

Environmental impact of wheat production using human urine and mineral fertilisers – a scenario study

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Abstract

Life cycle assessment methodology was used to compare conventional wheat production with a scenario where source-separated human urine replaced mineral fertilisers. A change-orientated perspective was used, including differences in capital goods between the scenarios. An optimal fertilising strategy regarding application time, technique and substitution of mineral fertiliser was demonstrated to be important for energy use, global warming and acidification. For reducing the energy use, a well designed collection system for urine also proved important, while recovery of the urine was essential for reducing eutrophication. Applying an agricultural perspective when evaluating the system highlighted potential conflicts regarding nutrient utilisation.

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1. Introduction

The present wastewater system of Sweden is functioning reasonably well, but has been questioned from the perspective of sustainability. One sustainability criterion often used when assessing wastewater systems is the potential recycling of plant nutrients, usually phosphorus, from the sewage product [1,2]. The use of sewage sludge in agriculture has, however, been debated, especially as regards heavy metals and organic pollutants found in sludge. Today, most Swedish food companies are reluctant to buy products from farms that use sewage sludge [3]. New alternatives for wastewater handling, e.g. source-separating systems, seem to a larger extent to fulfil the agricultural requirements of a fertiliser product with a high nutrient value, but without many of the hazardous compounds found in sewage sludge.

Source-separation of human urine is one promising technique for improving the wastewater system. Human urine is the largest contributor of nutrients to household wastewater. In Sweden, with 9 million inhabitants, approximately 36 000 tonnes of nitrogen and 3300 tonnes of phosphorus are found in the urine fraction (calculated from Vinnerås [4]). These figures can be compared to the consumption of mineral fertilisers in agriculture, which was 170 000 tonnes of nitrogen and 15 000 tonnes of phosphorus in Sweden in 2001 [5]. By closing the nutrient cycle, nitrogen and phosphorus are used as resources in agriculture, while at the same time the eutrophying emissions from wastewater treatment plants are reduced. Several environmental systems analyses of wastewater systems also rate urine-separation as a more favourable alternative than a conventional system in most environmental aspects [6–8]. The results from an environmental systems analysis are influenced by the system boundaries. The studies referred to above showed a reduced need of mineral fertilisers as an important aspect for the environmental

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outcome, but different alternatives for handling the urine on farm level were not highlighted.

In many systems analyses, only the operating phase is included, and the construction phase is disregarded. One reason for this might be that the environmental load related to the construction is assumed to be negligible. Including the construction of the technical system is also more time-consuming. However, construction of smaller wastewater systems consisting of many components may give a considerable contribution to the total environmental load [6,7]. Introduction of a urine-separating system complementing an existing wastewater system will inevitably require some additional investment, e.g. collection tanks, which should therefore be taken into consideration.

Several existing Swedish urine-separating systems have been evaluated with respect to function, users' habits and content of nutrients and heavy metals [9–11]. Less information is available on how the urine is used in agriculture. A Swedish survey of 10 farmers' experiences of human urine revealed that the handling of urine differed considerably between the farmers in terms of spreading techniques, choice of crop and time of spreading [12]. Most of the nitrogen and phosphorus in urine are directly available to plants. In both field trials [13] and pot experiments [14,15] the fertilising effect of urine, concerning both phosphorus and ammonium, has been comparable to that of mineral fertilisers when the volatilisation of ammonia was considered. Mineral fertiliser can therefore be substituted by urine. When using a fertiliser such as human urine, the farmer needs to take other practical considerations into account besides the plant nutrient value, e.g. when and how to spread the urine. Conflicts might be involved, e.g. nutrient utilisation versus soil compaction and costs for spreading. The farmer makes his decisions based on agricultural and economic considerations affecting his enterprise, but those decisions might influence the environmental outcome for the whole recycling system. In-depth studies from an agricultural perspective are therefore needed to highlight the conflicts involved and to provide information on both potential and expected environmental performance when introducing a separating system where the urine is used as fertiliser.

2. Goal and scope of the study

2.1. Objectives

The main objective of this study was to evaluate the environmental consequences when human urine replaces mineral fertilisers in arable farming. Life cycle assessment (LCA) methodology was used to compare two scenarios: conventional wheat production using only mineral fertilisers and wheat production using a combi-

nation of source-separated human urine and mineral fertilisers.

Sub-objectives were to analyse how the environmental load was influenced by the design of the urine-spreading scenario and also to discuss how the system boundaries affected the results.

2.2. Environmental aspects considered

The environmental aspects considered were:

- Resources: energy, water and land.
- Ecological effects: global warming, eutrophication and acidification.

