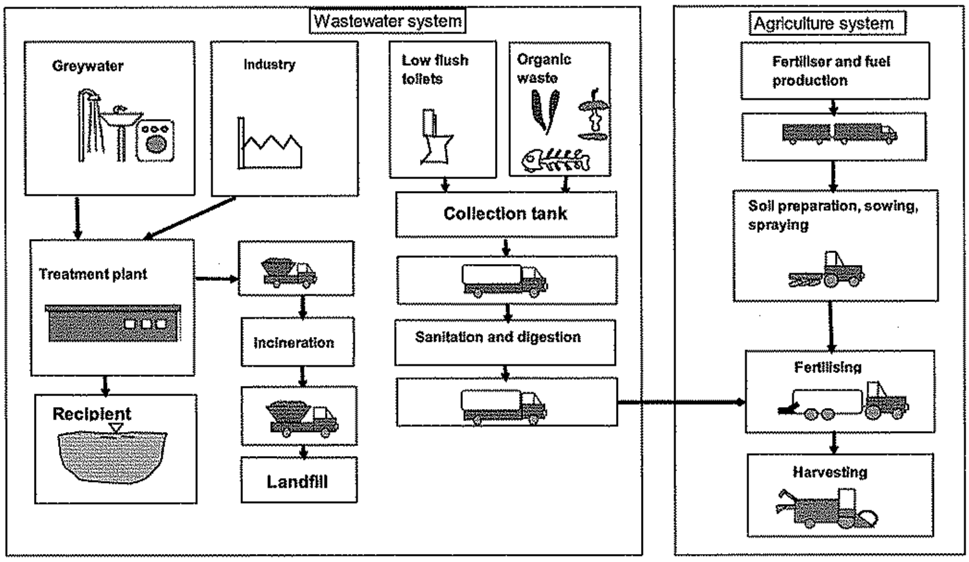

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ABSTRACT

Recycling of plant nutrients in sewage products to arable land is regarded as a step towards a more sustainable society, as today's use of scarce resources is a threat to future generations. Sewage sludge is the predominant sewage fertiliser product available today. However, the use of sewage sludge in agriculture is a controversial issue. Blackwater from separating systems seems to fulfil agricultural requirements on a fertiliser product to a higher degree than sewage sludge without many of the hazardous substances in sludge.

The main objective of this study was to analyse environmental impact and resource use in systems integrating wastewater management and agriculture. The methodology used was based on LCA methodology. Three different wastewater systems were evaluated together with the agricultural production potentially affected. The first alternative (the Surahammar reference system) represented a system that a large part of the population in Surahammar is connected to today. Food waste disposers were installed in 50% of the households, wastewater was treated in a conventional wastewater treatment plant and the sewage sludge was used for production of a soil conditioner. The second alternative (the sludge utilisation system) symbolised a wastewater system more commonly represented in Swedish municipalities, and included also agricultural use of the sewage sludge. The third alternative (the blackwater system) was based on a future vision of Surahammar. Here, toilet water from low-flush vacuum toilets and milled organic waste were digested separately. The blackwater product was stored and spread in growing oats, thereby replacing mineral fertilisers. Data on the wastewater system were derived from simulations by the substance-flow model URWARE/ORWARE. Assumed conditions for the agricultural system were mainly based on site-specific data from a farm producing according to the Svenskt Sigill label.

All energy used and all emissions were related to a functional unit. The functional unit included wastewater treatment for 8830 persons in Surahammar, disposal of the sewage products and production of 2100 tonnes of oats on 486 hectares.

As regards the operating phase of the whole system, the blackwater system required less fossil fuel and electricity than the other two systems. Although the blackwater system required considerably more fossil fuel for collection and transport, the total use of fossil fuel was lower due to a reduced need for mineral fertiliser. Construction of storage tanks and pipes for the blackwater system may, however, give a considerable contribution to the total environmental load. Including the construction phase too revealed that the use of fossil fuel increased considerably and was highest from the blackwater system.

The emissions of greenhouse gases were of the same magnitude for all three systems, although slightly lower for the blackwater system. This was also evident when the construction phase was considered. The eutrophying emissions were reduced considerably in the blackwater system according to a maximum scenario, mainly due to reduced emissions of ammonium from the treatment plant. The emissions of SO_2 were of the same magnitude for all three systems studied, although slightly lower for the sludge utilisation system. As regards NH_3 and NO_X, the emissions were highest for the blackwater system.

A high substitution of mineral fertiliser, an optimal spreading technique and an appropriate design of the system for collecting and storing the blackwater were highlighted as important for many environmental aspects in the blackwater system.

SAMMANFATTNING

Återföring av avloppets växtnäring till produktiv mark anses som ett steg mot ett mer uthålligt samhälle, eftersom dagens användning av ändliga resurser är ett hot mot kommande generationer. Avloppsslam är den vanligast förekommande avloppsprodukten idag, men användningen av avloppsslam är kontroversiell. Svartvatten från separerande system verkar i högre utsträckning än slam att uppfylla jordbrukets krav på ett gödselmedel utan flera av de potentiellt farliga ämnena i slam.

Huvudsyftet med studien var att analysera miljöeffekter och resursanvändning i system som integrerar avloppshantering och jordbruk. Den använda metoden baserades på livscykelanalys. Tre olika avloppssystem utvärderades tillsammans med den jordbruksproduktion som potentiellt påverkades. Det första alternativet (Surahammar referenssystem) representerade ett system som en stor andel av Surahammar befolkning är anslutna till idag. Matavfallskvarnar var installerades i 50% av hushållen, avloppsvattnet behandlades i ett konventionellt reningsverk och slammet användes sedan för jordtillverkning. Det andra alternativet (slamanvändningssystemet) symboliserade ett avloppssystem som är vanligare förekommande i svenska kommuner, men inbegrep även jordbruksanvändning av slam. Det tredje systemet (svartvattensystemet) baserades på en framtida vision av Surahammar där toalettvatten från snålspolande vakuumtoaletter och köksavfall rötades separat. Svartvattenprodukten lagrades och spreds i växande havre där den ersatte mineralgödsel. Uppgifter från avloppssystemen kom från simuleringar i substansflödesmodellerna URWARE/ORWARE. De förhållandena som antogs för jordbrukssystemet baserades i huvudsak på platsspecifika uppgifter från en Sigillgård.

Energianvändningen och emissionerna relaterades till en funktionell enhet som inkluderade både avloppsbehandlingen för 8830 personer i Surahammar, avyttring av avloppsprodukterna och produktion av 2100 ton havre på 486 hektar.

I svartvattensystemets användarfas användes mindre fossila bränslen och elektricitet än i övriga system. Även om svartvattensystemet krävde betydligt mer energi för insamling och transport, var den totala användningen av fossil energi lägre på grund av ett reducerat behov av inköpt mineralgödsel. Tillverkningen av lagringstankar och rör för svartvattensystemet gav dock ett betydligt bidrag till miljöbelastningen. Om man inkluderar även anläggningsfasen, ökade användningen av fossil energi betydligt och var högst i svartvattensystemet.

Utsläppen av växthusgaser var i samma storleksordning för samtliga tre system, dock något lägre för svartvattensystemet. Detta resultat stod sig även när anläggningsfasen beaktades. Utsläppen av eutrofierande ämnen minskade betydligt i svartvattensystemet, i huvudsak genom minskade utsläpp av ammonium från reningsverket. Svavelutsläppen var i samma storleksordning för alla tre systemet, dock något lägre för slamanvändningssystemet. Vad beträffar NH_3 and NO_X, var utsläppen högst för svartvattensystemet.

Viktiga aspekter för att reducera energianvändning och minska luftutsläppen var kopplade till utformningen av uppsamlingssystemet. Andra viktiga faktorer var att en hög andel av mineralgödsel ersattes och att spridningen utfördes optimalt.

PREFACE

In the research programme 'Sustainable Urban Water Management' financed by MISTRA, different model cities are evaluated from the perspective of sustainability. Surahammar is one of these model cities, with Erik Kärrman (Ecoloop) as project leader. An overview of the research activities performed in Surahammar is summarised in Kärrman (2005). Environmental systems analysis of different wastewater systems was one of the projects performed in Surahammar. The present report gives a thorough description of the systems and assumptions made in the environmental systems analysis.

Pernilla Tidåker (SLU) was responsible for modelling the agricultural system. She also compiled the results for the whole system and was responsible for writing this report under revision of the other authors. The chapter Inventory of the wastewater system was mainly written by Erik Kärrman. He was also responsible for setting up the systems studied, together with a local stakeholder group from Surahammar. Andras Baky (JTI) made the simulations of the wastewater systems in URWARE /ORWARE with advice from Håkan Jönsson (SLU), Ulf Jeppsson (LTH) and Daniel Hellström (Stockholm Vatten AB).

Many people in Surahammar contributed to this project. In particular, we want to express our gratitude to the farmer Ove Fellin, who provided valuable information on the agricultural preconditions in the region and to Sari Virkkala and Alf Thunström, both employees at Surahammar Kommunalteknik AB, who provided information about Surahammar's wastewater system. Thanks to all of you.

April 2005

Pernilla Tidåker Erik Kärrman

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BACKGROUND

Recycling of plant nutrients in sewage products to arable land is considered to be a step towards a more sustainable society, as today's use of scarce resources is a threat to future generations. In the Swedish debate, special consideration has been given to phosphorus recycling, but other plant nutrients, such as nitrogen and potassium, are also emphasized by e.g. the Swedish EPA (2002). Sewage sludge is the predominant sewage product available, as almost all Swedish households in urban areas are connected to municipal treatment plants. Whether to use sewage sludge in agriculture is, however, a controversial issue (Bengtsson, 2002). Agricultural organisations and the food industry are in general reluctant towards the use of sewage sludge on arable land, citing potentially harmful substances in sewage sludge, which might compromise consumer confidence in their products (Berglund, 2001). Blackwater (closet water) from separating systems seems to a higher degree than sewage sludge to fulfil agricultural requirements on a fertiliser product without many of the hazardous substances in sludge.

The way in which a sewage product is used in agriculture might influence the environmental impact from the whole system. A study of wheat production using human urine revealed that the handling of urine on farm level had a decisive influence on several environmental impact categories (Tidåker, 2003). Including agricultural aspects when assessing different options for wastewater handling will therefore generate valuable information on the environmental benefits and drawbacks with systems integrating wastewater management and farming.

In the research programme Sustainable Urban Water Management, abbreviated to Urban Water, different wastewater systems under different conditions are evaluated from the perspective of sustainability. Multi-disciplinary research is taking place in five Model cities, which aim to cover typical Swedish conditions. Within the model cities, different wastewater systems are modelled and evaluated. One of these model cities is Surahammar, a small town with almost 9 000 inhabitants in central Sweden. Recycling of plant nutrients is one of the main themes in the model city Surahammar. In the present report, detailed descriptions of the wastewater and agricultural systems are given.

LCA METHODOLOGY

The methodology used was based on Life Cycle Assessment (LCA). An LCA evaluates the environmental aspects and potential impacts in a cradle-to-grave perspective, from raw material acquisition through production, use and disposal (ISO 14040). Different phases are included in an LCA: goal and scope definition, inventory analysis and impact assessment. The interpreted results may then be used as input in a decision-making process.

GOAL AND SCOPE OF THE STUDY

Objectives

The main objective of the study was to analyse environmental impact and resource use in systems integrating wastewater management and agriculture. Three different wastewater systems were evaluated together with the agricultural production potentially affected by the sewage use.

Functional unit

When comparing different alternatives in an LCA, these must fulfil the same functions. The *functional unit* is thus a central concept in LCA and is defined as a relevant, well-defined and strict measure of the main function(s) of the system (Lindfors *et al.*, 1995).

The functional unit in this study was defined as consisting of two main functions:

- Providing wastewater treatment for 8830 p.e. (person equivalents) in the town of Surahammar, including disposal of the sewage products.
- Producing a certain quantity of grain on a given area (2100 tonnes on 486 hectares).

Impact categories studied

The following impact categories were assessed in this study:

- Use of energy and phosphorus ore
- Global warming
- Eutrophication
- Acidification

Flows of nitrogen, phosphorus and cadmium in the plant and soil system were further quantified and presented.

Municipality of Surahammar

The municipality of Surahammar with 10 200 inhabitants is situated in Västmanland in central Sweden and consists of three small towns, Surahammar, Ramnäs and Virsbo. The town of Surahammar is surrounded by forest and arable land. Wastewater from most of the inhabitants is treated in the Haga wastewater treatment plant. Surahammar has a slowly decreasing population, which means that the capacity of the urban water systems is not fully utilised. This has been an incentive for introducing kitchen waste disposers connected to the sewer system. Today, around half of the households are equipped with waste disposers. In the treatment plant, blackwater, grey water and organic waste are treated together with industrial wastewater. After mechanical, biological and chemical treatment, the wastewater is discharged to the recipient water, Kolbäcksån. Sewage sludge is digested, dewatered on drying beds and composted. The composted sludge is then transported to Västerås where it is used for soil production. Surahammar kommunalteknik, responsible for management of the water, wastewater and organic waste in the municipality, has since long been interested in the development and improvement of the system. In the years 2001-2002, there was a plan to implement a separate piping system for blackwater and organic household waste for 20 households in a renovation project. The ambition was further to digest this mix separately and use it as a fertiliser in agriculture. However, at the time of writing this report, the plan had been postponed due to lack of funds.

General description of the systems selected

Within the research activities in the model city Surahammar, three different alternatives for wastewater handling were studied, which are briefly described below. A more thorough description of the wastewater and agricultural systems is found in the chapters 'Inventory of the wastewater system' and 'Inventory of the agricultural system'. In Figure 1, the system boundaries of the study, including both the wastewater system and the agricultural system, are shown.

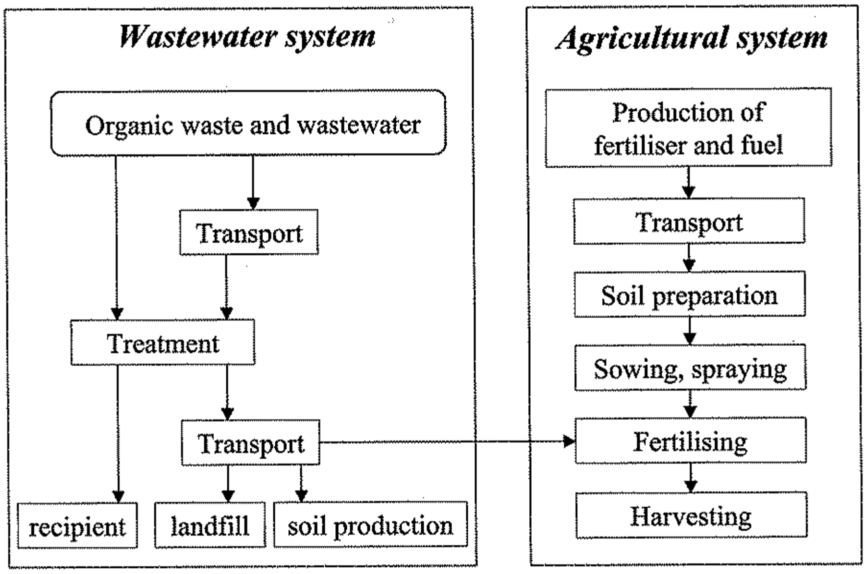

Figure 1. Schematic flow chart of the systems studied, including both the wastewater system and the agricultural system. Depending on wastewater handling, sewage treatment products may end up on agricultural land, in soil products, on landfill and in the effluent from the wastewater treatment plant. Composted sewage sludge and sanitised blackwater are the two sewage products used in crop production.

