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Problem or Resource - Why It Is Important For the Environment to Keep Track of Nitrogen, Phosphorus and Carbon in Wastewater and Sludge Management

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Abstract

This paper discusses how the fate of nitrogen, phosphorus and carbon in wastewater and sludge management affects the environmental performance as it may easily be shifted from a resource to a problem and vice versa. The paper explores the impact of some variations in wastewater treatment technology with resulting shifts of elements between forms and media. To this end, life cycle assessment (LCA) results were calculated for a model municipal wastewater treatment plant with primary settling and secondary treatment, and anaerobic digestion of mixed primary and secondary sludge and subsequent use of the sludge in agriculture (baseline scenario). The effect of changing plant operation to increase nitrogen removal and to add also phosphorus control was studied, using data from mass and energy balances. Further, the paper shows that how data for many flows containing nitrogen, phosphorus and carbon is selected in LCA within ranges found in literature may have a large influence on the results. This effect was studied by varying the flows in the baseline scenario between high and low values found in literature. It was shown that LCA results are considerably affected by both considered operational changes and by assumptions on the magnitudes of some flows. The paper argues that more careful consideration of flows of these elements should be made in the operation of wastewater treatment plants and in selection of data in life cycle assessment (LCA) studies.

Keywords: Agricultural use; LCA; Life cycle assessment; Nutrients; Sewage sludge; Wastewater treatment

Abbreviations: AP: Acidification Potential; CHP: Combined Heat and Power; COD : Chemical Oxygen Demand; EP-F: Eutrophication Potential, Freshwater ecosystems; EP-M: Eutrophication Potential, Marine ecosystems; EP-T: Eutrophication Potential, Terrestrial ecosystems; GWP: Global Warming Potential; ILCD: International Life Cycle Data System; LCA: Life Cycle Assessment; PE: Person Equivalent; POFP: Photo-oxidant Formation Potential; TN: Total Nitrogen; TP: Total Phosphorus; WWTP: Wastewater Treatment Plant

Introduction

Today, wastewater collection and treatment has been implemented in many densely populated areas to avoid problems related to spreading of diseases, odor, eutrophication and organic pollution. Collected wastewater and sludge resulting from its treatment contain a wide range of substances, reflecting activities in the serviced area. When nutrients, energy and other components can be recovered and valorized, wastewater and sludge management will not only contribute to solving some of the problems already mentioned, but it can also result in some environmental savings. It must be remembered, however, that problematic constituents in wastewater and sludge, for example organic micro-pollutants, heavy metals and pathogens, can make resource recovery challenging. Also, when additional activities are performed to make resource recovery from wastewater and sludge possible, extra input of energy and chemicals in the life cycle or changed patterns of direct emissions from wastewater and sludge may increase the environmental impact so that benefits from resource recovery are off-set. It is clear that available options for wastewater and sludge management should be assessed from a life-cycle perspective and in terms of both their potential benefits and their potential impacts to allow for purposeful selection and optimization. Some constituents of sludge have the interesting characteristics that they are involved in both some major environmental impacts potentially resulting from wastewater and sludge management and in resource recovery in the sense that they either constitute or can carry the valuable features (the latter is the case when carbon (C) flows are utilized as energy carriers). And, depending on the fate of these constituents in the management of wastewater and sludge, they can easily shift from being a potential resource to a potential problem and vice versa. This is particularly true for nitrogen (N), phosphorus (P) and C, major elements in both wastewater and in sludge. The diversion of these elements from the wastewater may lead to both important air-borne pollutants (such as nitrous oxide (N_2O), ammonia (NH_3) and methane (CH_4)) and to possibilities of resource recovery (e.g., as biogas and as a fertilizer), and these elements may also escape both to air and to water also in subsequent resource recovery activities. Environmental assessments are generally made to provide important information to decisions of varying kind, e.g. in technology development or selection. In order for such information to be useful, it needs to capture relevant aspects of environmental impacts. Which environmental impacts to look into in an environmental assessment must therefore be selected based on both current environmental challenges and on which impacts that the studied system will significantly contribute to. In terms of current environmental challenges, the work by Steffen et al. [1] on planetary boundaries can provide some guidance. According to their estimates, the areas where we are currently subjected to high risk because we are already transgressing planetary boundaries are for biochemical flows of N and P and for genetic diversity. For climate change and for land-system change, we are rapidly moving towards the high risk zone. For some areas, the authors claim that knowledge is still too low for good