Flows of nitrogen, phosphorus and cadmium were further quantified and presented for the two scenarios.

2.3. Functional unit

The functional unit (FU) was 1 kg of winter wheat harvested.

2.4. Description of the scenarios

2.4.1. Region studied

The scenario study was geographically restricted to the catchment area of Lake Mälaren in the eastern part of Sweden, which hosts 1.2 million inhabitants. Lake Mälaren is the third biggest lake in Sweden, and is an important source of drinking water. In the region of Stockholm, 90% of the drinking water comes from this lake [16]. Eutrophication has been a dominant problem in the lake for a long time. When chemical precipitation was introduced into the municipal treatment plants during the 1960s and 1970s, large improvements occurred. Since 1985, however, there have been no obvious signs that the situation has further improved. A short-term goal for the lake is that the phosphorus concentration must be 10–25% lower within 10 years [17]. Further improvement in the water-quality is therefore an urgent task in the catchment area. A reduction in the nitrogen load is also important, as the lake flows out into the sensitive nitrogen-limited Baltic Sea.

Agriculture in the region is dominated by cereal production and livestock density is low. Less than one third of the cereals in the region have access to manure [5]. Sedimentary clay soils are dominating. Soil compaction when performing field operations during wet conditions is a serious and obvious threat to the long-term productivity of the soil.

2.4.2. Data sources

A brief description of the reference scenario and the urine-spreading scenario is found below, with main data sources for different parts of the system summarised in

Table 1. A more detailed description of the two scenarios is given in Tidåker [18] including all references. In that report, results from wheat and barley production are presented. As the general conclusions were similar independent of cereal type, only the results from the wheat study are presented here.

2.4.3. Reference scenario

In the reference scenario, conventional winter wheat production in accordance with current practices in the region was assessed. Information on agricultural practices was obtained from statistical data, literature and interviews with agricultural advisors working in the region studied. Field operations usually performed include stubble cultivation, ploughing, harrowing, sowing, fertilisation, spraying and harvesting, and those operations were included in the scenario. A distance of 1 km between farm centre and the fields was assumed. The nitrogen application rate was based on recommendations given by the Swedish Board of Agriculture [34], i.e. in total 145 kg of nitrogen per hectare, applied on two occasions as N28 (calcium ammonium nitrate). The amount of phosphorus applied was of the same order as the amount of phosphorus removed by the crop, i.e. 19 kg in the reference scenario. Due to the potassium-rich clay soils in the area, no potassium fertiliser is normally required. The yield was set to 6000 kg per hectare in the reference scenario, which is the standard yield in this area [35]. Seed production was taken into account in both scenarios through subtraction of the amount of seed required (210 kg per hectare), from the total yield.

2.4.4. Urine-spreading scenario

The design of the urine-spreading scenario was based on studies of existing and experimental wastewater systems and field trials. It was assumed that the separating system was implemented in a near future and therefore currently available techniques were modelled. As an overall criterion, the management of urine at the farm was designed in a way that optimised

the use of plant nutrients while minimizing the hygiene risks. The same field operations as in the reference scenario were performed, but the second fertilisation was made with urine. Combining mineral fertilisers with urine in the same season instead of using only urine has practical advantages. Mineral fertiliser can be used when the risk for soil compaction is evident, and urine when soil conditions are better. Using a combination of urine and mineral fertiliser also optimises the use of plant nutrients, as the amounts applied better correlate to the amounts required. The strategy chosen in the urine-spreading scenario was to replace 50% of the nitrogen mineral fertiliser with directly plant-available nitrogen (ammonium) from urine. The application rate of urine might range within a wide span, but the 50% level was set to facilitate an evaluation of the substitution. With the strategy chosen, the same total amount of plant-available nitrogen was applied in both scenarios, but the total amount of nitrogen was higher in the urine-spreading scenario. The concentrations of N-total, $\text{NH}_4\text{-N}$ and P in the urine mixture were set to 2.3, 2.1 and 0.23 kg per m^3 , which were median concentrations reported from seven different separating systems in Sweden [36]. Urine was assumed to be collected in detached households with individual concrete storage tanks holding 2.8 m^3 with one year of storage capacity. The calculations were based on a transport distance of 10 km between households and the farm. It was further assumed that before spreading, the urine was stored at the farm centre in a 800- m^3 concrete tank covered with a plastic roof and that it was spread in a growing crop with a 10- m^3 spreader equipped with trail hoses. The calculations were based on a rate of 34.5 tonnes of urine per hectare. The amounts of plant nutrients given as mineral fertilisers and as urine are shown in Table 2. If an appropriate technique is used, e.g. band application with harrowing within 4 h of application or application in a growing crop, ammonia losses could be less than 5% according to field trials performed with human urine [13]. Volatilisation of ammonia from urine was set to 5% of the total $\text{NH}_4\text{-N}$ during storage and 5% during spreading.