Surahammar reference system

The first alternative represented a system that a large part of the population in Surahammar is connected to today. In this alternative, food waste disposers were installed in 50% of the households. The milled food waste was conducted together with wastewater in the sewer system to the treatment plant, where the wastewater was treated mechanically, biologically and chemically before its discharge to the recipient water. The sewage sludge was digested, dewatered, composted and transported to a soil production company that manufactures soil products to be used for city parks etc. The distance between the sludge composting plant and the soil production was estimated at 25 km. Organic waste from households not equipped with disposers was composted at home in 25% of the households, and collected and transported to a central composting plant in 25% of the households.

The agricultural system consisted of oat production. As no sewage product was generated for agricultural disposal, only mineral fertilisers were used. The Surahammar reference system is schematically presented in Figure 2.

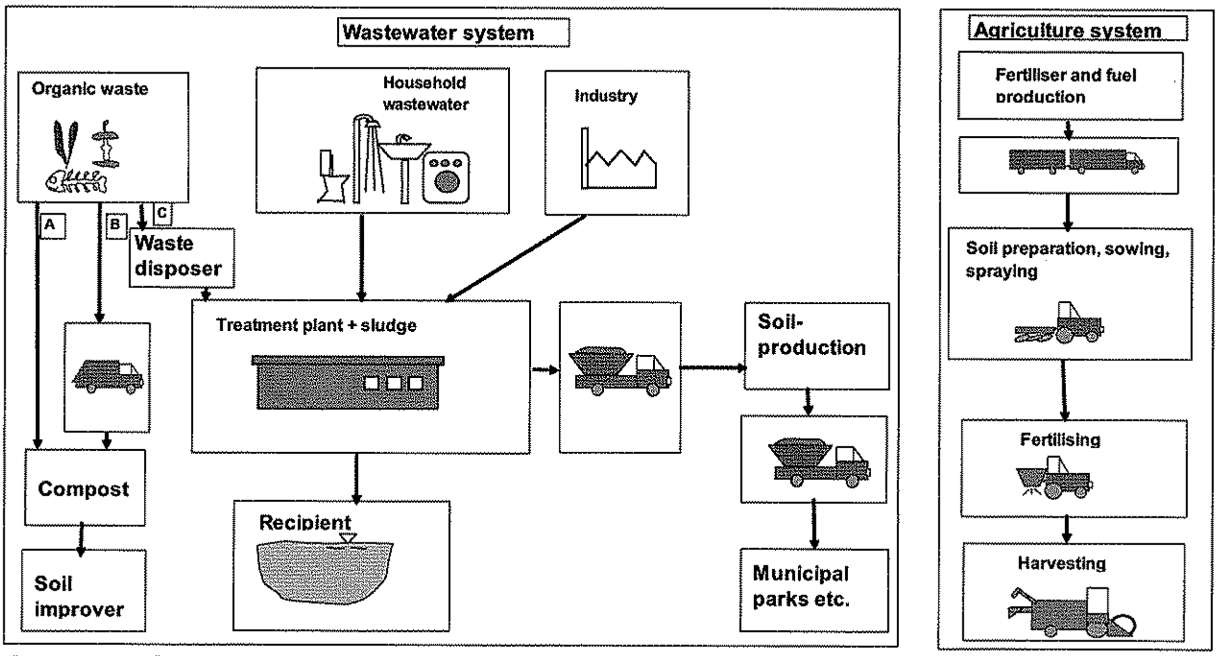

Figure 2. Flow chart presenting the Surahammar reference system.

Sludge utilisation system

The second alternative was a conventional wastewater system where wastewater was led through a sewer system to a wastewater treatment plant. The treatment plant operated as in the Surahammar reference system. Sewage sludge was digested, dewatered, composted, transported to arable land and spread in the autumn before oats were sown in the spring. The distance for transporting the sewage sludge to arable land was estimated at 10 km. Sewage sludge was mainly replacing phosphorus fertiliser, while the crop requirement for nitrogen was covered by calcium ammonium nitrate, N28. Solid organic waste was collected separately, transported to a composting plant and further used for soil production. The distance for transporting the bio-waste to the composting plant was estimated at 25 km. The sludge utilisation system is schematically presented in Figure 3.

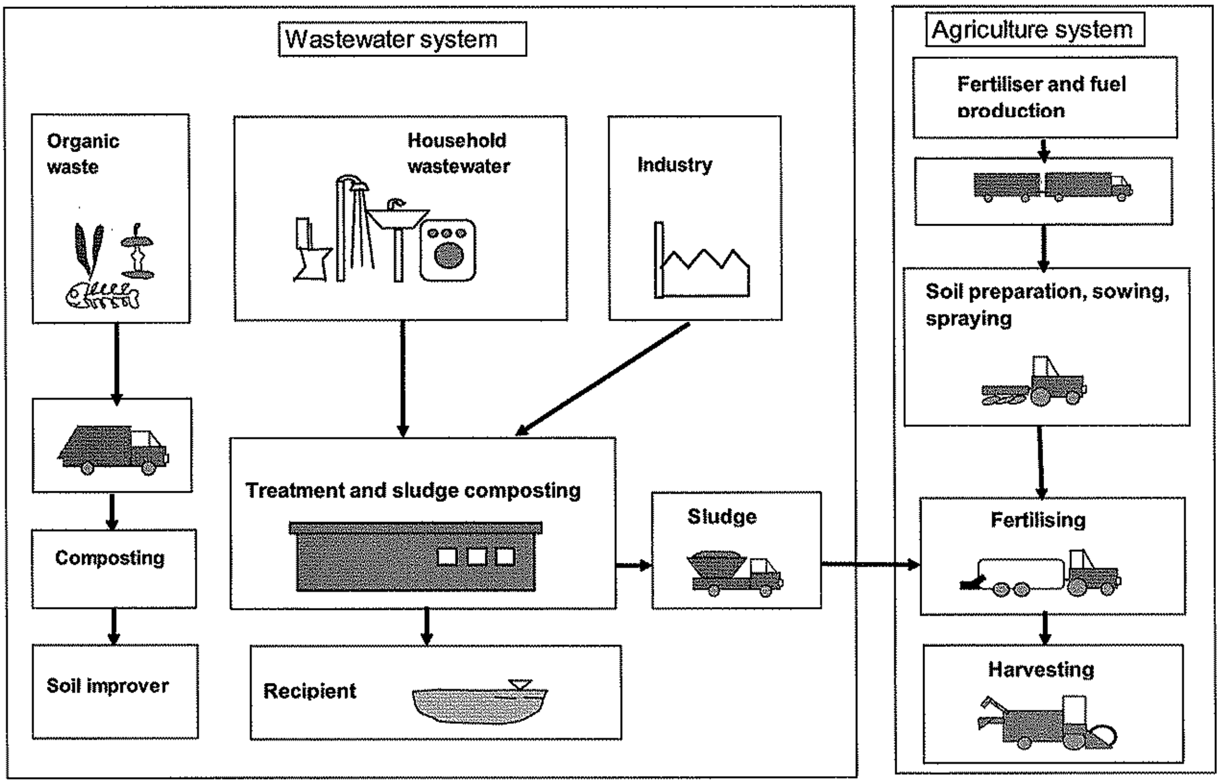

Figure 3. Flow chart presenting the sludge utilisation system.

Blackwater system

The intention with the third alternative was to generate a fertiliser product only originating from urine, faeces, and food waste for further use in agriculture. Here, toilet water from low-flush vacuum toilets and milled organic waste (through the use of food waste disposers) were digested separately, while the wastewater from bathing, dishwashing and laundry was conducted to the treatment plant for conventional treatment. The sewage sludge produced was incinerated and landfilled. The landfill was assumed to be situated close to the incineration plant (no transport was assumed). The blackwater product was transported 10 km to agriculture, stored in storage tanks and spread in growing oats. The blackwater product replaced half the required amount of nitrogen and phosphorus mineral fertilisers. The blackwater system is schematically presented in Figure 4.

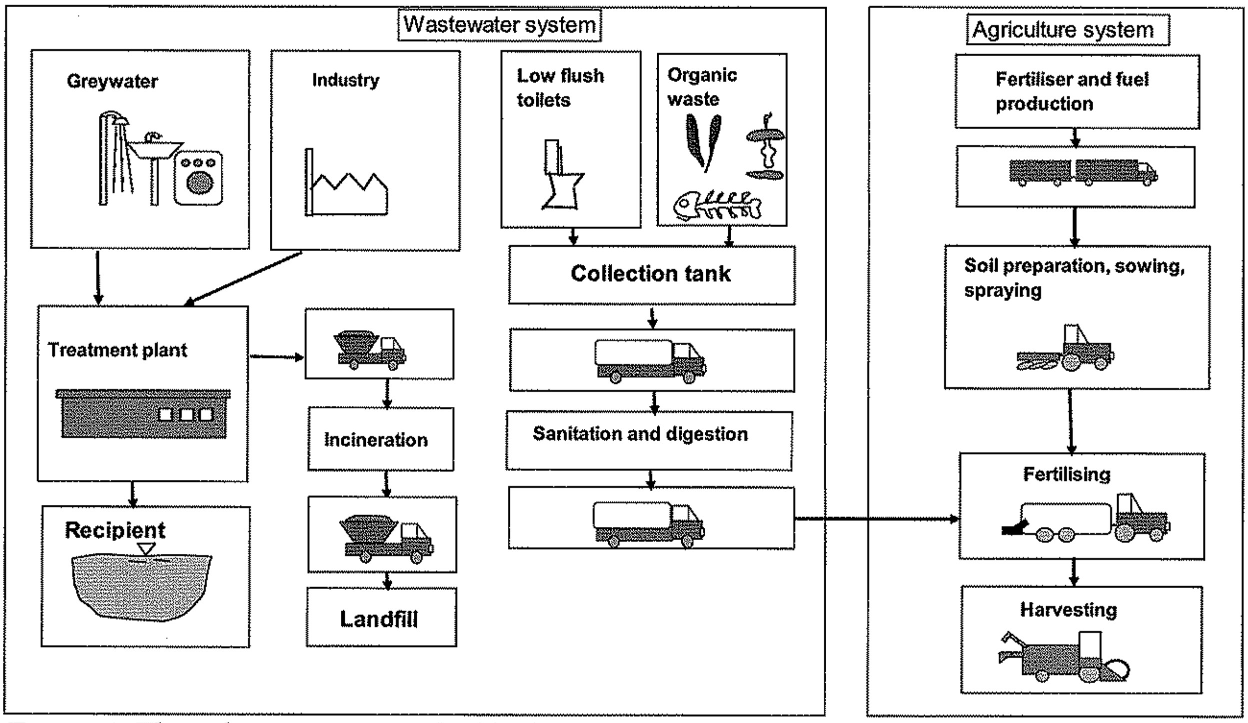

Figure 4. Flow chart presenting the blackwater system.

Systems boundaries

Area requirement

The agricultural system embraced 486 hectares. This was the area required by the blackwater system based on the assumption that 50 tonnes of blackwater were spread per hectare. The sludge fertilising system required only 40 hectares for sludge disposal, therefore additional area fertilised only with mineral fertilisers was included.

The yield obtained per hectare was lowest in the blackwater system. Thus, the other two agricultural production systems required less area to produce the same amount of grain as the blackwater system. The surplus area not required for grain production in these two sub-systems was assumed to be set-aside area (Figure 5).

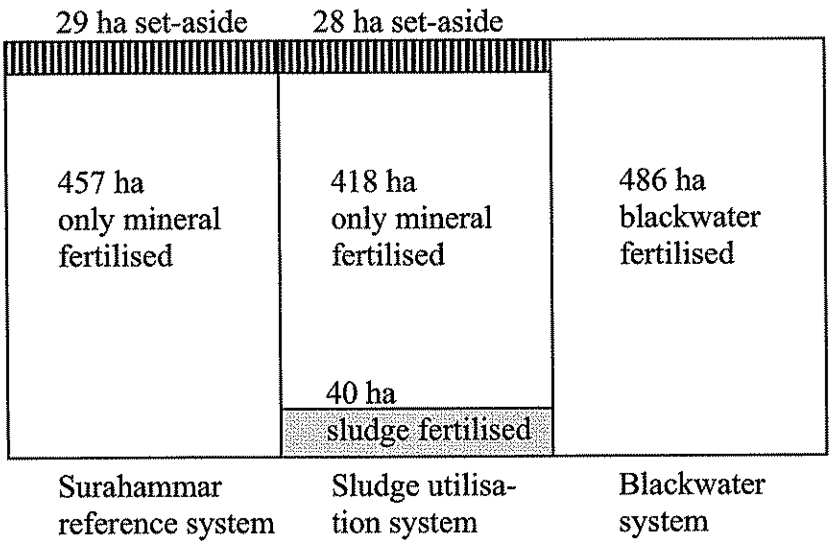

Figure 5. The system boundaries of the agricultural sub-systems (486 hectares) divided between grain production and set-aside area.

Production capital

Only the operation phase was included within the system boundaries. However, the blackwater system required additional infrastructural investments, e.g. additional pipes for transporting blackwater and kitchen waste as well as storage tanks both on household level and farm level. Therefore, the environmental load related to the production phase of these investments was calculated in a sensitivity analysis and further compared to the total environmental load from the systems.

Time perspective

The time horizon was one year. Effects originating from activities performed during the year but appearing later were all transferred to the year under study, e.g. future soil compaction and plant nutrients mineralised after the first year.

Data sources and data quality

Data on the wastewater system were derived from simulations in the substance-flow model URWARE (Jeppsson *et al.* 2005). In URWARE, different activities such as drinking water production, wastewater treatment, transport, digestion, composting, incineration and landfill are modelled and simulated using either default values or site-specific data. An input vector consisting of 84 substance elements, e.g. organic matters, nutrients and heavy metals, were used in the simulations.

Data and parameters for soil qualities, cultivation practices etc. for the agricultural sub-system were taken from Tistersta Farm, owned by Ove Fellin. Production is carried out according to the 'Svenskt Sigill' label, a set of quality rules ensuring that environmental concerns are considered in the production. In cases where site-specific data were not available, more general data were used.