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estimates, e.g. for chemical pollution. For stratospheric ozone depletion, however, the risk is currently low and stable. It thus seems reasonable in environmental assessments of wastewater and sludge management to look into the flows of N, P and C as they are an intricate part of several of the highlighted areas; in particular the biochemical flows of N and P and of climate change. Life cycle assessment (LCA) is a methodology commonly applied to assess the environmental performance of different products or services. The method has been used to assess the environmental performance of wastewater and sludge management in numerous studies; for extensive reviews see Corominas et al. [2] and Yoshida et al. [3]. The relevance of results from LCA depends on how the modelled system is set up and on the quality and completeness of the inventory data used, all in relation to the goal and scope of the study. In LCA literature, the difficulties of correctly estimating different flows, in particular gaseous emissions, from wastewater and sludge has been noted, as has their potentially large influence on the environmental life cycle performance; see e.g. Johansson et al. [4], Foley et al. [5] and Kampschreur et al. [6]. As an example, Johansson et al. [4] found that assumptions regarding emissions of N_2O from the sludge after application on agricultural soil can completely determine the outcome in terms of the climate impact for some sludge management systems. In LCA, the environmental impact categories that are the most strongly affected by air- and waterborne emissions originating from wastewater and sludge management are eutrophication, acidification and climate change, matching the concerns of Steffen et al. well, and these should therefore be included in LCAs of such systems. However, to be able to reveal impacts related to other aspects throughout the life cycle and the possible burden-shifting between parts of the life cycle when e.g. operational changes are considered, it may be important to look into also other impact categories, but this needs to be decided based on each specific case. This paper intends to illustrate the importance of keeping track of some elements in wastewater and sludge management. It focuses on flows of N, P and C throughout wastewater and sludge management, as the fate of these elements has a strong impact on the environmental performance because of their involvement in some environmental problems that are perceived to be important and as they are closely linked to most resources of interest in sludge; they can easily shift from being a resource to being a problem and vice versa. The paper intends to show the importance of considering the fate of these elements in design and operation of wastewater and sludge management and illustrates this by exploring how the environmental impact, as determined using LCA, changes as a result of some changes in operation for a model plant. It also intends to show the importance of selecting specific enough data for flows of these elements in LCAs of wastewater and sludge management by looking into the variability related to both plant operation and to selecting high or low values from literature regarding the fate of these elements.

The Fate of N, P and C in wastewater and sludge management

Wastewater treatment plants (WWTPs) are often designed to reach certain targets in terms of organic and nutrient load in the effluent, as these characteristics of the wastewater have been considered the most problematic for recipient ecosystems. Successful treatment will thus transfer these substances into other media, sometimes with a simultaneous change in their chemical appearance. Many different chemical, microbiological and physical processes will take place in the wastewater and in the sludge on the way from collection to release or end-disposal, resulting in different types of emissions to air and to water, and to different resource recovery opportunities. In particular, N and C have air-borne forms that are of high interest as they may give rise to environmental impacts of concern. N in wastewater is typically diverted either to air as N gas (increasingly, as biological N removal is commonly being installed in WWTPs today) or to sludge. N gas emitted to air is unproblematic as it is already the main constituent of air. Some N, however, may escape to air during wastewater treatment in the form of NH_3, potentially causing eutrophication and acidification, and N_2O, potentially causing climate change and stratospheric ozone depletion. As for N, the C may take different forms in the wastewater treatment and it may be turned into gaseous species, some being less problematic, such as carbon dioxide (CO_2), an emission of a greenhouse gas that in this case is normally not considered to contribute to an atmospheric increase as most of the C originates from biogenic sources, and CH_4, which is more problematic as it is a very potent greenhouse gas. CH_4 formation is often utilized in biogas generation in anaerobic digesters in which some C (about half) is instead turned into a valuable resource (biogas consists roughly to 70 percent of CH_4 and 30 percent of CO_2). Emissions of N and C to air can, besides the problems that the direct emissions may give rise to in themselves, also be seen as a loss of potential resources. P is in some ways easier to manage and to model the flows of than N since it does not notably transfer into air-borne forms in wastewater treatment and sludge management. Therefore, the goal of wastewater treatment in terms of P is to transfer enough of P from the wastewater to the sludge to avoid eutrophication of receiving waters. A large part of the N, P and C in the wastewater will eventually find its way to a sludge that will be managed in different ways, with incineration and land application among the main end-disposal alternatives currently proposed in Europe [7]. Both these end-of-life alternatives allow for recovery of some resources. In incineration, the energy content can be valorised, especially in presence of a combined heat and power (CHP) unit - in this case it is the organic (or C) content that constitutes the resource, as an energy carrier - and potentially also P if extracted from the ashes and used as a fertiliser[1]. When sludge is land applied, in particular when sludge is used in agriculture, the nutrients (N and P, in particular) can be valorised. The extent of nutrient up-take by plants will be determined by many different things, for example the exact form of N and P in the sludge, the soil conditions, time and mode of spreading, climate and so forth. The expected up-take is often quantified as the plant up-take of nutrients from sludge in relation to the up-take from mineral fertilisers spread under similar conditions, as a ratio. The sludge may also provide other interesting benefits to soil when land applied as many soils have a less than optimal level of soil organic matter. The soil conditioning effect of the organic matter in land applied sludge, coupled to the C content, and the potential C sequestration in soil, are sometimes discussed but are generally not addressed in LCA [8,5]. Anaerobic digestion of the sludge as part of the sludge treatment makes it possible to transfer some of the C content into CH_4, which can, for example, be burnt for energy recovery in a CHP unit or be upgraded and used as a vehicle fuel. C can also be turned into other potentially useful forms, e.g. already during wastewater treatment, such as polyhydroxy alkanoates (PHAs). Although these different resource recovery opportunities all provide possibilities to save environmental impacts by replacing other means of providing the same functions, they may also lead to increased direct emissions of the discussed elements to air and to water both during and after the wastewater treatment, and to other environmental impacts from additional use of energy or chemicals throughout the life-cycle. Figure 1 shows the flows that are explored further in this paper, all potentially important in the mapping of the fate of N, P and C at a wastewater and sludge management facility with agricultural use as the end-disposal option for the sludge, when determining the life cycle environmental performance. Some of the flows shown in Figure 1 are commonly