The yield in the urine-spreading scenario was determined to be 5650 kg per hectare, i.e. 94% of the yield in the reference scenario. The assumed difference in yield was explained by higher ammonia losses in the urine-spreading scenario (2.4% yield decrease), as well as effects from soil compaction and wheel traffic in the growing crop (1.5 and 2%, respectively). The more immediate effects from soil compaction and any future effects were both accounted for in the yield obtained in the urine-spreading scenario as a reduction in the yield in the year under study.

The urine-separation system was assumed to be an additional part of an already existing conventional system, with a wastewater treatment plant operating

Table 1
Main data sources for different parts of the system

Activities	References
Field operations	[19]
Fertiliser production	[20]
Soil compaction	[21]
Ammonia volatilisation	[13]
Direct and indirect emissions of N_2O	[22]
Leaching of P and N from field	[23,24]
Production of capital goods	[25,26]
Electricity	[27]
Transport	[27–29]
Water production	[30]
Wastewater treatment	[31–33]

Table 2
Flows of total N, P and Cd per hectare and year through the plant and soil systems according to the two scenarios

	Reference			Urine-spreading		
	N (kg)	P (kg)	Cd (mg)	N (kg)	P (kg)	Cd (mg)
<i>Input</i>						
Mineral fertiliser ^a	145	19	171	73	11	99
Urine ^b				79	7.9	20
Deposition ^c	5.5	0.5	700	5.5	0.5	700
Total input	151	19.5	871	158	19.4	819
<i>Removal</i>						
Kernel ^d	102	19	224	96	18	211
Leaching ^e	10	0.5	400	10	0.5	400
Air emissions (N ₂ excluded)	4.5			7.5		
Total removal	117	19.5	624	114	18.5	611
<i>Accumulation</i>	34	0	247	44	0.9	208

^a According to information from the supplier [37], Cd-content in P20 is 6–12 mg/kg P. Here, 9 mg Cd/kg P was used.

^b Cadmium content in urine mixture according to Vinnerås [4].

^c Deposition of cadmium in Jansson [38]. P-deposition from Knulst [39].

^d Concentration of Cd in kernel from Eriksson et al. [40].

^e Cd in soil solution referred to in Jansson [38].

regardless of the urine-separation system, treating other wastewater fractions from the households. Installation of source-separating toilets decreases the amount of water required for the flushing function. Thus, the need for treatment, distribution and pumping of the drinking water and wastewater is affected, which was accounted for. A decreased amount of phosphorus entering the treatment plant also affects the amount of precipitation chemicals required, and therefore affects the production and transportation of those. A reduced need for nitrogen reduction in the treatment plant was also accounted for. The amount of water saved due to urine-separation was set to 8 l per litre urine mixture. This figure, based on studies of three separating systems in Sweden by Jönsson et al. [11], was used for the calculation of the reduced use of energy and avoided emissions. Of the influent to the wastewater treatment plant, 40% of the nitrogen was assumed to be denitrified and 20% to be captured in sludge. Hence, 40% was emitted with the treated water. Reduction of phosphorus in the wastewater treatment plant was set to 95%. The plant nutrients in sludge produced in the treatment plant were not assumed to replace mineral fertilisers. No difference in environmental load in the handling of sewage was accounted for.

2.5. System boundaries

A change-orientated perspective was used, focusing on changes occurring when the urine-spreading scenario

was introduced compared with the reference scenario. In the reference scenario, all activities related to yearly grain production were included. Thus agricultural activities performed in the field, production and transportation of mineral fertilisers and fuel as well as machine transport within the farm were included. Grain production using human urine as fertiliser, as in the urine-spreading scenario, does, however, fulfil a function beyond the actual food production, i.e. providing wastewater handling. The source-separating system also affects the consumption of water used for flushing. In a systems analysis, the systems under comparison should deliver the same functions. When the studied systems provide different functions, this can be accounted for either by adding subsystems that provide additional functions or by subtracting subsystems with excessive functions. Here, subtraction was used, i.e. the system boundaries included affected parts of the water and wastewater systems in the urine-spreading scenario in the sense that burdens avoided when separating urine were subtracted from the agricultural system. The system boundaries are illustrated in Fig. 1. The agricultural system in this figure is identical with the reference scenario. Activities in the wastewater system were only considered in the urine-spreading scenario.