INVENTORY OF THE WASTEWATER SYSTEM

URWARE sub-models used

In addition to the recently developed URWARE model describing the wastewater treatment plant, sub-models from the ORWARE (ORganic WAste REsearch) model were used to simulate the surrounding environment (Dalemo *et al.*, 1997). The main models used were collection and transportation, incineration, composting and landfill (Eriksson *et al.*, 2002). The models were tools for an environmental systems analysis of waste management. The separate sub-models can be combined to design a waste management system for a city, a municipality or a company. Emissions from transport, treatment processes and other sources are allocated as emissions to air, water and soil.

Solid waste and wastewater generation

Although data were available for the amount and composition of wastewater in the existing system in Surahammar, this study was based on default values given by Jönsson *et al.* (2005). The main reason for this was that no information was available regarding the sources of different components in the existing wastewater. This information was crucial for the analysis of the third alternative, the blackwater system, which included a separation of wastewater fractions. The default values used for the wastewater fractions are presented in Appendix 1.

Wastewater treatment plant

The models describing the wastewater treatment processes included primary, secondary and final sedimentation units, thickeners and dewatering units, sand filtration and biological reactors. These can be connected in any way and recycle flows when required. The models are based on a detailed COD (chemical oxygen demand) description of the organic matter but also total suspended solids (TSS), volatile solids (VS), total solids (TS) and biological oxygen demand (BOD) are calculated throughout the system. Five to seven nitrogen fractions (depending on the sub-model) including $N_2$and N_2O gas production were maintained, as well as four sulphur (including sulphide), three phosphorus and two potassium fractions. The physical mechanisms are modelled in a straightforward way, whereas biological reactions are described by an extended ASM1 model (Henze *et al.*, 2000) with inspiration from both ASM2d and ASM3. The main extensions are related to phosphorus, sulphur and potassium. The modelling of seven heavy metals represented another modification. Although the complete URWARE model was primarily intended for steady-state analysis, the biological models describing the wastewater treatment plant were fully dynamic. The models also allowed for chemical precipitation of phosphate, addition of external carbon sources, polymer addition, temperature dependency, calculation of energy consumption, etc. To enhance realistic behaviour of the models and assist the human user, every sub-model included a significant number of on-line validation routines to ensure, for example, complete mass balances, realistic choice of parameter values, consistent correlation between BOD, COD, VS, TSS and TS and reasonable nutrient contents of biomass. The details of the models and their behaviour are described in Jeppsson *et al.* (2005).

Collection and transportation

Sub-models describing vehicles for different types of transport were used. For collection of waste, there were back-packer and front-loader models. Blackwater and sewage sludge were transported to agriculture with an ordinary truck. For transport of primary and secondary wastes like fly ash and slag, there were two sub-models: ordinary truck and truck with trailer (Sonesson, 1996).

Composting

Different compost models were used for different purposes. The model for sludge composting was an open windrow composting model and the model for food waste composting assumed a semi-permeable cover.

In the composting models a carbon/nitrogen ratio of 30 was assumed. From this ratio the model estimated that 22.7% of the nitrogen was lost with the compost gas. The nitrogen in compost gas was divided into 98% NH_3-N and 0.5% N_2O-N. The remainder consisted of nitrogen gas.

The semi-permeable cover was assumed to reduce the ammonia losses by 85% compared to open compost (Jönsson *et al.*, 2003) during half of the composting process. Therefore 13% of the nitrogen was assumed to be emitted as ammonia.

Anaerobic digestion

The anaerobic digestion model described the digestion process for a completely stirred tank reactor (CSTR) working at mesophilic conditions (35 °C). The model is only valid in steady state and it will only provide reasonable results when the digester is operating properly. A more thorough description of the anaerobic digestion model is given by Jeppsson *et al.* (2005).

Landfill

The landfill sub-model is described by Björklund (1998). In this case study, only fly ash and slag were landfilled. The sub-models are designed to behave as Swedish average landfills and the site-specific adjustments are few. Energy consumption in the form of electricity and diesel oil was accounted for.

Gas utilisation

Biogas from the digesters was combusted in a stationary gas engine where 30% of the energy was transformed to electricity (Dalemo, 1996).

Incineration

The incineration sub-model consisted of pre-treatment, incinerator and air pollution control (Björklund, 1998). In the incinerator, the waste was combusted and the outputs were raw gas, slag and fly ash. After the air pollution control, the purified gas was released to the air. Energy was transformed to heat and further distributed to the district heating system.

Soil production

Surahammar reference system produced a soil product for city parks etc. Only environmental impacts from the transport of composted sludge to the soil production plant was considered. In the sensitivity analysis, the phosphorus value in the sludge is discussed.

INVENTORY OF THE AGRICULTURAL SYSTEM

In this chapter, the agricultural system is described in detail. The three different fertilising strategies for the oat production were:

- Production using only mineral fertilisers (in Surahammar reference system)
- Production using sewage sludge and mineral fertilisers (in sludge utilisation system)
- Production using blackwater and mineral fertilisers (in blackwater system)

Inventory data for the three fertilising strategies and for set-aside areas are summarized in Appendix 2.

Agricultural conditions in the region

Soil characteristics and field operations performed were based on site-specific data from the farm 'Tistersta', situated in the county of Västmanland in an area with sedimentary clay soil. Normally, the farmer grows oats, barley and wheat. Occasionally, other crops such as rapeseed or ley seed are included in the crop rotation. The expected yield for oats is 4500-5000 kg per hectare, depending on the soil fertility in the specific field. The expected yield in the county of Västmanland according to Statistics Sweden (2003) is 3740 kg per hectare. The yield level at the farm is thus approximately 20-35% higher than the average for the area.

The content of cadmium in soil was analysed in 1997. In total, seven samples were taken, and all samples contained between 0.20 and 0.29 mg Cd per kg dry soil, with an average value of 0.23 mg. The corresponding average value for the county of Västmanland is 0.27 mg Cd per kg dry soil (Eriksson *et al.*, 1997). The content of labile phosphorus and potassium is moderate, P-AL (ammonium lactate-acetate-soluble phosphorus) classification is III and K-AL classification is III on a scale between I and V. The stored supply is moderate for phosphorus (P-HCl III) and high for potassium (K-HCl V). The pH value is around 6.5.

Characteristics of soil organic matter

The median value for the soil organic matter content of arable land in Sweden and in the county of Västmanland is 4.1%, corresponding to 74 tonnes of carbon per hectare (Eriksson et *al.*, 1997). The organic matter status is maintained through incorporation of fresh organic materials. A higher yield results in more residues, thus increasing the organic matter content in the soil more than a crop resulting in a lower yield. A higher organic matter status also results in higher yields as reported by e.g. Mattsson (1999). Analysis of 300 field experiments revealed that the uptake of N by the crop increased by 3 kg N per percentage unit soil organic matter in a clay soil.

Application of sewage sludge will increase the organic matter content of the soil. According to a Swedish long-term soil organic matter experiment, 50% of the total amount of carbon applied and 38% of the nitrogen applied as sewage sludge during 36 years was found in the topsoil as an increase in the organic matter content (Kirchmann *et al.*, 1994). The yield-increasing effect from sludge application was noted in field trials in the south of Sweden (Andersson & Nilsson, 1999). Comparisons were made between two treatments, both receiving an optimal application of NPK according to crop requirements, but with one treatment also receiving an additional application of sludge corresponding to 1 tonne of DM per hectare and year. The yield-increasing effect on spring cereals during 16 years was on average 1.7%. The yield-increasing effect on winter wheat was slightly less. Due to the experimental design, it was not possible to draw conclusions as to whether the positive response was due to additional plant nutrients applied in the plot receiving sewage sludge or an effect from improved soil structure.

Machine operations

Field operations usually performed at the farm are:

- Stubble cultivation/ploughing
- Harrowing
- Sowing
- Fertilising
- Pesticide application
- Harvesting

These were also the field operations considered in this study. The farmer's intention is to reduce tillage as far as possible. Therefore, ploughing is preferably replaced by stubble cultivation. In the production system using sludge, ploughing was assumed while in the other two fertilising strategies, stubble cultivation was assumed.

Data from Lindgren *et al.* (2002) on fuel consumption and exhaust emissions when performing different agricultural field operations were used (Tables 1 and 2). The figures used were in most cases based on measurements made on a Valtra 6600 tractor. The figures used for handling of sludge were based on measurements of similar operations performed with a Valtra 6650 tractor.

Pesticide application was assumed to have the same fuel consumption and exhaust emissions as spreading of mineral fertilisers.

Table 1. Fuel consumption and exhaust emissions when performing different field operations on a clay soil (Lindgren et al., 2002) [1]

Field operations	Fuel (kg/ha)	CO_2 (g/ha)	CO (g/ha)	HC (g/ha)	NO_X (g/ha)
Stubble cultivation	12.7	41200	24	8.6	450
Ploughing	14.4	46700	32.8	11	530
Harrowing	2.8	9100	6.7	2.6	94
Sowing	4.2	13700	12.8	4.7	138
Mineral fertilising	0.4	1300	2.9	0.7	17
Urine spreading	1.6	5200	5.7	2.0	61
Solid manure spreading	4.4	14300	14.1	4.4	162
Harvesting	11.8	38400	104	6.6	368

[1)] The measurements were made on standard diesel (MK1) with an energy content of 43.2 MJ/kg and a density of 0.814 kg/l.

It was further assumed that filling a tank with blackwater took 20 seconds per m^3 and that transport speed within the farm was 10 km per hour. When calculating the environmental load related to front loading of sludge, a loading cycle of one minute and a bucket capacity of 0.6 m^3 were assumed.

Table 2. Fuel consumption and exhaust emissions during filling, loading and transport operations (Lindgren et al., 2002)

Operations	Fuel (kg/h)	CO_2 (g/h)	CO (g/h)	HC (g/h)	NO_X (g/h)
Filling urine 1)	4.1	13300	40.4	8.8	140
Loading 2)	3.8	12200	22.6	6.6	77
Transportation	6.4	20800	33.3	7.9	257

1) Emission factors for urine were assumed to be the same as for blackwater
2) Emission factors for front loading of gravel were used for loading of sludge

According to calculations by Sjöberg (2003), the diesel required for mixing of blackwater is 0.045 litres per m^3. The emission factors used for mixing were assumed to be the same as for filling.

The emission of SO_2 was defined as 0.0935 g/MJ, based on the sulphur content in the fuel (Hansson & Mattsson, 1999). In the above figures, only fuel requirement and emissions for the actual field operations were included. Production of fuel also gives an environmental impact, i.e. pre-combustion. In Table 3, figures on pre-combustion impacts are presented.

Table 3. Energy and emissions (per MJ fuel) related to pre-combustion of diesel fuel (Arnäs et al., 1997)

	Fossil energy (MJ)	CO_2 (mg)	NO_x (mg)	HC (mg)	CH_4 (mg)	CO (mg)	SO_2 (mg)
Diesel pre-combustion	0.06	3500	31	33	2	2	19

Plant nutrients

Plant nutrient supply in soil

The organic matter content is a determining factor for the nitrogen supply in the soil. In a typical Swedish soil with an organic matter content of 4.1%, almost 7000 kg of nitrogen is found in the plough layer (Eriksson *et al.*, 1997). According to the same source, the supply of phosphorus, expressed as P-HCl, is on average 2600 kg. The total potassium content is in general high, although only a minor proportion of the total fraction is available for the crop. Clay soils have a high capacity to deliver potassium. A high total content and a high weathering capacity give a yearly contribution of 50-100 kg/ha (Öborn *et al.*, 2001).

Copper and zinc are two heavy metals regulated by the Swedish legislation on sewage sludge disposal, but they are also essential micronutrients for plants. The soil content of Cu and Zn in the plough layer is on average 46 kg/ha and 184 kg/ha, respectively, in Sweden (Eriksson *et al.*, 1997).

Plant requirement

A recommended nitrogen application rate according to the Swedish Board of Agriculture (Jordbruksverket, 2002) for an oat yield of 5000 kg is approximately 90 kg, assuming a relative high nitrogen delivery capacity of the soil (N-mineralization 30-40 kg/ha, 0-60 cm). The phosphorus application rate depends on the P status. With a moderate soil status (P-AL III), the recommendation is approximately 15 kg/ha. The consumption of magnesium and sulphur is roughly 10 kg/ha. The recommended potassium application rate ranges from 0 to 65 kg/ha, depending on the soil status (Jordbruksverket, 2002).

The requirement of copper is normally less than 100 g/ha. Deficiency can arise on soils containing less than 15 kg per hectare (Jordbruksverket, 2002). For Zn, 20-150 mg per kg crop DM is required (Aasen, 1986).

Quality of the sewage products

The expected characteristics of the sewage products regarding plant nutrients and heavy metals according to URWARE are shown in Table 4.

Table 4. Expected quality of the sewage products in the study

	Blackwater	Sewage sludge
% dry matter	0.80	50
N (kg/tonne)	1.3	21
NH_4-N (kg/tonne)	1.1	0.21
NO_3-N (kg/tonne)	0.0	1.2
P (kg/tonne)	0.15	24
K (kg/tonne)	0.36	3.6
Cd (g/tonne)	0.0019	0.49
Cu (g/tonne)	0.20	127
Zn (g/tonne)	1.3	180

Plant utilisation

Ammonium and nitrate are directly available for plants, whereas organically bound nitrogen must be mineralised before it becomes available for uptake by the crop. The rate at which organically bound nitrogen is mineralised is not easy to predict. According to a literature survey on compost use in agriculture (RVF, 2000), approximately 10% of the nitrogen in compost can be expected to be available for the crop during the first year. The long-run nitrogen mineralisation can be expected to be 30%. The above figures were used in this study. Half this 30% was further assumed to be released when no crop was available, and half when the crop was growing, thereby reducing the future need for mineral fertiliser.

Remaining ammonium after volatilisation in pig slurry is calculated to have the same yield-increasing effect as nitrogen in mineral fertilisers (Jordbruksverket, 2002). This was also assumed for the blackwater product.

According to guidelines from the Swedish Board of Agriculture (Jordbruksverket, 2002), phosphorus should, if possible, be applied to each crop in the crop rotation. For only a few crops, e.g. sugarbeet and potatoes, the recommendation is to apply additional phosphorus also for one or two succeeding crops, respectively. An experiment on a limed soil illustrates how water-soluble phosphorus becomes less available with time (Hahlin & Johansson, 1977). The share of the phosphorus applied that was found to be easily available according to the AL-method two years after application was 40%. The corresponding figure after 6 years had decreased to 24%.

Numerous studies have investigated the extent to which phosphorus in sewage sludge is plant available. According to literature reviews compiling information from many studies performed, the results are ambiguous (Linderholm, 1997; Johansson, 2000; Kvarnström, 2001). The discrepancies between different studies in P-availability from sludge can be attributed to several factors, e.g. differences in origins and treatment of the sludge, analysis and experimental techniques and length of the experiments (Johansson, 2000). Additionally, the capacity of the soil to deliver phosphorus is not always described, and occasionally the amount of plant nutrients applied differs in the comparisons (Linderholm, 1997). Johansson (2000) concluded from a literature review that fresh sludge appeared to have higher availability than dried sludge. This was, however, not in accordance with an experimental study by Kvarnström *et al.* (2000), in which the dewatering processes did not change the sludge P availability significantly.