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[1] Many different options for P recovery from wastewater and sludge both before and after incineration have been suggested; see for example documentation from the P-REX, EU FP7 project on http://p-rex.eu/.

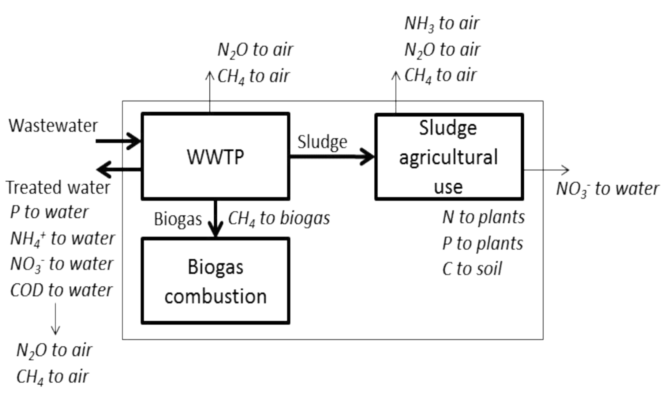

Figure 1: Flows of N, P and C in wastewater and sludge management that have been explored in this study (in italics).

included in LCAs on wastewater and sludge management, while others are only rarely included; for a review of how some flows are handled in LCA [2], and for a review of variations in some flows [5]. Typically, a complete lack of data for some flows and lack of specific data for many other flows makes it difficult to make such assessments complete and relevant. As assumptions on the magnitude of some of these flows have been shown to strongly influence LCA results, there is a need to explore which assumptions are more critical to the environmental outcome. Also, in design of wastewater and sludge management, process parameters can sometimes be adjusted to affect how much of different substances that are transferred to different media and in which form. It is important to be able to understand what types of shifts (between media and between forms) should be avoided because of a potentially large influence on the environmental performance, or which precautions that need to be taken when some technologies are implemented. With the purpose of illustrating the effect of such changes and of selecting high or low literature data for flows from wastewater and sludge management, some calculations were made in this study for a model wastewater and sludge management system.

Method and Details for the WWTP Model

The fate of N, P and C in wastewater and sludge management was simulated for model WWTPs specifically designed to highlight the effect of different technical options in environmental LCA. A typical WWTP configuration was selected and mass and energy balances were performed for both the baseline case and for two upgraded cases, the first one with improved N removal from the wastewater and the second one adding also chemical P control, thus changing the fate of N, P and C in two different steps. LCA was used to model the environmental life cycle performance of the three cases, using data generated by the mass and energy balances and gathered from literature. Finally, for the baseline case, the effect of varying the magnitude of some flows between high and low values found in literature was investigated.