All main changes in the urine-spreading scenario compared with the reference scenario were considered, including production of capital goods not identical in the two scenarios. Therefore, the construction of pipes and storage tanks both on household level and farm level was included in the scenario using human urine, as the construction of those was exclusive for the urine-spreading scenario. For the same reason, the energy consumption related to the manufacture of the urine spreader was taken into account. The pipes and storage tanks were calculated to be in use for 30 years and the spreader on 1500 hectares during its lifetime. The urine-separating toilets were assumed to be installed only when old toilets had to be exchanged or in newly-built areas. The construction phase of these was therefore not taken into account. No other consideration was given to resources and energy needed to construct and maintain the machinery and buildings used in agriculture or in the wastewater system. The environmental impacts from this phase are not negligible when compared with the user phase, but were not considered to be of major importance to the comparison, since they were similar in both scenarios.

Intensive field traffic with tractors and heavy vehicles, e.g. slurry spreaders, leads to soil compaction, which may affect plant growth negatively. Wheel traffic in a growing crop partly damages the crop and thereby decreases the yield. Only the yield reduction related to the spreading of urine was considered here, as this was the only difference between the scenarios.

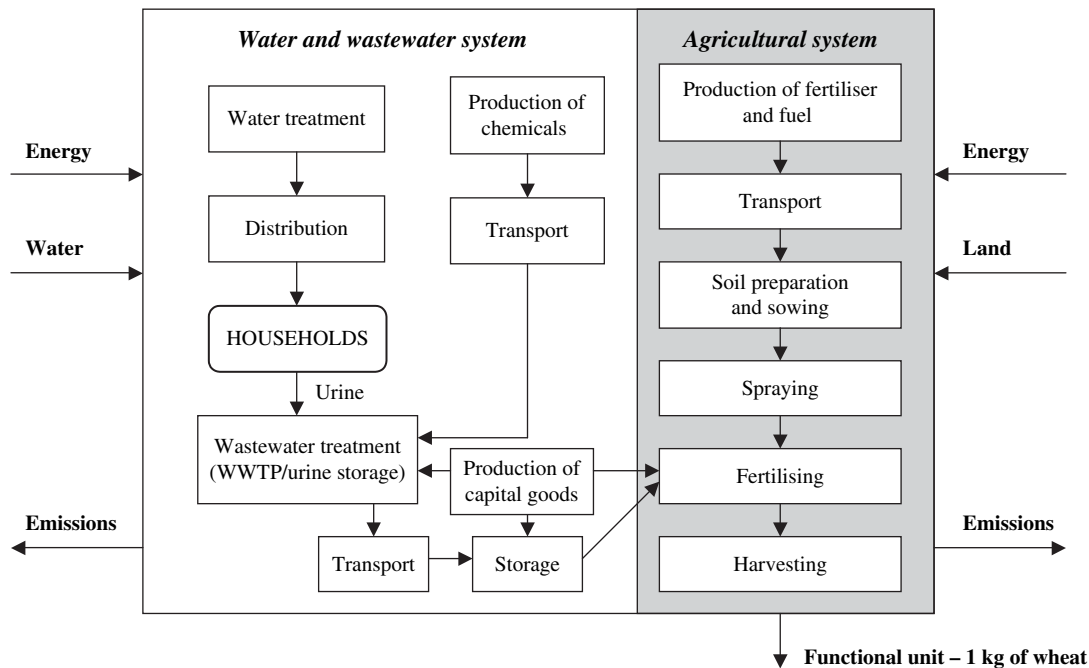


Fig. 1. Flow-chart of the system studied.

3. Results

3.1. Flows of nitrogen, phosphorus and cadmium

The flows of nitrogen, phosphorus and cadmium through the soil and plant systems per hectare and year are shown in Table 2. The calculated yield in the urine-spreading scenario also included the long-term effects from soil compaction.

The surplus of nitrogen was higher in the agricultural system using urine due to the fertilisation strategy chosen and the lower yield. The system using urine also had a small surplus of phosphorus, but the difference between the two fertilising strategies was small. By replacing half the nitrogen in mineral fertiliser with urine, 42% of the phosphorus in the mineral fertiliser was also replaced. The accumulation of cadmium in the soil was slightly less in the system using urine with deposition as the most important factor determining the accumulation in both scenarios.