An evaluation of the long-term effects of sludge amendment showed that the relative P availability of sludge compared to water-soluble P was 60% (Kvarnström, 2001). However, this result was not significantly different from 100%. A conclusion based on a Swedish pot experiment was that twice the mineral fertiliser rate was required when phosphorus in sludge was used (Ottabong 2003). In Bengtsson *et al.* (1997), substitutability for nitrogen and phosphorus was also discussed. For phosphorus, an interval between –20 and +120% was presented, and the probable value for sewage sludge was set at 70% substitutability. In this report, 50% of the phosphorus in sewage sludge was assumed to replace commercial phosphorus fertiliser. This might both reflect a lower availability of phosphorus in sludge, compared to P mineral fertilisers, as well as a lower utilisation due to a higher application rate than the actual need of the crop during one year. The phosphorus in the blackwater product was assumed to be as plant-available as mineral fertiliser, in accordance with experiences from manure (Steineck *et al.*, 2000).

Fertilising strategies chosen

Multi-nutrient fertiliser products, e.g. NP 27-5, are frequently used among farmers. However, in this study only use of N28 and P_2O_5 (P20) was assumed. The calculated application of N and P could thus be exactly correlated to crop requirements, which facilitated comparisons between different fertiliser products. The environmental load associated with production of mineral fertiliser products was taken from an inventory made by Davis & Haglund (1999).

General approach: In all three agricultural systems, the crop was provided with an equal amount of plant-available nitrogen, i.e. 102 kg per hectares after volatilisation of ammonia. The total nitrogen fertilisation rate was therefore higher for the sewage products than for mineral fertiliser due to both a higher volatilisation of ammonia occurring during spreading and an additional content of organically bound nitrogen. The application of phosphorus in the two systems using either mineral fertiliser or a combination of mineral fertiliser and blackwater was 16 kg/ha, which was of the same order as the amount of phosphorus removed by the crop. When using sewage sludge, the phosphorus application rate was considerably higher, 154 kg P/ha, which provided the succeeding crops with phosphorus during several years.

Surahammar reference system

In the agricultural system using only mineral fertilisers, the calculations were based on the application rates of 102 kg N/ha applied as N28 (calcium ammonium nitrate), and 16 kg P/ha applied as P20 (triple superphosphate, P_2O_5).

Sludge utilisation system

The value of sewage sludge as fertiliser is related to its high content of phosphorus. Even a moderate quantity will provide the crop with considerably more phosphorus than the requirement. Modern manure spreaders offer limited possibilities for an even and precise distribution when applying low rates of manure (Malgeryd & Pettersson, 2001). Modified constructions have shown that rates lower than 5 tonnes/ha could be applied fairly evenly (Malgeryd *et al.*, 2002). The strategy chosen in this study was to assume the highest phosphorus application rate allowed according to current legislation (SNFS, 1994) for a soil with moderate phosphorus status, i.e. 154 kg P/ha, applied on one occasion in a seven-year crop rotation. This amount of phosphorus corresponded to 6.5 tonnes of sludge. The reduced future need for phosphorus was included in the study and transferred to the year studied.

Sewage sludge also provided the crop with nitrogen. During the year studied, 22 kg N/ha was calculated to be available for the crop. An additional 80 kg of N/ha was applied as mineral fertiliser. Plant-available nitrogen mineralised in the future was included in the same way as phosphorus.

Blackwater system

In the blackwater system, mineral fertiliser was assumed to be applied first, and later blackwater, 50 tonnes/ha, was spread in the growing crop. The strategy chosen was to provide half the plant-available nitrogen and phosphorus as mineral fertiliser. Thus 51 kg N/ha and 8.3 kg P/ha were applied. Using blackwater, an additional 51 kg/ha of directly-available nitrogen as ammonium and 7.7 kg P/ha were provided. The blackwater application also supplied the crop with 18 kg of potassium.

N-emissions

Ammonia emissions

Mineral fertiliser

Emissions of NH_3 from mineral fertilisers depend on type of fertiliser applied, soil type, meteorological conditions and time of application. Factors for NH_3 emissions from foliar emissions and soil after fertilising have been proposed for different regions (EMEP/CORINAIR, 2003). For calcium ammonium nitrate applied on arable land, an emission factor of 0.006 kg NH_3-N/kg N applied is used. If the fertiliser granule is placed into the soil at the same depth as the seed, emissions may be negligible. The above emission factor of 0.006 was used for mineral fertiliser.

Storage and spreading of sewage products

Volatilisation of ammonia occurs during storage. With an efficient cover, these losses can be reduced almost entirely according to investigations on slurry (Sommer *et al.*, 1993). Here, 4%

of the ammonia was assumed to be emitted during storage from both the blackwater product and the composted sewage sludge.

Knowledge on emissions related to blackwater spreading is limited. However, comparisons could be made between blackwater and pig slurry. According to a Swedish field investigation, 7% of the ammonia applied was lost when pig slurry was spread with trailing hoses in a growing crop (Malgeryd, 1996). When the slurry was diluted, the emissions decreased substantially, and were below 1%. As the blackwater product is considerably more diluted than slurry, the emissions could be expected to be lower than 7%. Here, 5% of the applied ammonia was assumed to volatilise during the spreading operation.

Volatilisation of NH_4-N when solid manure is spread followed by harrowing within four hours is estimated at 35% (Karlsson & Rodhe, 2002). This emission factor was used for sewage sludge in this study.

Crop

The emission of ammonia from crops varies with e.g. temperature, water status and plant development stage. In a field investigation of ammonia exchange between barley and the atmosphere, the loss of ammonia from the canopy amounted to 0.5-1.5 kg N/ha (Schjoerring *et al.*, 1993). According to a literature review by Holtan-Hartwig and Böckman (1994), losses from different crops are expected to be in the range 1-2 kg N/ha. They recommend a calculation factor of 1.5 kg N/ha to be used as a general emission figure for NH_3-N from the crop canopy. Under unfavourable conditions, emissions could, however, be considerably higher. If fertiliser is applied in amounts substantially exceeding recommended levels, ammonia emissions will also increase. In this study, 1.5 kg N/ha was assumed to be lost as ammonia by the leaves.

Emissions of nitrogen oxides

Emissions of NO_X (as NO and NO_2) from the fertiliser used in the field are considered to be very small. Less than 0.1% of the total nitrogen applied is reported to be emitted (Svensson *et al.*, 1999). The above figure of 0.1% was used here as the emission factor.

Emissions of nitrous oxide

The International Panel on Climate Change (IPCC, 1997) proposes the emissions of N_2O from arable land to be calculated as a percentage (1.25% N_2O-N losses) of the total nitrogen applied. However, the amount of nitrogen applied is not solely responsible for the N_2O emissions according to several studies referred to by Kasimir-Klemedtsson (2001). The total content of nitrogen in the soil and drainage conditions have also been identified as important factors. Even if no nitrogen is applied, N_2O continues to be emitted due to the background level of nitrogen in the soil. Based on studies performed under agricultural conditions relevant for Sweden, Kasimir-Klemedtsson (2001) proposed changed emission factors for application of nitrogen, as well as a specific emission factor for background emissions from mineral soils. These emission factors have also been adopted by the Swedish Environmental Protection Agency (Swedish EPA, 2003) in their National Inventory Report 2003, submitted under the United Nations Convention on Climate Change. The proposed Swedish emission factor for manure is 2.5% N_2O-N of the total amount of N applied. However, blackwater contains a smaller fraction of organically bound nitrogen than manure, probably influencing the potential emission. In this study, 16% of the nitrogen in the blackwater product was assumed to be bound in organic matter. In different types of manure, the fraction of organic nitrogen compared to the total content of nitrogen ranges considerably. A typical figure could be 50% (Steineck *et al.*, 2000; Jordbruksverket, 2002). Thus, the emission factor for blackwater needs to be revised and a specific emission factor for blackwater was determined for this study (Table 5). Digested manure might give rise to lower emissions than undigested manure (Kasimir-Klemedtsson, 2001). No data for reduced emissions of N_2O after digestion seem to exist and therefore no correction was made for the digested blackwater product. In Table 5, the emission factors used in this study are summarised.

Table 5. Factors for emissions of nitrous oxide used in this study

	Emission factor	Unit	Source
Mineral fertiliser	0.8	% of N applied	Swedish EPA
Blackwater (factor used in this study)	1.3	% of N applied	Assumption
Background emission from mineral soils	0.5	kg N_2O-N/ha	Swedish EPA
Indirect emissions, air deposition	1	% of N deposited	IPCC
Indirect emissions, leaching	2.5	% of N leached	IPCC

Nitrogen used in agriculture also gives rise to indirect N_2O emissions. Nitrogen emitted to water undergoes nitrification and denitrification, and N_2O is produced. Atmospheric deposition of e.g. nitrogen oxides and ammonium fertilise the soil and water and thus enhance biogenic N_2O formation (IPPC, 1997). A proposal from IPPC (1997) is to calculate indirect emissions of N_2O as 0.01 kg N_2O-N/kg NO_X-N and NH_3-N emitted. The emission factor proposed for nitrogen leaching from arable land is 0.025 N_2O-N/kg N. For nitrogen emitted from a wastewater treatment plant, an emission factor of 0.025 N_2O-N/kg N is proposed. According to Kasimir-Klemedtsson, these emission factors for indirect emissions seem to be too high for Swedish conditions, and she proposes considerably lower factors for indirect emissions. However, more data are needed if national emission factors are to be used. The Swedish EPA therefore proposed IPCC default values to be used until more reliable national data are available. IPCC default values were used in this study. Before direct emissions of N_2O were calculated, volatilisation of ammonia was taken into account through subtraction of the NH_3 emitted from the total N applied.

Nitrate leaching

The amount of nitrate leaching from arable land depends on several factors, e.g. soil type, crop and climate, and may therefore show considerable spatial and temporal variations. Both measurements and computer-based models can be used for estimation of nitrate leaching on a local scale. Here, an empirical model for estimation of nitrate leaching on farm and field level was used (Aronsson & Torstensson, 2004). The model takes into account soil type, climate, time for tillage, fertiliser rate, time and technique for spreading manure, N fertilisation and uptake during autumn and residual crop effects.

The nitrate leaching was calculated to 23 kg N/ha for areas fertilised only with mineral fertilisers or with a combination of mineral fertilisers and blackwater. For areas fertilised with sludge, the nitrate leaching was calculated to 25 kg N/ha. The slightly higher figure for sewage sludge was explained by a higher content of organically bound nitrogen, which releases nitrogen even when no crop is available. The nitrate leaching from the set-aside area was calculated to 14 kg N/ha.

P-emissions

The yearly average loss of phosphorus from Swedish agriculture is estimated at 0.3 kg/ha, with a huge variation in time and space. Losses in the range of 0.01-3.4 kg/ha are not unusual (Ulén, 1997). Results from a Swedish water quality monitoring programme indicate that phosphorus losses from a clay soil in the south-east of Sweden are expected to be approximately 0.5 kg per hectare and year (Johansson *et al.*, 1999).

Large application rates of phosphorus may result in high incidental phosphorus losses, which could be a more important source for P losses than diffuse losses through the soil (Withers *et al.*, 2003). This is one argument to adapt the application in accordance to crop requirements in the time perspective of one year (Ulén & Mattsson, 2003). However, the risk for phosphorus losses to water from agricultural land amended with dewatered sewage sludge is low due to its lower P solubility (Withers *et al.*, 2001). For this reason, no additional P losses per hectare were accounted for in the alternative using sewage sludge, despite a considerably higher application rate per hectare. Based on the above, losses of 0.5 kg phosphorus per hectare and year were used in this study independent of fertiliser product used.

Soil compaction and wheel traffic in the growing crop

Intensive field traffic with heavy vehicles, e.g. slurry spreaders, leads to soil compaction, which may affect plant growth and production costs and give environmental effects. As a tool for predicting the effects, a computerized empirical model for estimating crop yield losses has been developed (Arvidsson & Håkansson, 1991). The model takes into account soil moisture, clay content, wheel equipment, weight of the vehicles and the distance driven in the field. Soil moisture is expressed on a scale between 1-5, where 1 is very dry and 5 is very wet. Using the model, one-year effects from wheel traffic, future yield losses caused by structural damage in the topsoil persisting after ploughing, and permanent yield losses due to subsoil compaction when spreading sewage products were accounted for.

Below, assumptions are given for blackwater and sludge spreading. Further assumptions considering e.g. wheel equipment are given in Arvidsson (1998).

Blackwater spreading

The two-axled spreader weighed 8 tonnes empty and 26 tonnes loaded. Tyre inflation pressure of the tractor wheels was 100 kPa and of the spreader wheels 180 kPa. Clay content was 30% and soil moisture was 2.5 in the topsoil and 4 in the subsoil at spreading in the growing crop. Spreading width was 12 m.

The cumulative yield reduction due to wheel traffic and soil compaction caused by spreading was 3.8% of one year's yield when both the effects in the topsoil and the upper layer of the subsoil were included (Table 6). The persistent effects in the deeper part of the subsoil were calculated to 0.04% yearly. When the yield reduction during the next 50 years was transferred to the crop under study, these yield losses accounted for another 2%.

Table 6. Effects on yield (%) from blackwater spreading

	Topsoil	Subsoil (25-40 cm)	Subsoil (>40 cm)
One year-effects from wheel traffic	1.9		
Future losses (% of one year's yield)	1.4	0.50	
Permanent future annual yield losses			0.039

In experiments with a 12 m wide spreader holding 6 m^3, the yield depression related to wheel traffic in growing barley was 0-1.2% (Rodhe & Salomon, 1992). The slightly higher yield effects from wheel traffic according to the model (1.9%) seem to be in agreement with these results, as a heavier spreader was assumed in the calculations.

Sewage sludge spreading

The one-axled spreader weighed 4 tonnes empty and 12 tonnes loaded. Tyre inflation pressure in the tractor wheels was 100 kPa and in the spreader wheels 150 kP. Soil moisture was 3.5?? in the topsoil and 3.5 in the subsoil at spreading in the autumn. Spreading width was 8 m.

The cumulative yield reduction, including the effects in the topsoil persisting after ploughing and the upper layer of the subsoil was 1.6% of one year's yield (Table 7). The persistent effects in the deeper part of the subsoil were calculated to 0.012% yearly, i.e. the accumulated yield reduction was 0.6% during 50 years.

Table 7. Effects on yield (%) from sewage sludge spreading

	Topsoil	Subsoil (25-40 cm)	Subsoil (>40 cm)
Yield losses (% of one year's yield)	1.4	0.19	
Permanent future annual yield losses			0.012

Yield

The yield was set to 4800 kg per hectare when using only mineral fertiliser, 4524 kg when using blackwater and 4693 kg when using sewage sludge, i.e. the yield when using blackwater and sewage sludge was 94 and 98% respectively of the yield when using only mineral fertiliser. The assumed difference in yield was explained by soil compaction and wheel traffic in the growing crop. The more immediate as well as future effects from soil compaction were included in the yield as a hypothetical yield reduction in the year under study. No yield-increasing effect related to improved soil structure when using sewage sludge was accounted for in this study.