Figure 2 shows some details on the selected WWTP configuration. The plant layout adopted in this study is a typical design for a municipal WWTP, including primary settling, secondary treatment (modified Lutzak-Ettinger) and anaerobic digestion of mixed primary and secondary sludge. The baseline scenario is considered to have a relatively low level of N removal (effluent total nitrogen (TN) of 18 mg/L) and no control on the effluent P (i.e. only minimum removal via sludge treatment and disposal). Dewatered sludge is considered to be used in agriculture, following 100 km transport by truck, replacing the use of N and P mineral fertiliser, and biogas is considered to be combusted in an on-site CHP unit, for internal use of the heat and replacing electricity by other means. The functional unit used as a calculation basis in the LCA reflects the considered capacity of the plant: 80,000 person equivalents (PE), with PE defined as 120 g COD/PE/d, 240 L/PE/d and COD:N:P of 100:8:1.1. In a typical WWTP, some operational flexibility is allowed, provided that the interdependency between the different sections of the plant is taken into account. Improved N removal in the first operational change was considered to be achieved by increasing nitrate (NO_3^-) recycling and biomass concentration to reach an effluent target TN of about 10 mg/L, and P control was added in the second operational change, in the form of chemical precipitation to achieve an effluent P concentration below 1 mg/L. Plant-wide mass and energy balances were performed as described in Bertanza et al. [9], in order to generate input to the inventory of LCA data for both baseline and upgraded scenarios. Figure 3 summarises the effects that the introduction of the changes described above have on the distribution of COD (or in some cases rather the removal of COD; as a proxy for C), TN and TP between the different exit routes (i.e. effluent, dewatered sludge, biogas and air). Results from the energy and mass balances are shown in Figure 3 and in the upper part of Table 1. As shown in Figure 3, the achievement of better N removal results in some secondary effects: i) increased transfer of C and N to air; ii) reduced transfer of C, N and P to sludge; iii) increased transfer of P to the effluent; iv) and slightly reduced transfer of C to biogas [10-15]. The addition of also P removal mainly shifts the fate of P from the effluent to the sludge. As shown in Table 1, both alternatives also affect the energy balance of the WWTP, with higher energy consumption for pumping and slightly lower electricity generation from biogas combustion in the CHP. As concentrations in sludge are also affected, they also of course ultimately affect the transfer of resources to agricultural soil. Furthermore, these operational changes influence the emissions to air of e.g. greenhouse gases, not only from the WWTP, but also from the soil receiving the sludge and from the recipient receiving the effluent [16-24].

LCA was applied to assess the life cycle environmental impact related to the baseline and the two alternatives, using a so-called attributional approach (that sets out to look at the system as it is rather than focusing on consequences of changes). As earlier mentioned, the functional unit considered WWTP operation during one day, from the entry of the wastewater to the WWTP and until the water is released, the sludge is disposed of and different by-products are valorised. Standard procedures were applied in the LCA; see ISO 14040, ISO 14044 and the International Life Cycle Data System (ILCD) handbook [25]. Construction of buildings or machinery was not included in the studied system as the focus is primarily on direct emissions of N, P and C; such impacts are also generally relatively small in comparison to other impacts when distributed over the whole life span of the facilities and the equipment [2]. As indicated in Figure 2, functions performed by the system in addition to what is considered in the functional unit were compensated for using substitution, as commonly done in many similar studies and as recommended by the ILCD handbook [25]. For the fertilising effect, calcium ammonium nitrate and triple super phosphate were assumed to be replaced and generated electricity was assumed to replace average EU-27 electricity production. Data for the LCA for the baseline and the two alternative scenarios as generated by mass and energy balances and gathered from literature, are listed in Table 1. Life cycle inventory data on energy generation and polyelectrolyte production were taken from the Gabi Professional database 2013, on replaced fertilisers from Davis & Haglund [26] and for production of ferric chloride, data were calculated based on the production process from Frohagen [27]. The environmental impact categories that were considered in this study are the ones that are likely

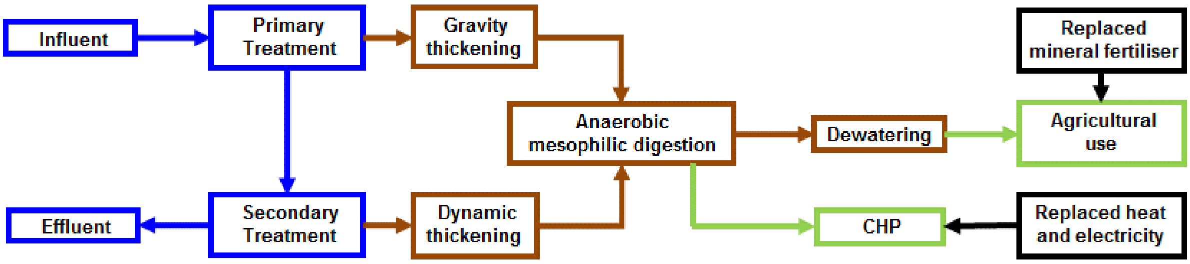

Figure 2: The selected WWTP configuration.