3.2. Resources: energy, water and land

The use of fossil fuel and electricity, expressed as primary energy, was 1.8 MJ per FU in the reference scenario and 1.2 MJ in the urine-spreading scenario (Fig. 2). Fossil fuel use was similar in the two scenarios, 1.6 MJ in the reference scenario and 1.7 MJ in the urine-spreading scenario. The difference in primary energy use between the scenarios emerged from the use of electricity. The electricity used in the reference scenario was entirely related to the production of mineral

fertilisers. The urine-spreading scenario, on the other hand, saved electricity, due to smaller quantity of drinking water produced, as well as a decreased need for pumping and treating wastewater. The reduced need for production of drinking water accounted for almost 50% of the electricity saved in the urine-spreading scenario. The reduced need for precipitation chemicals accounted for 16% of the electricity saved and reduced biological nitrogen removal for 18%. Production of capital goods in the urine-spreading scenario accounted for 43% of the total primary energy used, which was primarily fossil fuel. The majority of this part (77%) originated from the construction of storage facilities at household level. The urine spreader stood for another 19% of the energy used for capital goods, while the

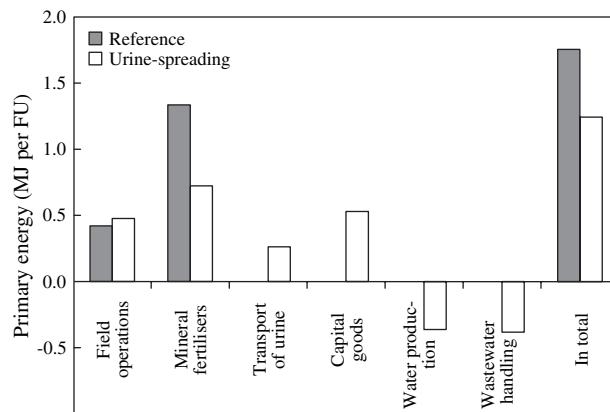


Fig. 2. Total energy use expressed as primary energy partitioned into different activities in the two scenarios.

production phase of the farm storage was almost negligible.

The urine-spreading scenario saved 51 l of water per FU compared to the reference scenario, due to the use of water-saving urine-separating toilets. Land use was slightly higher for the urine-spreading scenario, 1.8 m² per FU compared with 1.7 m² in the reference scenario. This difference originated from the lower yield in the urine-spreading scenario.

3.3. Global warming

The emissions of greenhouse gases, expressed as global warming potential (GWP), from the two scenarios were of the same magnitude, although slightly higher from the reference scenario (Fig. 3). Production of mineral fertilisers contributed most to global warming in the reference scenario. Emissions of N₂O dominated the release of greenhouse gases, and contributed to 72% of the GWP in the reference scenario and 68% in the urine-spreading scenario. The main source of N₂O was field emissions occurring from natural soil processes during the conversion of nitrogen, followed by emissions from production of ammonium nitrate. CO₂ accounted for the remaining contribution to GWP, while negligible amounts of CH₄ were released.

3.4. Eutrophication

The potential contribution to eutrophication was considerably higher for the reference scenario than for the urine-spreading scenario (Fig. 4). The difference between the scenarios was determined by the reduced emissions of nitrogen from the wastewater treatment plant (N-wastewater effluent) when urine was separated. Air emissions of both NO_x and NH₃ were higher in the urine-spreading scenario. NO₃ leaching was calculated to be 10 kg nitrogen per hectare in both scenarios using an empirical model by Hoffmann et al. [23]. Field

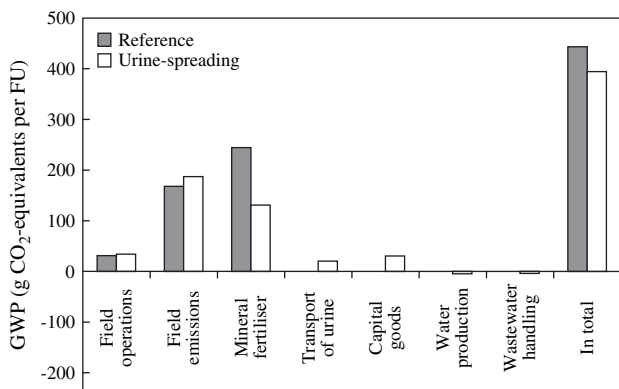


Fig. 3. Contributions to global warming potential (GWP) in a 100-year perspective from different activities in the two scenarios.