The seed required for one hectare is generally 190 kg per hectare (Hammar, 1990). The seed production was taken into account through subtraction of the amount of seed needed from the total yield.

Transport

Transport distances used in this study were as follows:

- Fertiliser products from production plant in Köping: 50 km.
- Phosphorus fertiliser product from Western Europe to Köping by ship: 1500 km.
- Blackwater/sewage sludge from households/treatment plant to the farm: 10 km.
- Sewage products from storage on the farm to the field: 1 km.
- Other transport between farm centre and field: 1 km.

Energy requirement and emissions related to transport operations between farm centre and field were based on calculations of a barley production system (Tidåker, 2003). Emission factors for truck and trailer and ship transport for mineral fertilisers were collected from NTM (www).

FLOWS OF NITROGEN, PHOSPHORUS AND CADMIUM

The flows of nitrogen, phosphorus and cadmium through the soil and plant systems per hectare and year for different fertilisation strategy are shown in Table 8. Data not presented earlier in this report are referred to below the table.

Table 8. Flows of nitrogen, phosphorus and cadmium through the soil and plant systems per hectare and year

	Mineral fertilised			Sludge fertilised			Blackwater fertilised		
	N (kg)	P (kg)	Cd (g)	N (kg)	P (kg)	Cd (g)	N (kg)	P (kg)	Cd (g)
Input									
Mineral fert. [a)]	102	16	0.14	80			51	8.3	0.07
Sewage product				135	154	3.2	65	8	0.09
Deposition [b)]	5.1	0.5	0.39	5.1	0.5	0.39	5.1	0.5	0.39
Total input	107	17	0.53	220	155	3.6	121	16	0.56
Removal									
Kernel [c)]	79	16	0.13	77	15	0.13	75	15	0.12
Leaching [d)]	23	0.5	0.32	25	0.5	0.32	23	0.5	0.32
NH3 emissions	0.6			0.5			3		
Total removal	103	16	0.45	103	16	0.45	100	15	0.44
Accumulation	4 [d)]	0.2	0.08	117	139	3.2	21	1.1	0.12

a) According to the supplier (Odal, undated), Cd-content in P20 is 6-12 mg/kg P. Here, 9 mg/kg P was assumed.
b) Deposition of N from Hallgren Larsson (2004), P assumed from Knulst (2001) and Cd from Eriksson (2001).
c) Cd concentration in kernel from Eriksson *et al.* (1997).
d) Leaching and surface run-off of Cd from Bengtsson (2005).

In Table 8, the input and removal are shown during one year when the crop is fertilised according to the different fertilising strategies. However, sewage sludge delivers nitrogen and phosphorus to the crop during several years. The high cadmium load when using sewage sludge is partly related to the high phosphorus application rate. As the phosphorus application is intended for several years, the cadmium supplied in the years following the sludge application will only be in the form of deposition.

CHARACTERISATION

In the following chapter, characterisation factors used for weighting different emissions are briefly described.

Global warming

The enhanced global warming caused by radiative forcing is the primary effect caused by the increase in greenhouse gases in the atmosphere. Emissions of CO_2 are considered to give the most important contribution to global warming but, especially in agricultural systems, other gases such as CH_4 and N_2O may contribute more than CO_2 (Cederberg, 1998). Secondary and tertiary effects such as climatic instabilities, increasing sea level and changing of oceanic streams have also been modelled, but these models are considered to be uncertain. In LCAs, only calculations based on the primary effect are recommended (Udo de Haes *et al.*, 2002). The most important gases contributing to climate change are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and synthetic, persistent and volatile compounds. Nitrogen oxides (NO_X) and volatile organic compounds (VOC) contribute indirectly to climate change through the potential forming of tropospheric ozone. As the magnitude of their contribution is uncertain, they are rarely taken into account in Life Cycle Impact Assessments (LCIA) (Udo de Haes *et al.*, 2002). In this study, a time-perspective of 100 years was used (Table 9).

Table 9. Global warming potentials (GWP) as CO_2-equivalents for different trace gases (IPCC, 2001)

Trace gas	GWP, 100 years
Carbon dioxide, CO_2	1
Methane, CH_4	23
Nitrous oxide, N_2O	296

Eutrophication

Eutrophication includes both impacts on terrestrial and aquatic systems. *Terrestrial eutrophication* covers the negative effects of excess nutrients (ammonia and nitrogen oxide) on plants and species composition. Terrestrial eutrophication is recommended to be included in LCA, however not usually characterised in LCIA of today (Udo de Haes *et al.*, 2002). In Lindfors *et al.* (1995), the amount of nitrogen emitted to air is presented without taking site-specific characteristics into account. More recent studies present site-dependent characterisation factors, which take fate, background deposition and ecosystem sensitivity into account (e.g. Huijbregts *et al.*, 2001).

Aquatic eutrophication is defined as nutrient enrichment of the aquatic environment leading to an increased production of biomass. During the decomposition of the biomass, oxygen is required. In Europe, most freshwater is phosphorus limited, whereas in marine waters, nitrogen limits production (Udo de Haes *et al.*, 2002). Weighting factors for eutrophication have been presented by Lindfors *et al.* (1995). These weighting factors do not account for the primary oxygen demand due to nitrification, i.e. when ammonia to air and ammonium to water are oxidised to nitrate in the recipient waters. Therefore, higher weighting factors for oxidation of ammonia and ammonium have been proposed (Kärrman & Jönsson, 2001). In Table 10, weighting factors used in this study are presented.

Table 10. Weighting factors for eutrophication expressed as a maximum scenario assuming that all substances mentioned contribute to eutrophication. (Lindfors et al., 1995; Kärrman & Jönsson, 2001)

Substance	Maximum (g O_2 per g)	Minimum (g O_2 per g)
N to air	20	
NO_x to air	6	
NH_3 to air	19.8	3.8
N to water	20	
NO_3 to water	4,4	
NH_4 to water	18.6	3.6
P to water	140	140
PO_4^{3-}	46	46
COD	1	1

As different aquatic systems are limited by different nutrients, a general characterisation raises questions. How to account for nitrogen emissions to air is also problematic, as only a fraction of the emissions will reach the aquatic system (Lindfors *et al.*, 1995). In order to overcome these problems, region-specific fate factors have been presented for direct deposition of ammonia and nitrogen oxide emitted to air in the European marine environment (Huijbregts & Seppälä, 2000).

Besides the direct deposition, air emissions could also reach the aquatic environment through run-off and leaching after deposition on the soil. Fate factors for this have been presented for the Netherlands, Europe and the world (Huijbregts & Seppälä, 2001). No regional factors for Sweden are currently at hand.

In this study, water emissions dominated totally the emissions of eutrophying substances. For this reason, no region-specific emission factors for nitrogen emitted to air were used in this study. Instead, the results were presented using emission factors from a maximum scenario according to Lindfors *et al.* (1995) and Kärrman & Jönsson (2001).

Acidification

Acidification is defined as any process that increases the acidity of water and soil systems, which in turn can damage plants and animals (Udo de Haes *et al.*, 2002). Acidification can further promote leaching of nutrients, which reduces forest and plant health, and leaching of aluminium, which leads to eco-toxicological impacts. The major acidifying emissions are nitrogen oxides, sulphur oxide and ammonia.

Most basic acidification equivalency factors are based on the hydrogen ions that theoretically can be formed per mass unit of a certain pollutant released. However, by using such basic models, the release of hydrogen from nitrogen will be overestimated, since nitrogen can be assimilated by the ecosystem and in this case will not contribute to acidification. These basic models also do not pay attention to the spatial or the regional variability (Udo de Haes *et al.*, 2002). Since the late 1990s, several characterisation methods have been developed, which take spatial and regional data into account. The only additional information needed is the location of the emission source. In this report, a maximum scenario was used assuming that all substances in Table 11 are contributing to acidification.

Table 11. Weighting factors for acidification for two scenarios, min and max (Lindfors et al., 1995)

Substance	Min [mol H+/g]	Max [mol H+/g]
SO_2	0.031	0.031
NO_x	0	0.022
NH_3	0	0.059

Furthermore, acidification factors based on a model by Potting *et al.* (1998) was used, taking regional and spatial characteristics into account (Table 12).

Table 12. Weighting factors for Sweden 2010 according to Potting et al. (1998)

Substance	Hectare/tonne
SO_2	4.31
NO_x	0.78
NH_3	4.61

RESULTS

The detailed inventory results for the different wastewater and agricultural systems are summarised in Appendices 2-4.

Energy use

Energy used was divided into fossil fuel and electricity. The amount of heat produced by the different systems was also calculated and presented separately.

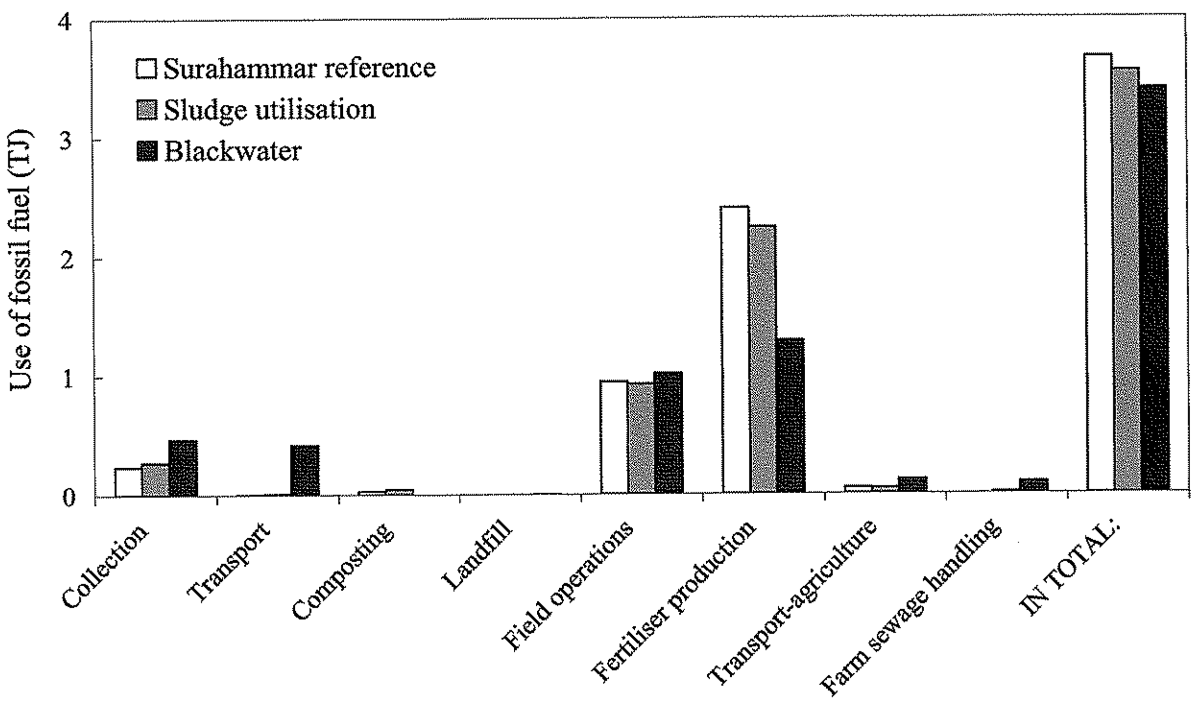

Figure 6. Use of fossil fuel in the three systems.

The use of fossil fuel by the operation phase was 3.7 TJ for the Surahammar reference system, 3.5 TJ for the sludge utilisation system and 3.4 TJ for the blackwater system (Figure 6). Although the blackwater system required considerably more fossil fuel for collection and transport, the total use of fossil fuel was lower due to a reduced need for mineral fertiliser.

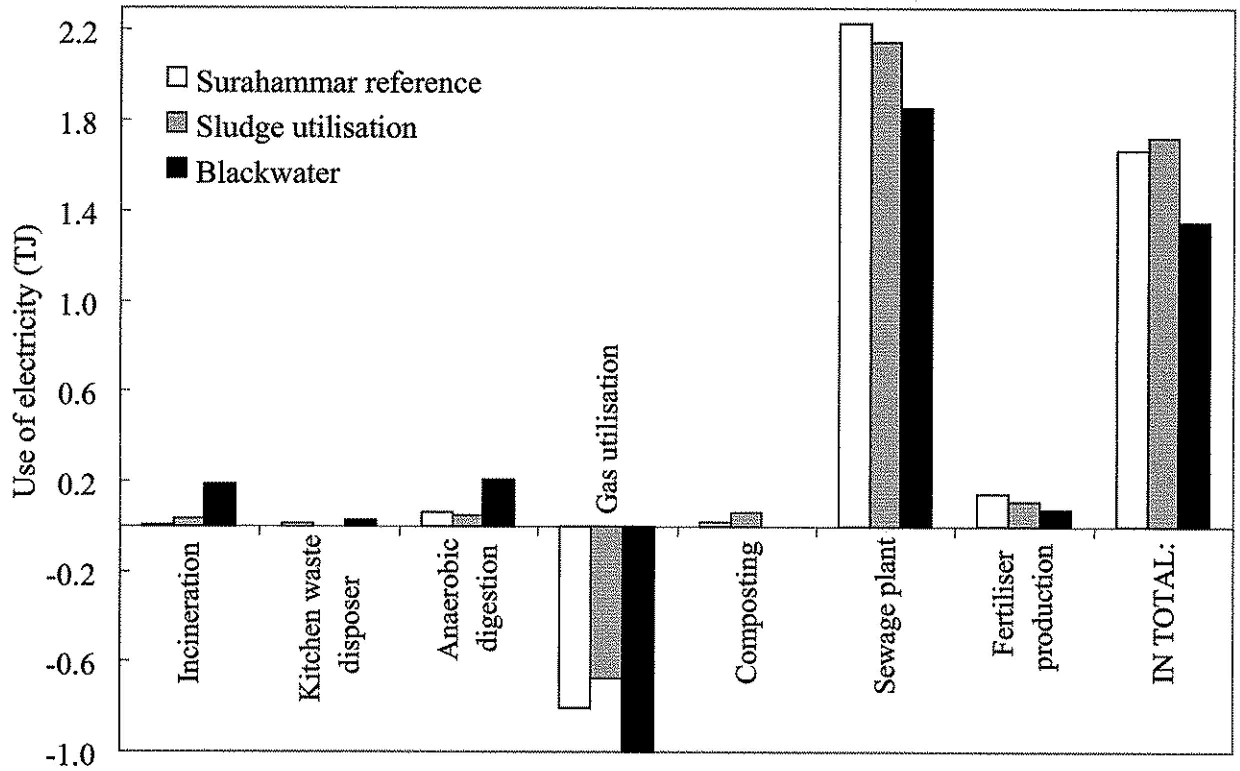

Figure 7. Use of electricity in the three systems.