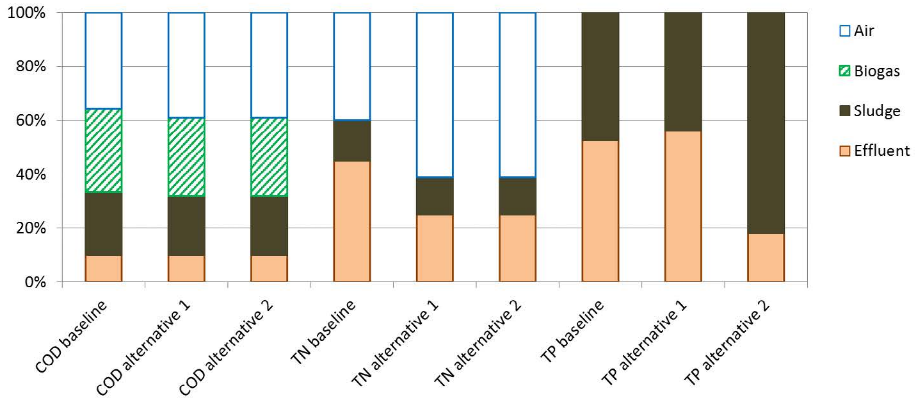

Figure 3: Distribution of N, P and C between the different WWTP outputs for baseline scenario, alternative 1 (increased N removal) and alternative 2 (alternative 1 plus P control). COD is here a proxy for C and sometimes represents COD removal to an exit flow rather than COD in itself.

Parameter	Baseline scenario	Alternative with N removal	Alternative also with P control
Effluent characteristics	38.2 kg NH_4^+-N/d 267.4 kg NO_3^--N/d 55.3 kg P/d 955 kg COD/d	9.5 kg NH_4^+-N/d 152.8 kg NO_3^--N/d 58.8 kg P/d 955 kg COD/d	9.5 kg NH_4^+-N/d 152.8 kg NO_3^--N/d 19.1 kg P/d 955 kg COD/d
Dewatered sludge	115 kg N/d 50 kg P/d 2240 kg COD/d	104 kg N/d 46 kg P/d 2088 kg COD/d	104 kg N/d 86 kg P/d 2088 kg COD/d
Electricity consumption Electricity generation	4830 kWh/d 3450 kWh/d	5570 kWh/d 3230 kWh/d	5660 kWh/d 3230 kWh/d
Natural gas consumption	20 Nm³/d	20 Nm³/d	20 Nm³/d
Chemicals consumption - polyelectrolyte	164 kg/d	147 kg/d	147 kg/d
- ferric chloride	-	-	324 kg/d
CH_4 emissions to air - from WWTP* - from effluent - from soil	5.5/11 wt% of generated biogas [10] 16 g CH_4/kg COD in effluent [11] 5 kg CH_4/ton dry solids applied [10]		
N_2O emissions to air - from WWTP (secondary treatment)* - from discharged effluent - from soil*	3/10/30 g N_2O-N/kg N denitrified [12] 2.5 g N_2O-N/kg N in effluent [11, 13] 3/10/30 g N_2O-N/kg N applied [11, 14]		
NO_3^- emissions to water from soil*	2/10/20 wt% of N applied [15, 16]		
NH_3 emissions to air from soil*	0.05/0.30/0.50 kg NH_3-N/kg NH_4^+-N applied [13, 14, 17]		
Plant availability compared to mineral fertiliser - N* - P*	25/50/75 wt% of N applied [4, 18-22] 25/50/75 wt% of P applied [5]		
C sequestration in soil*	0/0.1 kg C/kg C applied [23, 24]		

Table 1: Data generated by mass and energy balances or gathered from literature for the baseline WWTP scenario and the two alternative scenarios, with improved N removal in both and P control also added in the second; per day of operation of a plant with a configuration as described in the paper. High and low values for some flows are also given*.*low/baseline/high value (in a few cases only baseline/high); low and high values are used only in the second part of the study where some flows are varied.

to be affected by the considered N, P and C flows, that are commonly assessed in similar studies, and that respond to concerns lifted by Steffen et al. [1]. Climate change is affected by emissions to air of N_2O and CH_4 from the WWTP, from the effluent and from the sludge, and also, indirectly, greenhouse gas emissions may be affected when e.g. electricity generation by other means is replaced (when C is recovered as biogas and used in CHP) and when production and use of mineral fertilizers are replaced (when N and P in sludge is applied to soil). For simplicity, the entire C in wastewater and sludge management was considered to be of biogenic origin in this study although it has been suggested that as much as 25 percent of the C may actually originally be fossil-based [28]. CO_2 of biogenic origin is normally not considered to contribute to climate change, neither is it in this study; nevertheless, the possible effect of sequestration of biogenic C in soil when sludge is land applied, thereby delaying the return of the C to the global C cycle, was tested. NH_3 emissions to air contribute to acidification. Emissions of N to air and to water and P to water contribute in different ways to eutrophication (P to water for freshwater ecosystems, N to water for marine ecosystems and N to air for terrestrial ecosystems). Finally, direct CH_4 emissions to air also contribute to formation of photochemical oxidants as does potentially also emissions of NO_x and hydrocarbons in general from different other activities, including replaced activities. All considered impact categories are potentially affected by changes in the background system, when for example the consumption of energy or chemicals change. Environmental impact categories were selected as recommended by the ILCD handbook: global warming potential (GWP; IPCC (the Intergovernmental Panel on Climate Change) method [29]), acidification potential (AP; method developed by Seppälä et al. [30] and Posch et al. [31]), eutrophication potential (EP; for terrestrial (EP-T), freshwater (EP-F) and marine ecosystems (EP-M), respectively; methods developed by Struijs et al. [30], Seppälä et al. [28] and Posch et al. [29]) and photochemical oxidant formation potential (POFP; method proposed by van Zelm et al. [31]). The geographical scope was the EU-27 countries, which was reflected in the choice of data for the modelling of electricity production and other inputs to the WWTP. LCA modelling was made using the Gabi 6 software.