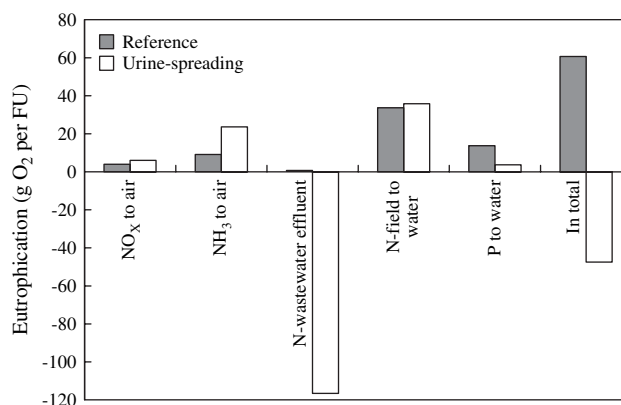


Fig. 4. Contributions to eutrophication (max scenario) in the two scenarios. Weighting factors from Lindfors et al. [41] except higher weighting factors for NH₃ to air and NH₄ to water due to including oxidation of ammonia and ammonium according to Kårrman and Jönsson [42].

emissions of phosphorus were estimated to 0.5 kg per hectare, which was similar to results from regional measurements in a water-quality monitoring programme [24]. Leaching of both nitrogen and phosphorus from field was, however, slightly higher per kg wheat in the urine-spreading scenario than in the reference scenario due to a higher yield in the latter.

3.5. Acidification

The urine-spreading scenario contributed most to acidification, expressed as a maximum scenario, through its higher emissions of NO_x and NH₃ (Fig. 5). In total, the potential contribution to acidification was almost twice as large in the urine-spreading scenario as in the reference scenario. The emissions of NH₃ in particular differed between the scenarios, due to losses during storage and spreading. The higher emissions of NO_x in the urine-spreading scenario originated mainly from

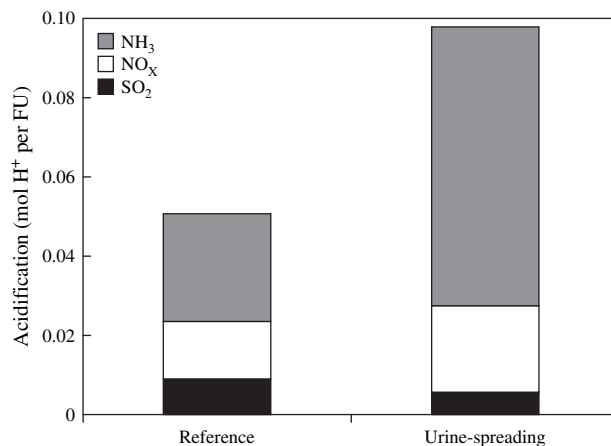


Fig. 5. Contributions to acidification according to the two scenarios. Weighting factors from Lindfors et al. [41].

transportation of urine and the production of the facilities for collecting the urine. The reference scenario had the highest emissions of SO₂ originating mainly from production of mineral fertilisers. If NO_x and NH₃ act as fertilisers, no acidification from these emissions will occur and thus a maximum scenario will overestimate the acidifying effect. By using site-dependent factors for acidification, the characteristics of the target area for the emissions are taken into account, e.g. the sensibility of the area. Potting et al. [43] have presented factors based on modelling of the situation in Sweden 2010. Using these factors revealed that the reference scenario had an acidifying impact on 0.04 m² per FU, compared with 0.07 m² for the urine-spreading scenario.

3.6. Sensitivity analysis

The design of a urine-spreading scenario may be conducted in different ways as regards the collection and handling of the urine. The assumptions made when defining the scenarios therefore influence the results, which make the use of sensitivity analyses crucial.

The following changes in the urine-spreading scenario were made and evaluated in a sensitivity analysis:

- Spreading during the spring using a larger spreader
- Spreading in the autumn before sowing using a larger spreader
- Urine storage in plastic tanks at household level
- Saved electricity considered as produced from coal

A spreader with higher capacity will be more time-efficient, but will also increase the soil compaction and thereby result in yield reduction. Hence, all environmental aspects considered are affected as the functional unit is related to the yield obtained. Calculations were made for an 18-m³ spreader during wet soil conditions, characteristic for the spring, on a clay soil. Further assumptions on wheel equipment, etc. are given in Arvidsson [44]. The yield reduction was 14% if both the more immediate and the future accumulated effects from the soil compaction were attributed to the year under study. The irreversible effects from compaction in the subsoil were calculated over 100 years. If instead urine was spread before sowing in early autumn, the corresponding yield reduction was only 5%. However, this spreading occasion utilises the plant nutrients in urine poorly. If e.g. cattle urine is spread during early autumn without following harrowing, up to 45% of the NH₄-N is expected to volatilise [45]. The remaining nitrogen may be lost during the winter through denitrification and leaching. Besides a higher contribution to acidification and eutrophication, nitrogen mineral fertiliser must replace the volatilised nitrogen in urine. Calculations based on an assumption that all nitrogen required was applied as mineral fertiliser resulted in

a higher use of primary energy and contribution to global warming in a scenario using urine than in the reference scenario. Under these circumstances, the use of primary energy per FU was 1.9 MJ and the contribution to global warming 550 g CO₂-equivalents per FU. Using a 2-m³ storage tank in plastic instead of concrete increased the use of primary energy from the urine-spreading scenario by 0.8 MJ to 2.0 MJ per FU.