The electricity use was lowest for the blackwater system due to decreased use of electricity by the sewage plant and an increased production of electricity from the gas originating from the anaerobic digestion (Figure 7). The total use of electricity was 1.7 TJ for the Surahammar reference system, 1.7 TJ for the sludge utilisation system and 1.4 TJ for the blackwater system.

Besides electricity, heat was also produced, which can be utilised by a district heating system. No district heating system exists in Surahammar, instead the heat production from the gas utilisation was assumed to be used for hygienising the incoming wastewater before digestion.

Including only heat produced from the incineration plant and fertiliser production plant, the heat production by the three systems was 0.33 TJ for the Surahammar reference system, 0.69 TJ for the sludge utilisation system and 0.35 TJ for the blackwater system. In the sludge utilisation and blackwater systems the major proportion of the heat was generated by the incineration plant, while in the Surahammar reference system the plant where the mineral fertilisers were produced generated the major proportion of the heat.

Global warming

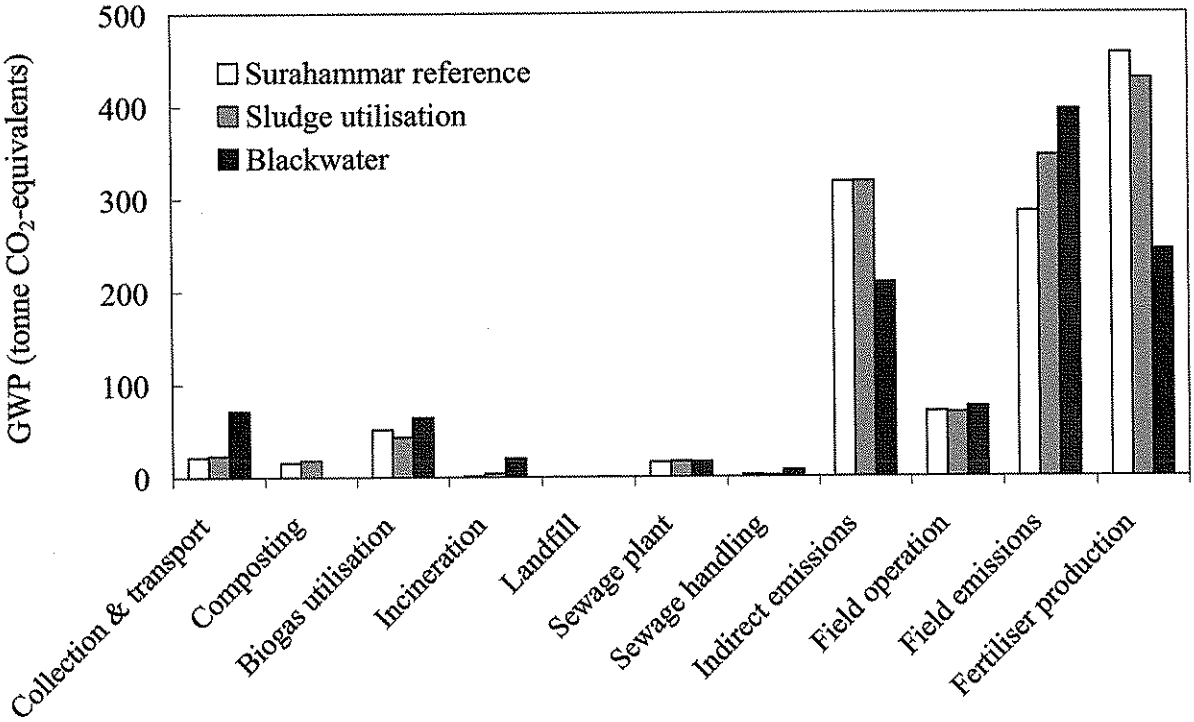

Figure 8. Global Warming Potential (GWP) in the three systems.

The emissions of greenhouse gases, expressed as CO_2-equivalents, were in total 1240 tonnes for the Surahammar reference system, 1270 tonnes for the sludge utilisation system and 1100 tonnes for the blackwater system (Figure 8). N_2O was the predominant greenhouse gas and accounted for approximately 75% of the greenhouse gases, independent of system. Reduced need for mineral fertiliser production in the blackwater system was a determining factor for the total result. The blackwater system also had lower indirect emissions of N_2O, but this was partly outweighed by higher field emissions of N_2O.

Eutrophication

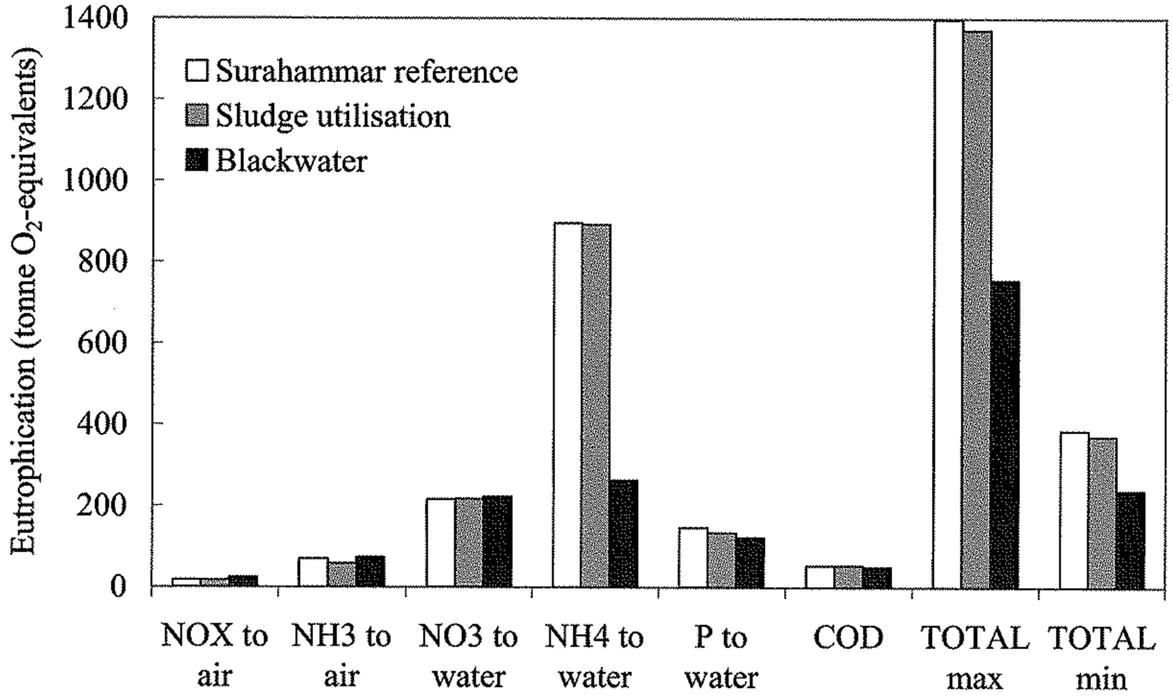

Figure 9. Potential eutrophication in the three systems according to a maximum scenario (Lindfors et al., 1995; Kärrman & Jönsson, 2001) assuming that both nitrogen and phosphorus contribute to eutrophication.

The eutrophying emissions were reduced considerably in the blackwater system according to a maximum scenario, mainly due to reduced emissions of NH_4 from the treatment plant. The emissions of NO_3 originated from the field and differed only slightly between the three systems.

However, the assumption that all substances in Figure 9 contribute to eutrophication is questionable, as nitrogen is not limiting algae growth in the direct recipient water, Kolbäcksån. By separating blackwater from the remaining wastewater fractions, the yearly emissions of phosphorus from the wastewater treatment plant decreased from 775 and 698 kg P for the Surahammar reference and sludge utilisation systems to 529 kg P for the blackwater system. However, due to higher emissions of phosphorus from the incineration plant in the blackwater system, the total load of phosphorus differed only slightly between the three systems. Assuming a minimum scenario for potential eutrophication, i.e. only BOD, phosphorus and nitrification of ammonia contribute to the oxygen demand, the potential eutrophication was 386 tonne O_2-equivalents for the Surahammar reference system, 371 for the sludge utilisation system and 237 for the blackwater system.

Acidification

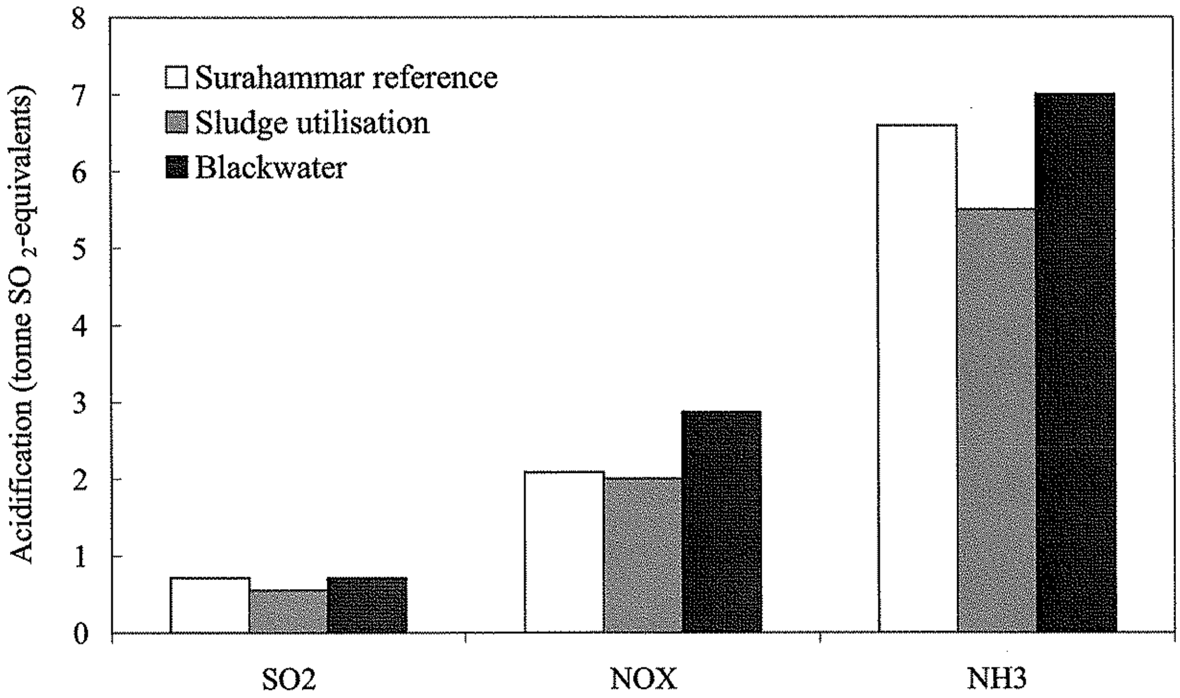

Figure 10. Potential acidification for the three systems according to a maximum scenario (Lindfors et al., 1995) assuming that all nitrogen compounds contribute to acidification.

The emissions of SO_2 were of the same magnitude for all three systems studied, although slightly lower for the sludge utilisation system (Figure 10). As regards NH_3 and NO_X, the emissions were highest for the blackwater system due to e.g. NH_3 emitted during spreading of blackwater and NO_X emissions related to transport and collection of blackwater.

By using site-dependent factors for acidification, characteristics of the target area are taken into account. Using the emission factors for Sweden 2010 presented by Potting *et al.* (1998), it was shown that Surahammar reference system had an acidifying impact on 22 hectares, the sludge utilisation system on 18 hectares and the blackwater system on 23 hectares.

NORMALISATION

The total anthropogenic impacts regarding selected emissions and use of resources is shown in Table 13.

Table 13. Total anthropogenic impact for Sweden

Emissions/use	Total anthropogenic impact in Sweden	References
GWP-gases (tonne CO_2-equivalents)	69 000 000	Statistics Sweden, 2002
NH_3 to air (tonne)	55 600	Statistics Sweden, 2004c
SO_2 to air (tonne)	58 000	Statistics Sweden, 2002
NOX to air (tonne)	247 000	Statistics Sweden, 2002
N to receiving water (tonne)	114 300	Brandt & Ejhed, 2002
P to water (tonne)	3 130	Brandt & Ejhed, 2002
Use of N-fertilisers in agriculture (tonne)	169 710	Statistics Sweden, 2004b
Use of P-fertilisers in agriculture (tonne)	14 040	Statistics Sweden, 2004b
Use of fossil fuel (gas, crude oil etc.) (TJ)	940 000	Statistics Sweden, 2005b
Use of electricity (TWh)	149	Statistics Sweden, 2004a
Cd to arable land (kg per year)	1 060	Statistics Sweden, 2005a; Andersson, 1992; Knulst, 2001

The data in Table 13 were used in a normalisation in which the environmental impact and use of resources by the three systems were compared to the total anthropogenic impacts for Sweden divided by the number of inhabitants in Sweden (9 000 000). The figures from the three systems were divided by the number of inhabitants in Surahammar (8 830). The contribution from the three systems compared to the total load was expressed as percentages (Table 14).

Table 14. Environmental impact and use of resources for the operating phase of the three systems compared to Swedish totals

Emissions/resource use	Total impact	Unit	Surahammar reference	Sludge utilisation	Black-water
GWP-gases (CO_2-eqv.)	7667	kg/p,yr	1.8%	1.9%	1.6%
NH_3 to air	6.2	kg/p,yr	6.4%	5.4%	6.8%
SO_2 to air	6.4	kg/p,yr	1.3%	1.0%	1.3%
NO_X to air	27	kg/p,yr	1.2%	1.2%	1.7%
N to receiving water	13	kg/p,yr	43%	43%	20%
P to water	0.35	kg/p,yr	34%	31%	28%
Replaced amount of N-fertilisers in agriculture	19	kg/p,yr	0%	1.0%	15%
Replaced amount of P-fertilisers in agriculture	1.6	kg/p,yr	0%	23%	27%
Use of fossil fuel (gas, crude oil etc.)	104404	MJ/p,yr	0.40%	0.38%	0.37%
Use of electricity	59600	MJ/p,yr	0.32%	0.33%	0.26%
Cd from fertilisers to soil	118	mg/p,yr	6.3%	16%	7.8%

As regards the emissions, nitrogen and phosphorus to water from the systems contributed significantly to the total environmental load.

Table 14 shows that the systems' largest relative impact, compared to the total anthropogenic impact for Sweden, was the discharge of eutrophying substances to water and the use of mineral fertilisers in agriculture. The relative share in terms of greenhouse gases was smaller, but larger than in a previous study of wastewater systems where a similar normalisation procedure was applied (Kärrman & Jönsson, 2001). This is due to updated estimation of N_2O-emissions from discharge of nitrogen to receiving waters and extended system boundaries. In comparison to the study by Kärrman & Jönsson (2001) this study also shows larger impacts in terms of NH_3 to air and use of fossil fuels due to wider system boundaries. The contribution of NH_3 was higher than 5% from all three systems, while the contribution to the use of energy was below 0.5% for all systems.