The sensitivity of the results to variations in data input was tested for the baseline scenario by varying, one by one, the magnitude of some flows, from a low to a high number, reflecting ranges found in literature, see Table 1.

As the focus of this paper is not to present a case study in itself but rather to discuss implications for the environmental impact of different operation of wastewater treatment and of selecting different literature data in quantifying some N, P and C flows originating from the wastewater or sludge, results are only presented in a characterised form for the mid-point impact categories mentioned above. Further, as we are not discussing the relative importance of different impact categories in this paper, only relative results are shown.

LCA Results and Discussion

LCA results for the three wastewater operation scenarios are shown in Figure 4. It can be observed that different parts of the system have a dominant contribution to different impact categories. The parts that have the strongest connection to major emissions of N, P and C that originate from sludge are the WWTP and sludge disposal, the parts that connect to the resources in sludge are the replaced fertiliser and the replaced electricity and parts that are more related to the background system are electricity consumed, chemicals, sludge transport and natural gas. The WWTP and its effluent are important for GWP, EP-F and EP-M, and the sludge disposal on agricultural soil for AP and EP-T. These categories are thus all strongly affected by N, P and C emissions. The fertiliser value of the sludge clearly provides an important benefit to many of the impact categories as does the electricity generation in the CHP unit, which are seen as negative impacts in the figure as they replace emissions when other activities can be avoided. It is thus important that resources in sludge are recovered and that such potential environmental savings are modelled in a meaningful way. Electricity use also has a major impact on several of the impact categories but chemicals, transport and natural gas (taken from the grid; very small compared to the generated biogas), however, all have a fairly low impact on the results, in particular in terms of differences between the scenarios. Electricity use is thus the part of the background system that has the largest impact. Some effects of the variations in the fate of N, P and C due to the considered operational changes can be clearly seen in Figure 4. In particular, the increased emissions of N_2O, connected to N removal, are main contributors to the notable increase of GWP in both alternatives. EP-M is strongly affected by decreased N content in the effluent in both alternatives and EP-F is strongly affected by decreased content of P in the effluent in the third alternative. In comparison to the baseline scenario, higher electricity consumption in both alternatives causes higher impacts on AP and POFP. Interestingly, both operational changes considered increase the environmental impact for most of the considered categories, and only reduce the impact for the ones that are directly addressed, i.e. the eutrophication due to nutrients in the effluent. From the specific example shown here, it thus seems as if gains in terms of decreased release of nutrients to water might be off-set by an increase in emissions in the background system due to increased electricity use, and by an increase in emissions from the foreground system due to increased emissions of N_2O. The assumption on one percent of denitrified N lost in N_2O in N removal [12] therefore stands out as an important assumption and is later tested in a sensitivity analysis. The choice of an EU-27 electricity mix is also important. This mix has roughly 50 percent fossil fuels, 30 percent nuclear power and 20 percent renewables. Had another electricity mix been used, e.g. Swedish with almost half nuclear power and half hydropower, this would have had an impact on the results for all impact categories where electricity has important contributions as there is a very low share of fossil fuels and of combustion processes in general in Swedish electricity generation. The diversion of P from the effluent to sludge has small and mixed effects on AP, EP-T and POFP, i.e., a positive impact due to the credit associated with fertiliser replacement and a negative impact due to increased consumption of chemicals. These categories are also slightly affected by the reduced transfer of N, P and

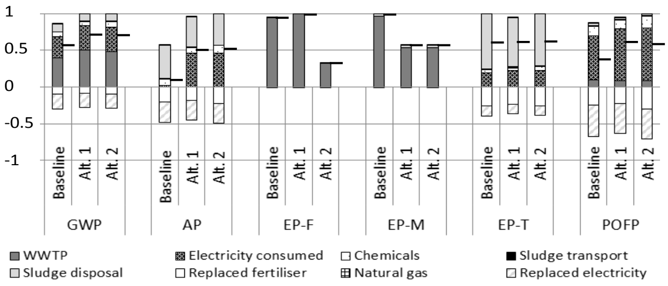

Figure 4: Normalised LCA results for the baseline scenario, for alternative 1 (increased N removal) and alternative 2 (alternative 1 plus P control), for different impact categories; GWP=global warming potential, AP=acidification potential, EP-F=freshwater eutrophication potential, EP-M=marine eutrophication potential, EP-T=terrestrial eutrophication potential and POFP=photochemical oxidant formation potential. Net results are indicated by black horisontal lines.