Emissions of CO₂ were the second largest contributor to global warming from the scenarios. However, the emission of CO₂ from electricity production depends to a high degree on the electricity mix used. In this study, the Swedish average was used, mainly produced from hydropower and nuclear power. A change in the use of electricity might, however, be a change in the marginal production of electricity, e.g. imported electricity produced in coal-based power plants. If the electricity saved in the urine-spreading scenario was produced from coal, the calculated emissions of CO₂ in the urine-spreading scenario decreased by 44%. The total contribution to GWP expressed as g CO₂-equivalents decreased from 423 to 352 per FU, including also avoided emissions of CH₄, compared to 467 g CO₂-equivalents in the reference scenario.

3.7. Normalisation

The potential effects of a large-scale regional change from conventional wheat production according to the reference scenario to the urine-spreading scenario were examined. In a normalisation, these changes were compared to figures on total impact for Sweden (Table 3). Emissions to air (GWP, NH₃, NO_x, SO₂) and water (N, P) as well as use of mineral fertilisers in agriculture and electricity were considered. The urine was assumed to be used on 33 000 hectares, corresponding to the quantity

Table 3
Change in anthropogenic impact (in %) of implementing a urine-spreading scenario on a large-scale involving 33 000 hectares

Emissions/use	Total anthropogenic impact in Sweden	Change after introduction in large-scale (%)
GWP-gases (tonnes CO ₂ -equivalents)	69 000 000 [46]	-0.01
NH ₃ to air (tonnes)	55 450 [47]	0.2
NO _x to air (tonnes)	247 000 [46]	0.02
SO ₂ to air (tonnes)	58 000 [46]	-0.03
N to receiving water (tonnes)	114 000 [48]	-0.9
P to water (tonnes)	3130 [48]	-0.4
N-fertiliser use in agriculture (tonnes)	170 000 [5]	-1
P-fertiliser use in agriculture (tonnes)	15 000 [5]	-2
Electricity use (TWh)	147 [49]	-0.01

of urine from approximately one million users of urine-separating toilets. The number of users was based on values of urine content in Vinnerås [4] when 70% of the urine excreted was assumed to be collected. The comparison between the up-scaled scenarios was based on the same amount of wheat produced, therefore the reference scenario embraced 31 000 hectares. Urine-separating in large-scale might affect the treatment of the remaining wastewater as regards infrastructure, but this was not considered in the normalisation.

The most noticeable change among the environmental aspects appeared in a lower discharge of nitrogen and phosphorus to water and substitution of nitrogen and phosphorus fertilisers.

As regards the discharge of nitrogen and phosphorus to water, the regional effects are important. Discharge of nitrogen from the region of Mälaren is approximately 10 500 tonnes per year after retention [50] and discharge of phosphorus to Lake Mälaren approximately 400 tonnes per year [17]. Using these figures, the reduction to the lake would be 9% for nitrogen and 3% for phosphorus. Regional data on emissions other than N and P to water would have been desirable, but those were not as easily available as national data.

4. Discussion

The urine-spreading scenario resulted in a reduced discharge of nitrogen and phosphorus to water. According to the normalisation, the change was relatively small compared with the total nutrient load, even in a regional context, mainly because urine-separation was compared to conventional wastewater treatment with efficient removal of nitrogen and phosphorus. However, not all treatment plants have such efficient removal of nitrogen, so the reduction due to urine-separation in reality could be higher, e.g. if installed as a supplement to poor on-site treatment. Reducing emissions of nitrogen and phosphorus could also be achieved by enhanced treatment in a conventional system through e.g. more advanced treatment or supplementing the existing treatment with constructed wetlands.

Recycling of plant nutrients to farmland in order to avoid depletion of resources is a long-term reason for introducing a urine-separating system. Special consideration has mainly been given to phosphorus, but lately other plant nutrients have been emphasised by the Swedish EPA in its action plan for future recycling of phosphorus from wastewater to arable land [51]. This action plan stresses that recovery of nitrogen, potassium and sulphur should also be considered to avoid sub-optimisation. In this respect, human urine fulfils nutrient recovery better than e.g. sewage sludge. A cautious use of the plant nutrients in urine is essential for an optimal use of resources. Animal farms have in