SENSITIVITY ANALYSIS

The assumptions made in the inventory might have a decisive influence on the results in an environmental systems analysis. In this section, several changes in assumptions are presented and examples of possible systems expansions are given.

Construction of capital goods

The construction of storage tanks and pipes required for separating wastewater may make a considerable contribution to the total environmental load from wastewater systems (Tillman *et al.*, 1996, Lundin *et al.*, 2000; Tidåker, 2003). Disregarding the construction phase will therefore underestimate the environmental impact from a source-separating wastewater system. However, including all investments required would definitely increase the number of aspects that need to be considered. One way to solve this is to use a change-orientated approach, and include only construction of capital goods that differ between the different systems (Tidåker, 2003). In the blackwater system, additional pipes and tanks were required compared to the conventional treatment system. Therefore, the environmental load and resource use related to the construction of these were estimated. Below, assumptions for the construction of these capital goods are presented. The user phase of the investments was set to 30 years for tanks and pipes. Energy required and emissions emanating from the construction are summarized in Appendix 5 and in the chapter 'Environmental load from capital goods' below.

Tanks on household level

For the blackwater system in Surahammar, the following assumptions were made. 80 concrete tanks containing 30 m^3 were placed belowground, each collecting wastewater from 50 households (Olin, 2003). The tanks were emptied every month. The cylindrical tanks were 3 m high and their walls 25 cm thick. Reinforcing bars comprised 3% of the total mass of material used. The environmental load relating to the production of concrete and reinforcing bars was taken from Björklund & Tillman (1997). In these data, the environmental load from the electricity production was not included. This was therefore added, assuming average Swedish electricity production.

Pipes

According to the municipal authority, approximately 80% of the inhabitants live in detached houses. The assumed size of the pipe dimension was Ø50 mm inside the houses and Ø 90 mm outside. The total length of the pipes per individual household was set to 4 m inside the house and 50 m outside. These assumptions were based on drawings of a 'typical' house area. The corresponding figures per household living in apartment blocks were 4 and 3 m, respectively. Weight per metre of the plastic pipes was assumed from data in Tillman *et al.* (1996) to be 1.4 kg/m for Ø90 and 0.75 kg/m for Ø50. Data for energy use and emissions related to production of polyethylene were taken from Boustedt (1993).

Excavation

The excavation for the pipes was set to 1.5 m deep and 0.4 m wide. Excavating also included filling and therefore the volume was multiplied by two. The figure of 3.05 MJ diesel oil/m^3 was taken from Stripple (2001). Emission factors were taken from Lindgren *et al.* (2002) and Stripple (2001).

For each 30 m^3 household tank, 100 m^3 was assumed to be excavated, including space arranging and refilling. For each tank, 3 m^3 macadam was used. According to a reference in Tillman *et al.* (1996), 11.15 MJ electricity and 8.95 MJ fossil fuel is required for production of 1 m^3 macadam.

Spreader

Based on assumptions given in Appendix 4 and data from Börjesson (1994), the energy required for production of raw materials, manufacturing and maintenance was calculated for the spreader. Tractor use during spreading was also included based on the use of the tractor during spreading compared to the total tractor use. The distribution between use of fossil fuel and electricity and the emission factors (expressed in g/MJ) was taken from production of reinforcement steel.

Storage tanks at farm level

Concerning the farm storage, it was assumed that the blackwater product was stored in a concrete tank covered by PVC plastic. In total, 24 300 m^3 of storage capacity was required in the blackwater system. Assuming that each storage tank held 2080 m^3, twelve tanks were required. Each tank consisted of 40 elements and the weight of each element was 1700 kg (Abetong, www). Three percent of the total weight consisted of reinforcing bars (Bringevik, pers. comm.). The thickness of the bottom concrete was set to 15 cm. It was further assumed that the weight of the PVC cover was 460 kg and that the storage was used during 30 years. Data for the environmental impact from the production of PVC were taken from a compilation in Finnveden *et al.* (1996).

Environmental load from capital goods

In Table 15, the environmental load from the construction phase of the blackwater system is summarised and compared to the environmental load from the operating phase of the same system. As is clearly illustrated, the energy use and the emissions of CO_2, SO_2 and NO_X were notably affected, while the change in emissions of CH_4 and N_2O by the production phase was negligible.

Table 15. Environmental load from the production phase compared to the operating phase for the blackwater system

	Fossil fuel (TJ)	Electricity (TJ)	CO_2 (tonne)	SO_2 (kg)	NOx (kg)	CH_4 (kg)	N_2O (kg)
Operation phase	3.4	1.35	262	712	4095	35570	805390
Construction-capital goods	1.0	0.13	48	90	204	50	0.062
Construction/operation (%)	30	10	18	13	5	0	0

Plant nutrient utilisation

Use of splash plate spreader in the spring

Spreading the blackwater in the spring is an alternative to spreading it in a growing crop. Therefore, spreading with a spreader equipped with splash plate was tested in a sensitivity analysis. The same tyre equipment as for blackwater spreading in a growing crop was assumed. However, soil moisture is higher in the spring and was set to 3.5 for the topsoil and 3.5 for the subsoil (Arvidsson, 1998).

The cumulative yield reduction due to wheel traffic and soil compaction caused by spreading was 9.2% of one year's yield when both the effects in the topsoil and the upper layer of the subsoil were included (Table 16). The persistent effects in the deeper part of the subsoil were calculated to 0.05% yearly. When the yield reduction during the next 50 years was transferred to the crop studied, these yield losses accounted for another 2.5%.

Table 16. Effects on yield (%) from spreading blackwater

	Topsoil	Subsoil (25-40 cm)	Subsoil (>40 cm)
One year-effects from wheel traffic, loss	6.2		
Future losses (% of one year's yield)	2.3	0.63	
Permanent future annual yield losses			0.049

Based on data for slurry (Karlsson & Rodhe, 2002), 15% of the ammonium in the blackwater was assumed to volatilise. Higher ammonia emissions implied a higher compensation of mineral fertiliser to ensure the same nitrogen availability. The yield received was lower as an effect of the soil compaction when blackwater was spread in the spring. The yield per hectare was calculated to 4241 kg per hectare, thereby affecting the total yield in the area studied. This resulted in a higher share of set-aside area in the Surahammar reference and sludge utilisation systems (59 and 58 hectares of set-aside area, respectively).

As shown by Table 17, the use of fossil fuel and emissions of greenhouse gases increased when blackwater was assumed to be spread in spring with a splash plate spreader, due to an increased need for mineral fertiliser. The differences between the two systems were also explained by the fact that the reference system decreased the use of fossil fuel and GWP-emissions due to less area required for grain production, as this was dimensioned by the grain produced by the blackwater system.

Table 17. Use of fossil fuel and emissions of GWP-gases for the Surahammar reference and blackwater systems when blackwater was assumed to be applied with a splash plate spreader during spring. (Figures for spreading in a growing crop are given in brackets)

	Surahammar reference system	Blackwater system
Fossil fuel (TJ)	3.49 (3.69)	3.52 (3.40)
GWP-gases (tonne CO_2-eq.)	1195 (1237)	1127 (1103)

Higher utilisation of sludge phosphorus

In this study, 50% of the phosphorus in sewage sludge was assumed to replace mineral fertiliser. However, this assumption could be questioned as the results from different studies have been ambiguous, as mentioned earlier. Therefore, the effect on use of energy and CO_2 and SO_2 emitted was examined when 100% of the phosphorus in sewage sludge replaced triple superphosphate (P20).

The use of fossil fuel in the sludge utilisation system thereby decreased from 3.56 to 3.48 TJ, and electricity decreased from 1.72 to 1.70 TJ. Emissions of CO_2 decreased from 1268 to 1257 tonne CO_2 equivalents and SO_2 from 0.56 to 0.48 tonne. To summarise, only small changes occurred in the environmental effects studied, and the order between the three different systems was not affected.

Sludge value in soil product

In the Surahammar reference system, phosphorus from sewage sludge and compost were used in a soil product. However, no consideration was taken of the fact that sludge might replace some other product. In reality, the contents of organic matter and of plant nutrients are considered important. According to construction directives (RA 98, 1999), 40-80 mg P per kg soil (P-AL) is desired in a soil product. Assuming that 40% of the phosphorus is immobilised within two years and that the total amount of soil produced in the Surahammar reference system was 3420 tonnes, this meant that 625 kg P from e.g. P20 was required. Sewage sludge supplied the soil product with in total 6330 kg P, of which 6224 kg originated from the sewage system and 109 kg from organic waste compost material. Considerably more phosphorus in sewage sludge was thus applied than the actual P requirement if a mineral fertiliser product had been used.

Thus, as illustrated in the previous sensitivity analysis when 100% of phosphorus in sewage sludge was assumed to replace superphosphate, the change related to substitution of phosphorus was small for the environmental impacts considered in this report.

DISCUSSION

Recycling of plant nutrients

One purpose with the model city Surahammar was to evaluate a future system designed for recycling the major proportion of the plant nutrients found in the wastewater. By using blackwater instead of mineral fertilisers, mineral fertilisers are replaced, thereby reducing energy required for the production of those. But as shown in this study, the production of capital goods together with collection and transport required more energy than hypothetically could be saved due to reduced need for mineral fertiliser. However, an advantage with a blackwater system is that a major proportion of the phosphorus found in the sewage could be recycled to arable land without being mixed with e.g. heavy metals and organic pollutants originating from sources other than blackwater.

In this study, all plant-available nitrogen and phosphorus in the blackwater system was assumed to replace mineral fertiliser products. However, the best handling in theory is often not practised by farmers. A Swedish survey covering ten Swedish farmers' experiences of spreading human urine revealed that the handling differed considerably between different farmers and that the urine was used far from optimally (Fernholm, 1999). Assuming that all plant-available nitrogen replaced mineral fertiliser therefore implies that the utilisation on the farms has to be improved.

A drawback with the Surahammar reference system is that the sludge is not utilised on farmland. With this relatively small change in the system a large proportion of the phosphorus would be recycled (even larger than for the sludge utilisation system since a large amount of food waste is conducted to the treatment plant). This change would not cause any considerable negative impacts in terms of use of energy, greenhouse gases, eutrophication or acidification compared to the sludge utilisation system.

Systems boundaries

Several environmental systems analyses of wastewater systems include agriculture in the sense that the reduced need for mineral fertiliser is accounted for. However, spreading of sewage products may have a considerable impact on yield, which is highlighted when the production is taken into account. By including the agricultural production within the system boundaries, a better understanding is also achieved of how a recycling system could be shaped in practice.

Production of capital goods required for separating systems could have a substantial impact on the use of energy (e.g. Tillman *et al.*, 1996, Tidåker, 2003). Tillman *et al.* (1996) conclude that in areas with the majority of the households being one-family houses, the energy use related to the production phase should be included within the systems boundaries. The results from this study also support the view that production of capital goods needs to be considered in environmental systems analyses of decentralised wastewater systems. At present, URWARE does not include production of capital goods, something that should be included in future versions of the model or handled in a parallel model.

Functions of the agricultural system

In many environmental systems analyses of agricultural production, the functional unit is related only to the quantity produced, e.g. 1 kg of grain or 1 kg of milk. In Sweden, however, an important goal beside the actual agricultural production is to ensure an open rural landscape of high aesthetic value. Land use in itself is therefore an important function. Area not required for agricultural production could also be used for other purposes, e.g. energy crop production. How to handle comparisons between production systems using different areas when producing the same quantity is, therefore, a delicate issue, which should be reflected in the functional unit defined or in the system boundaries.

Set-aside subsidies are an established part of the common agricultural policy within the EU aiming at decreasing agricultural over-production. In 2004, the set-aside duty was 5%. If the total agricultural production increases, the additional available area could either be used for purposes other than agricultural production, e.g. energy crop production, afforestation, or the set-aside area needs to increase. A general reduction of yield will thus reduce the demand for set-aside area. An individual farmer can also regulate the set-aside area within the farm. This is of interest in particular in regions with high grain production cost. If the market supply of grain increases and prices decline as a consequence of this, set-aside subsidies could be an alternative to grain production on the farm.

Based on the discussion above, a proposal is to define land use as one function of the system, and a change in the area required for producing a certain quantity of grain could be handled as a change in the set-aside area.

Soil organic matter

Adding organic matter to soil is one important argument for the use of e.g. sewage sludge on arable land as organic matter improves soil structure, particle stability, moisture storage and nutrient supply. However, how to value this in an environmental systems analysis is complicated. One hypothetical way could be to value organic material resulting in a higher yield. In this study, the long-term release of plant nutrients was accounted for as a reduced future need for mineral fertiliser. It was not possible to estimate the way in which an improved soil structure results in a higher yield. Another approach to handle the supply of organic matter in a systems analysis could be to state that all systems should add or remove the same amount of organic matter to the soil. An alternative to increase the soil organic matter without adding e.g. sewage sludge is to incorporate green manure into the soil. From a systems analysis perspective, this can potentially be solved through evaluation of green manure production on set-aside areas.

Using straw as a fuel in district heating plants is an alternative to incorporating the straw into the soil. If too much organic material is removed, losses in soil humus content limit future supply of straw. It is therefore recommended that straw should not be removed more than once in a crop rotation (Nilsson, 1999). If organic matter is added as sewage sludge, more straw could be removed without decreasing the soil organic matter status. In that case, a systems analysis could be expanded to also include heat production. Currently, straw is not frequently used for heating, something which makes this alternative rather unrealistic.

Heavy metals

A target set by the Swedish EPA is that the levels of non-essential metals in agricultural soil should not increase in the long term. A more immediate target is that levels in arable soil should not double within 500 years. Heavy metals not fulfilling this requirement should be monitored or regulated (Swedish EPA, 2002). Cadmium is particularly highlighted by the Swedish EPA as even with the current restrictions, the cadmium levels imply a risk for negative health effects. According to a comprehensive study of trace elements in sludge from 58 sewage treatment plants, the mean concentration was 44 mg Cd per kg P. In the environmental reports from Surahammar municipality 1997-2001, the mean concentration was 46 mg Cd per kg P in sewage sludge. In this study, the concentration of Cd was simulated as 21 mg per kg P. Thus, in this study, the simulated result from URWARE seems to significantly underestimate the cadmium load.

Silver and tin have been identified by the Swedish EPA (2002) as potentially toxic elements which may occur in sewage sludge in relatively large amounts and restrictions have therefore been proposed for reducing discharges to arable land. These metals are not currently part of the URWARE, but ought to be considered in future development.