C to sludge and C to biogas, which is associated with the increased N removal. These variations affect the credits that can be achieved from agricultural use of sludge and from generated electricity.

When varying the data for some flows to high and low values from literature, as indicated in Table 1, some variations had a large impact and some had a smaller impact; the effect also varied between impact categories. A summary of the results is shown in Table 2. Some environmental impact categories are hardly affected at all by the variations in data, in particular EP-F and EP-M, and some variations do not considerably influence any of the impact categories, such as NO_3^- leakage to water from soil after spreading, and C sequestration in soil after spreading. Particularly interesting results of varying some flows are shown in more detail in Figure 5 (A-D). The first bar in each part of the figure shows LCA results for the baseline scenario for that particular environmental impact category; the subsequent bars show results for when one parameter at a time is varied to a different value, low or high, as explained in Table 1. As can be seen from Figure 5, for GWP, the variation of emissions of different greenhouse gases from the WWTP or from soil have a marked effect, but the consideration of potential C sequestration from build-up of C in soil, however, does not seem to be important. The assumption that ten percent of the C in the sludge that is land applied will be stored in the soil indefinitely-a deduction from the impact from sludge disposal in part A of Figure 5 - will have a minor impact compared to the varied emissions of the more potent greenhouse gases CH_4 and N_2O and compared to the effect of varying nutrient availability to plants. For AP and EP-T, varying the NH_3 emissions from soil clearly has a large impact. For POFP, the considered level of plant availability of N and P has an important effect. The results thus have implications for what to consider in an LCA study of WWTPs of this type and what data to select. The LCA analyst should, for example, make an effort to ensure that N_2O and NH_3 emissions to air are included and that the magnitudes are relevant for the studied system, or dealt with in different scenarios that reveal the sensitivity to different assumptions. The same is valid for the plant availability of nutrients in the sludge. The major conclusion in this respect is that more case-specific considerations should be made when selecting data for LCAs of systems of the kind assessed in this paper. The results also provide advice to WWTP designers/operators. In particular, they need to consider not only effluent quality, energy demand and other direct effects of the operation but also indirect effects. In particular, N removal should be pursued without much increased emissions of N_2O. It could also be discussed whether the transfer of N to air as N_2 should be seen as a missed opportunity to recover resources. In fact, the N removal in our example leads to less N and C in the sludge, and thus decreases possibilities for resource recovery in biogas production and land application of sludge. Other options for increasing N removal should be evaluated, e.g. separate treatment of reject waters, in order to maintain secondary sludge and related biogas production. This study focused on major flows of N, P and C in wastewater and sludge management and environmental impact categories that are directly affected by these flows. In actual decision-making situations around wastewater and sludge management, the type of information that can be generated by studies of the type discussed here should be complemented with other information and considerations, for example of economic, technical and legislative type (for example as done in the EU FP7 Routes project for different wastewater and sludge management case studies, see Svanström et al. [32]). Even for environmental concerns, there are other issues that should be explored that are not covered by this study. In this study, the included impact categories were selected both because they are the most common in LCAs of similar systems and because they are the ones that are directly affected by many emissions that contain N, P and C and match the concerns listed by Steffen et al. [1] well. However, environmental impacts may also be connected to other aspects than flows of N, P and C [33]. A more detailed mapping of the metabolism of N, P and C in wastewater and sludge management may include also some other species than the ones included in this study. For agricultural use of sewage sludge, it might seem interesting to include for example toxicity potential and pathogen risk. However, for both methodological and data accessibility reasons, they are more challenging to assess in LCA today [34,35] for a discussion and a newly developed approach for inclusion of pathogen risk in LCA). Further, there are also other possible benefits of the agricultural use of sludge than the ones considered in this study, such as a soil conditioning effect. However, only a few attempts have been made to partially address such effects [8]. The present study has thus pointed towards some areas that need more careful consideration but does not preclude that there may be other areas that need similar attention. The relative importance of different environmental impact categories is not discussed in this paper but needs to be considered in actual decision-making situations. In order to provide a more holistic understanding of the results, it needs to be established which environmental impact categories that are of greater concern than others. Is, for example, a slight increase in the climate impact when operational changes are being made more critical than a large increase in the impact on eutrophication? There are different value-based weighting methods in LCA that can be applied for this purpose, or stakeholders can be involved in a multi-criteria analysis exercise. The present study exemplifies for wastewater treatment and agricultural use of sludge some flows that need to be better mapped to provide more relevant input to decision-making. However, the reader should not see it as an LCA case study for the specific technologies that are explored. Further, although information on some flows are gathered in this paper, there is a need for studies that provide more detailed inventories of some flows for different technologies and situations, extending the scope of e.g. the study by Foley et al. [5].