most cases a surplus of phosphorus and potassium [52], and their need for additional plant nutrients is modest. Farms specializing in grain production are therefore more interesting from the aspect of resource use. However, the organisation responsible for disposing of the urine, e.g. a municipality, may prefer to collaborate with an animal farm, as those often have both storage facilities and spreading equipment available. Human urine has been proposed as an interesting fertiliser product for organic farms with limited access to manure due to its high content of easily available nitrogen. However, according to current EU-regulations [53], source-separated human urine is not allowed in organic farming. An analysed nutrient content and optimised use concerning crop and application technique are important factors when using urine. However, the best handling in theory seems not to be practised among farmers [12]. The difference between what is assessed in a systems analysis and practical performance in reality is important to bear in mind when discussing the results from a systems analysis. In this scenario study, urine was assumed to be spread to the growing crop with a small spreader equipped with trail hoses. Hereby, the soil compaction was reduced while the plant nutrient efficiency was kept high. If only a spreader with splash plate is available, the spreading operation can be performed either in the spring or in the autumn. As illustrated in the sensitivity analysis, spreading in spring with a heavier spreader resulted in a substantial yield loss due to soil compaction. In this situation, spreading in the autumn could be a tempting alternative for the farmer, as the plant nutrient value of the urine could be lower than the cost of spreading when soil compaction is also included. However, spreading in the autumn implies that most of the environmental benefits of urine-separation are lost. As the handling of urine on farm level is critical for many environmental aspects, the design of a urine-separating system should include motivated recommendations for the agricultural handling of urine. It is also important that organisations responsible for nutrient recycling systems are aware of the different conflicts involved.

Whether a urine-separating system, where urine is used as fertiliser, is more energy-efficient than a conventional system depends to a large extent on the design of the system. By using a change-orientated perspective in this study, major changes in the construction of capital goods were taken into account, without considering the construction phase as a whole. Production of capital goods contributed noticeably to the primary energy used in the urine-spreading scenario. The calculated lifetime for the capital goods is therefore important. If the longevity is shorter than assumed in this study, the energy required for this phase will be even higher. The choice of material for storage tanks was also an important factor for the use of energy. In this respect,

concrete tanks were preferable to plastic tanks. The long distance sometimes required for transporting the urine has been pointed out as a weakness with a source-separating system without further concentration of the urine mixture. In fact, transportation of urine 10 km had a small influence on the total energy use compared to other factors. The assumptions used in this study allowed transportation of 42.5 km (one way) in the urine-spreading scenario, before the primary energy use in the urine-spreading scenario exceeded that in the reference scenario. Concentration of urine as an additional step in order to reduce the energy use required for transportation should therefore be compared to the construction of capital goods required for this concentration.

The environmental benefits of reduced efforts for the handling of water and wastewater were also important in the energy calculations, especially the amount of water used. To what extent water is saved due to a separating system is not easy to predict, as the variation may be considerable due to different user habits and construction of the toilets [11]. The uncertainty in this assumption is therefore important to bear in mind, as is the fact that considerable water-saving is also possible with non-separating toilets. The way in which urine-separation affects the existing wastewater treatment is scale-dependent according to simulations made by Wilsenach and van Loosdrecht [54]. These simulations also show that methane production originating from digestion of sludge might be higher when urine is separated due to decreased sludge age and a larger degradable fraction. If this had been accounted for here, the energy saved in the urine-spreading scenario would have been even higher.

5. Conclusions

This study demonstrated that an agricultural system using human urine has several environmental benefits if the system is well designed. Emissions of nitrogen and phosphorus to water were lower in the urine-spreading scenario than in the reference scenario. A minor decrease in greenhouse gases was also apparent. Due to emissions of NH_3 during storage and spreading of the urine, the contribution to acidification increased in the urine-spreading scenario. Under the assumptions given in this study, the urine-spreading scenario decreased the use of primary energy compared to the reference scenario. However, this depended on several factors and implied a well-functioning, long-lasting system where the urine was used in an optimal way. The production of capital goods in particular contributed noticeably to the primary energy used in the urine-spreading scenario. Calculations on a large-scale urine-spreading scenario revealed that the change in environmental impact, compared with

figures on total emissions in Sweden, was highest for eutrophication.

Using a change-orientated perspective in this study gave interesting results on the environmental impact related to a conversion to a urine-spreading scenario. Major differences in the construction phase between the scenarios were taken into account, without any need for considering the construction of the whole system.

Applying an agricultural perspective when assessing a urine-separating system gave valuable information on how agricultural production using human urine could be designed. Effects influencing the yield, e.g. soil compaction and wheel traffic in a growing crop from spreading operations, could thereby be included. An optimal fertilising strategy concerning application time, technique and substitution of mineral fertiliser was demonstrated to be important for reducing the environmental load and avoiding soil compaction. The approach also highlighted potential conflicts regarding nutrient utilisation.

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