Greenhouse gas emissions

In a coming evaluation of Swedish digestion systems for organic waste handling, approximately 5% of the total biogas production is estimated to be lost to air during the production phase and subsequent storage (Starberg, pers. comm.). However, the variation between different systems can be considerable and more knowledge of greenhouse gas emissions is needed. Measurements performed in a Danish project revealed that CH_4 emissions accounted for 0.8% of the biogas produced by the reactor (Gabriel *et al.*, 2003). As regards systems where sewage sludge is stored, data are even scarcer. A Swedish Master's thesis examined air emissions of methane, nitrous oxide and ammonia when dewatered sewage sludge was stored (Flodman, 2002). Emissions of nitrous oxide made a considerably higher contribution to global warming than emissions of methane. The emissions from dewatered sludge were estimated at 3.1 kg CH_4 and 5.0 kg N_2O per tonne of dry matter. In this study, no greenhouse gas emissions during storage were accounted for, mainly due to uncertain data. More studies within this field are therefore urged.

Indirect emissions and field emissions were two important sources for emissions of nitrous oxide. Both these sources were, however, based on vague assumptions as the variation in nitrous oxide emitted under different conditions could be considerable. The high emission factors for indirect emissions have also been questioned for Swedish conditions (Kasimir-Klemedtsson, 2001).

CONCLUSIONS

Comparing the impacts from the systems studied with the total anthropogenic impact in Sweden illustrated that the largest relative impact was the discharge of eutrophying substances to water and the use of mineral fertilisers in agriculture.

As regards the operating phase of the whole system, the blackwater system required less fossil fuel and electricity than the other two systems. Although the blackwater system required considerably more fossil fuel for collection and transport, the total use of fossil fuel during the operational phase was lower due to a reduced need for mineral fertiliser. However, the construction of tanks and pipes for blackwater system may give a considerable contribution to the total environmental load. Including the construction phase too revealed that the use of fossil fuel increased considerably and was highest for the blackwater system.

The emissions of greenhouse gases were of the same magnitude for all three systems, although slightly lower for the blackwater system. This was also a fact even when the construction phase was considered. The eutrophying emissions were reduced considerably for the blackwater system evaluated for a maximum scenario, mainly due to reduced emissions of NH_4 from the wastewater treatment plant. The emissions of SO_2 were of the same magnitude for all three systems studied, although slightly lower for the sludge utilisation system. As regards NH_3 and NO_X, the emissions were highest for the blackwater system.

No significant difference in environmental impact appeared when comparing the Surahammar reference system and the sludge utilisation system. This means that installation of food waste disposers only had a minor influence on the environmental impact categories studied.

The URWARE model was used for environmental systems analysis of the operational phase of the wastewater systems. A positive aspect of using a model like URWARE is that large amounts of data around different processes are collected and are easily available from one study to another. In future versions of URWARE, including the construction phase of the systems into the model library should be considered. The agricultural system could also be modelled with higher accuracy.

A unique condition for this study was that the wastewater management was studied in combination with a thorough analysis of the use of wastewater products in agriculture. Differences compared to previous more limited analyses of the agriculture component were that soil compaction affecting the yield was included.

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APPENDIX 1. CHARACTERISATION OF WASTE AND WASTEWATER FRACTIONS

Table 1:1. Composition of waste and wastewater fractions included. Quality marking: Well validated data, data based on few references, *initiated guesses*

Parameter	Faeces+ toilet paper	Urine	Greywater	Organic waste (fraction possible to grind)
H_2O (g/p,day)	*110.6*	1487	130000	140.8
TS (g/p,day)	53.1	20	71.2	35.2
TSS (g/p,day)	*48.0*	0.76	17.6	33.4
VS (g/p,day)	46.4	7.4	41.6	29.9
COD_{tot} (g/p,day)	*64.1*	*8.5*	62.4	48.0
$COD_{sol,bio}$ (g/p,day)	*5.2*	*7.23*	*24.7*	1.3
$COD_{sol,in}$ (g/p,day)	*0.4*	*0.67*	*1.3*	1.1
$COD_{part,bio}$ (g/p,day)	*47.2*	*0.46*	*27.4*	25.1
$COD_{part,in}$ (g/p,day)	*11.3*	*0.14*	*9.0*	20.5
BOD_7 (g/p,day)	*34.1*	5.0	33.8	17.2
N_{tot} (g/p,day)	1.5	11.0	1.53	0.81
$N_{NH3/NH4}$ (g/p,day)	*0.3*	10.3	0.25	0.09
N_{NO3} (g/p,day)	*0.0*	0	0.01	0.00
$N_{sol,org}$ (g/p,day)	*0.45*	*0.6*	*0.47*	0.04
$N_{part,org}$ (g/p,day)	*0.75*	*0.1*	*0.80*	0.68
P_{tot} (g/p,day)	0.5	0.9	0.68	0.14
P_{PO4} (g/p,day)	*0.1*	*0.81*	*0.29*	0.02
P_{Part} (g/p,day)	*0.4*	*0.09*	*0.39*	0.12
S_{tot} (g/p,day)	0.166	0.70	0.46	0.08
K_{tot} (g/p,day)	1.0	2.4	0.79	0.32
Pb (mg/p,day)	*0.040*	0.012	0.42 (1.3)	0.13
Cd (mg/p,day)	0.010	0.0005	0.013 (0.05)	0.005
Hg (mg/p,day)	0.009	0.00082	0.0013 (0.005)	0.0007
Cu (mg/p,day)	1.10	0.10	5.2 (10.3)	0.6
Cr (mg/p,day)	0.13	0.010	0.26 (1.3)	0.26
Ni (mg/p,day)	0.19	0.011	0.52 (1.6)	0.13
Zn (mg/p,day)	*10.7*	0.3	5.2 (13)	1.6

APPENDIX 2. OAT PRODUCTION USING DIFFERENT FERTILISERS

Table 2:1. Energy (MJ) and emissions (g) in oat production using mineral fertilisers

Operation	Fossil fuel	Electri-city	District heat	CO_2	N_2O	CH_4	NO_x	HC	CO	SO_2	PO_4^{3-}	P	NH_3	N to water	NO_3
Precombustion farm operation	120			7014		4.0	62	66	4.0	38					
Stubble cultivation (twice)	1097			82400			900	17.2	48	103					
Harrowing	121			9100			94	2.6	6.7	11					
Sowing	181			13700			138	4.7	12.8	17					
Fertilising	17			1300			17	0.7	2.9	2					
Pesticide application	17			1300			17	0.7	2.9	2					
Harvesting	510			38400			368	6.6	104	48					
Transport within the farm	60			4509			48	2.0	8.1	6					
Application of fertiliser					1275		335						743		
Soil emissions					786							500			103186
Plant emissions													1821		
Indirect emissions					951										
Production of 364 kg N28	4878	170	-444	328692	2046	315	782	0.009		466	0.037	0.0003	75	41	
Production of 80 kg P20	372	141		51680	4.8	95	307	0.0035		642	2.03E-02	55	0.024	1.7	
Transport of P fertiliser	38			2832			66	2.3	3.2	43					
Transport of N fertiliser	12			874			8	0.8	0.8	0.2					
Per hectare:	7424	310	-444	541801	5062	414	3142	104	193	1377	0	555	2639	43	103186
Per kg oat	1.6	0.07	-0.10	118	1.10	0.09	0.68	0.02	0.04	0.30	0.00	0.12	0.57	0.01	22

Table 2:2. Energy (MJ) and emissions (g) in oat production using blackwater and mineral fertilisers

Operation	Fossil fuel	Electri-city	District heat	CO_2	N_2O	CH_4	NO_x	HC	CO	SO_2	PO_4^{3-}	P	NH_3	N to water	NO_3
Precombustion field operations	141			8243		4.7	73	78	4.7	45					
Stubble cultivation (twice)	1097			82400			900	17.2	48	103					
Harrowing	121			9100			94	2.6	6.7	11					
Sowing	181			13700			138	4.7	13	17					
Fertilising	17			1300			17	0.7	2.9	1.6					
Bandspreading	69			5200			61	2.0	5.7	6.5					
Pesticide application	17			1300			17	0.7	2.9	1.6					
Harvesting	510			38400			368	6.6	104	48					
Stirring + filling blackwater	128			9629			101	6.4	29	12					
Transport-band spreader	154			11556			143	4.4	19	14					
Others farm transport	60			4509			48	2.0	8.1	5.7					
Storage & fertiliser application					1962		366						5792		
Soil emissions					786							500			103629
Plant emissions													1821		
Indirect emissions					1020										
Production of 183 kg N28	2453	85	-223	165292	1029	158	278	0.004		234	0.019	0.0002	38	21	
Production of 42 kg P20	193	73		26851	2.5	49.5	160	0.002		334	0.011	28.8	0.013	0.2	
Transport P-fertiliser	20			1471			35	1.2	1.7	22					
Transport N-fertiliser	6			439			4	0.4	0.4	0.1					
Per hectare:	5168	158	-223	379389	4799	213	2802	127	246	856	0	529	7651	21	103629
Per kg oat:	1.2	0.04	-0.05	88	1.1	0.05	0.65	0.03	0.06	0.20	0.0	0.12	1.8	0.0049	24

Table 2:3. Energy (MJ) and emissions (g) in oat production using sludge and mineral fertiliser

Operation	Fossil fuel	Electricity	District heat	CO_2	N_2O	CH_4	NO_x	HC	CO	SO_2	PO_4^{3-}	P	NH_3	N to water	NO_3
Precombustion field operations	109			6358		3.6	56	60	3.6	35					
Spreading of sludge	190			14300			162	4.4	14	18					
Ploughing	622			46700			530	11.0	32.8	58					
Harrowing	121			9100			94	2.6	7	11					
Sowing	181			13700			138	4.7	13	17					
Fertilising	17			1300			17	0.7	2.9	1.6					
Pesticide application	17			1300			17	0.7	2.9	1.6					
Harvesting	510			38400			368	6.6	104	48					
Front loading of sludge	42			3152			20	1.7	6	4					
Transport of spreader	55			4160			51	1.6	7	5					
Transport-others within the farm	60			4509			48	2.0	8.1	5.7					
Storage and fertiliser application					6298		707						971		
Soil emissions					786							500			109386
Plant emissions													1821		
Indirect emissions					1010										
Production of 287 kg N28	3860	134	-351	259496	1615	249	437			368	0.030		59	33	
Transport N-fertiliser	9			690			6	0.6	0.6	0.14					
Reduced future use of 67 kg N28	-905	-31	82	-60835	-379	-58	-102			-86	-0.007		-14	-8	
Reduced future use of P20	-1790	-678		-248710	-23	-458	-1478	-0.02		-3092	-0.098	-266	-1E-	-8E+00	
Reduced transport P-fertiliser	-185			-13629			-320	-11.2	-15.3	-208					
Transport sludge															
Per hectare:	2915	-575	-268	79990	9307	-264	751	85	186	-2813	-0.075	234	2837	17	109386
Per kg oat:	0.6	-0.1	-0.1	18	2.1	-0.1	0.2	0.0	0.0	-0.6	0.00	0.052	0.63	0.0038	24

Appendix 2:4. Energy (MJ) and emissions (g) for set-aside areas

Operation	Fossil fuel	Electricity	District heat	CO_2	N_2O	CH_4	NO_x	HC	CO	SO_2	PO_4^{3-}	P	NH_3	N to water	NO_3
Precombustion field operations	1			60			1	1		0.3					
Pesticide application	17			1300			17	0.7	2.9	1.6					
Soil emissions					786							500			60671
Indirect emissions					538										
Per hectare:	18	0	0	1360	1324	0	18	1	3	2	0.000	500	0	0	60671

APPENDIX 3. ENERGY USE BY THE WASTEWATER SYSTEMS

Table 3:1. Energy used by the three wastewater systems (MJ per year)

Parameter	Surahammar reference	Sludge utilisation	Blackwater
Collection of organic waste, flats	3 950	10 804	0
Collection of blackwater, small houses	0	0	351 150
Collection of organic waste, small houses	218 766	246 183	0
Collection of blackwater, flats	0	0	88 212
Compost to soil manufacturing	783	3 133	0
Reject from compost to incineration	970	3 881	0
Sludge to incineration	0	0	17 449
Blackwater to arable land	0	0	375 984
Sludge to arable land	0	1 537	0
Soil manufacturing	24 776	8 336	0
Maintenance waste reactor compost	6 692	26 767	0
Maintenance sludge windrow compost	20 921	15 424	0
Maintenance ash landfill	27	107	705
Maintenance slag landfill	61	245	957
Electricity, used at incineration plant	8 272	33 089	186 464
Electricity, used by kitchen waste disposer	13 188	0	26 377
Electricity, used by anaerobic dig, Plant	0	0	178 214
Electricity, used by anaerobic dig, Plant, wwtp	62 891	49 902	28 265
Electricity, used by org waste reactor compost	15 954	63 814	0
Electricity, used in wwtp (presedimentation)	1 324 084	1 316 223	1 249 021
Electricity, used in wwtp (Active sludge, anox)	45 773	45 587	43 539
Electricity, used in wwtp (Active sludge, aerob)	582 912	529 231	346 009
Electricity, used in wwtp (Active sludge, ideal settler)	188 624	187 645	178 644
Electricity, used in wwtp (thickener)	22 833	20 355	15 696
Electricity, used in wwtp (Dewatering)	88 876	70 226	40 165
Electricity, from gas utilisation, blackwater digestion	0	0	-660 020
Electricity, from gas utilisation, sewage plant	-805 402	-677 400	-342 257
Heat from incineration for district heating	122 469	489 874	246 191

Twice as much heat as electricity was assumed to generated in the conversion from biogas to electricity (Dalemo, 1996). The heat was further assumed to be used for sanitation of blackwater and sewage sludge. The heat required was calculated to 312 000 MJ for the Surahammar reference system, 248 000 for the sludge utilisation system and 1019 000 MJ for the blackwater system.

APPENDIX 4. CONSTRUCTION OF CAPITAL GOODS

Assumptions made for tractor use

Weight (kg)	7000	
Duration of life (years)	15	
Hectare use/year	115	

Energy required for tractor production

Raw material production (kWh)	45150	
Manufacturing (kWh)	18900	
Maintenance (kWh)	26261	
In total	90311	kWh
	52	kWh per hectare and year
	188	MJ per hectare and year
	28	**MJ per hectare and year for the tractor** during slurry spreading (15% of total use)

Assumptions made for the slurry spreader:

Weight (kg)	8000	(weight from Arvidsson, 2002)
Duration of life (years)	15	
Hectare use/year	100	

Energy required for production of spreader

Raw material production (kWh)	48000	
Manufacturing (kWh)	10400	
Maintenance (kWh)	26572	
In total	84972	kWh
	305899	MJ
	204	**MJ per hectare and year for slurry spreading**

Table 4:1. Energy use and emissions related to construction of capital goods

Operation	Fossil fuel (MJ)	Electricity (MJ)	CO_2 (g)	N_2O (g)	CH_4 (g)	NO_X (g)	SO_2 (g)
Excavation	20626		1546960	30	1	20007	710
Macadam	72	89	6070	0	4	71	8
Pipes	621857	62952	8776533			87765	55851
Household tanks	158486	29292	16087786	21	22991	40445	14664
Farm storage tanks	119938	15941	16263602	11	11137	46608	11488
Machinery	92457	20295	5344445		15673	9358	7216
In total	1013436	128569	48025396	62	49806	204254	89937