Conclusions

This study evaluated how assumptions on major N, P and C flows affect the environmental life cycle performance of wastewater treatment and sludge use in agriculture. It was shown that LCA results are considerably affected by considered operational changes and by variations in data found in literature for some flows. The improvement of effluent quality, in terms of first N removal and then also P control, resulted in improved freshwater and marine eutrophication potentials, but comes at the cost of decreased environmental performance for other studied impact categories. The global warming potential is strongly affected by assumptions about emissions to air from the WWTP [36]. Emissions from sludge as well as nutrient plant availability need to be carefully evaluated in case of sludge agricultural use as these parameters strongly influence acidification, terrestrial eutrophication and photochemical oxidant formation potential results. For LCAs of wastewater and sludge management, detailed information on the fate of different elements throughout the different activities involved is needed to enable correct modelling of environmental impacts. More case-specific considerations should be made when selecting data for LCAs of systems of the kind assessed in this paper. LCA analysts need advice on what levels of emissions that would be relevant in different cases, which warrants further research efforts. In selecting configuration and operational details for wastewater and sludge management, operators need to consider the potential impact on the fate of N, P and C flows, as this may strongly influence resource recovery opportunities and environmental impacts.

Variation of flows compared to baseline level	Impact on LCA results for different environmental impact categories:					
	GWP	AP	EP-F	EP-M	EP-T	POFP
Doubling of CH_4 to air from the WWTP	high	-	-	-	-	-
N_2O to air from secondary treatment, from about a third to three times	high	-	-	-	-	-
N_2O to air from soil after spreading, from about a third to three times	medium/high	-	-	-	-	-
NH_3 to air from soil after spreading, from a sixth to double	-	high	-	-	high	-
NO_3^- to water from soil after spreading, from a fifth to double	-	-	-	low	-	-
Plant nutrient availability (N and P) in sludge after spreading, from half to 1.5 times	low	medium	-	-	medium	high
C sequestration in soil after spreading, from null to 10%	low	-	-	-	-	-

Table 2: Summarized results from varying some N, P and C flows compared to the baseline case; '-' means that results are not changed because the flow does not contribute to this category, 'low' is a deviation less than 10% from the baseline result, 'medium' is a deviation between 10 and 30% and 'high' indicates an even larger impact on the baseline results. GWP=Global warming potential (climate impact); AP=acidification potential; EP-F=freshwater eutrophication potential; EP-T=terrestrial eutrophication potential; POFP=photo oxidant formation potential (smog formation).

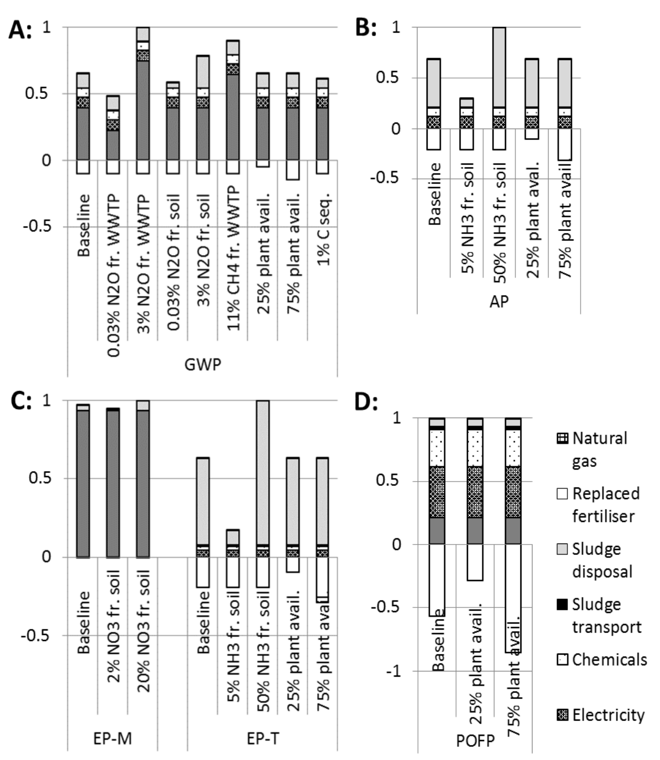

Figure 5: Results of varying some N, P and C flows for the baseline scenario, for different impact categories: (A) global warming potential (GWP); (B) acidification potential (AP); (C) marine and terrestrial eutrophication potential (EP-M and EP-T, respectively) and (D) photochemical oxidant formation potential (POFP). Electricity is in this graph reported as a net value (electricity consumed minus replaced electricity) as this part is not in focus.

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