Deriving Environmental Life Cycle Inventory Factors for Land Application of Garden Waste Products Under Northern European Conditions

The amount of waste which is being recycled is increasing in Europe. Garden waste is increasingly composted and land applied. However, composting to full maturity requires resources in terms of space, equipment and labour. Alternatives could include a simple shredding, or composting for a shorter time. Finally, an option could be to remove trunks and large branches which are not easy to compost and incinerate them to recover energy. In order to assess these options and the associated environmental impacts, it is necessary to have good estimates of emissions and other inventory factors during the different steps of the life cycle of the compost products. Especially, the impacts occurring after land application are difficult to estimate. The objective of the current paper is to estimate environmental inventory factors for land application of four garden waste products: shredded garden waste, shredded garden waste after removal of the woody fraction, immature garden waste compost and mature garden waste compost. Soil incubations of the materials were conducted in order to assess the carbon (C) and nitrogen (N) dynamics occurring after incorporation in soil. Subsequently, the results were used to calibrate the mineralisation kinetics of the materials in the agroecosystem model Daisy. Subsequently, the model was used to simulate C and N dynamics under different environmental conditions and emissions to the environment and used to derive inventory factors. Nine soil and climate combinations were included in the simulation study to cover local conditions commonly found in Northern Europe. The degradability of the garden waste products increased when the woody fraction of garden waste was removed and generally the degradability of the product was decreased by composting. All four products showed initial immobilisation of N in soil, but it was clear that removal of the woody fraction and composting reduced the length and severity of the immobilisation phase. The approach taken in the current paper using soil incubations to estimate decomposition parameters for the materials and subsequently an agroecosystem model to extrapolate the observations proved efficient at estimating inventory factors under various environmental conditions and fertilisation levels. Under low N availability conditions, the harvest factor, which estimates the fraction of N harvested in response to application of an amount of compost ranged between 0.10 and 0.18 for a sandy loam soil and medium precipitation conditions commonly found in Northern Europe while it ranged from negative values to 0.12 under conditions of ample N supply. These results were also clearly reflected in the emission factors for N leaching to the groundwater and losses to surface water proved to be very dependent on the local conditions like the soil type, precipitation regime and general fertilisation level, whereas the biochemical composition of the materials was of less importance for these factors. In contrast, the C sequestration factor was almost unaffected by the environmental conditions but depended to a large extent on the degradability of the added material.
Life cycle assessment of sewage sludge management options including long-term impacts after land application

A life cycle assessment (LCA) was performed on five commonly applied sewage sludge treatment practices: dewatering of mixed sludge (DMS), lime stabilisation of dewatered sludge (LIMS), anaerobic digestion of mixed sludge (ADS), dewatering of anaerobically-digested sludge (DADS) and incineration of dewatered anaerobically-digested sludge (INC). In the first four scenarios, the sludge residues were applied on agricultural land, while in the fifth scenario ash from sludge incineration was landfilled. It was found that the sludge treatment technology influenced in which processes C and N emissions happened. In general, the INC scenario performed better than or comparably to the scenarios with land application of the sludge. Human toxicity (non-carcinogenic) and eco-toxicity showed the highest normalised impact potentials for all the scenarios with land application. In both categories, impacts were dominated by the application of zinc and copper to agricultural soil. For the eutrophication potentials, different scenarios appeared beneficial depending on the receiving compartment in focus. The fate of P dominated freshwater eutrophication, while the fate of N had a profound effect on all non-toxic impact categories other than freshwater eutrophication. The sensitivity analysis showed that the results were sensitive to soil and precipitation conditions. The ranking of scenarios was affected by local conditions for marine eutrophication. Overall, the present study highlighted the importance of including all sludge treatment stages and conducting a detailed N flow analysis, since the emission of reactive N into the environment is the major driver for almost all non-toxic impact categories.

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Estimation of long-term environmental inventory factors associated with land application of sewage sludge

Land application of sewage sludge has a number of advantages over other alternatives, but is also associated with environmental impacts. To make proper assessments of different sludge treatments, it is crucial to have reliable estimates of emissions after the application of different sludge types. However, because of the complexity of the agricultural production system, it is difficult to estimate emissions consistently under different conditions. In the current paper, a mechanistic agro-ecosystem model was calibrated to be able to simulate different sludge types stabilized using different techniques. Subsequently, 100 year model simulations were used to provide emission factors as well as harvest and carbon sequestration factors (collectively called environmental inventory factors) under a variety of environmental conditions. Environmental inventory factors were calculated under both high crop response conditions (i.e. when nitrogen was limiting) and low crop response conditions (i.e. when nitrogen was not limiting). The average high response nitrogen harvest factor over the tested environmental conditions was ranging from 0.06 to 0.30 for the different sludge types included. This means that if an additional 1 kg of nitrogen is applied with sludge, between 0.06 and 0.30 kg additional nitrogen is harvested. This is considerably lower than for mineral fertilizer with an average value of 0.63. The low response harvest factors were considerably lower, ranging from 0.03 to 0.13. The emission factor for nitrous oxide nitrogen was ranging from 0.024 to 0.034, consistently being higher under high response conditions. For nitrogen leaching to the groundwater, the high response emission factor ranged from 0.20 to 0.50 for the different sludge types while the low response were slightly higher ranging from 0.18 to 0.55. The average carbon sequestration factor across the different environmental conditions ranged from 0.03 to 0.05 for the different sludge types. In conclusion, the approach using an agro-ecosystem model to estimate inventory factors associated with land application of sludge under varying conditions proved very powerful and would have been virtually impossible by experimental means.
Long-Term Emission Factors for Land Application of Treated Organic Municipal Waste

The agro-ecosystem model Daisy was used to explore the long-term fate of nitrogen (N) after land application of compost and digestate (based on source separated organic municipal solid waste (MSW)). The cumulative crop N yield response and emissions for mineral fertilizer (MF), anaerobically digested organic waste (MSW-D), and composted organic waste (MSW-C) were derived by fitting a linear mixed model to the outcomes of the simulations. The non-linearity of crop N yield responses and emission responses to increasing N fertilizer application was addressed by dividing these responses into high and low crop response conditions. The crop N yield response and five emission pathways (NO₃⁻ leaching to groundwater, NO₃⁻ and NH₄⁺ loss to surface water, and NH₃ and N₂O emissions into the atmosphere) were quantified as environmental inventory factors, which were calculated for both high and low response conditions. The crop N yield response cumulated over time from the application of N fertilizer almost levelled out for MF within 3 to 5 years after application, while it increased over a time period of 100 years for MSW-C. In addition, MSW-D showed features of both MF and MSW-C, a steep rise in crop N yield response due to high inorganic N content and a gradual increase thereafter, due to the slow mineralization of organic N. Overall, 52–69 % of N applied as MF was up-taken by plant biomass, while plant uptakes of 15–28 % by MSW-D and 19–29 % by MSW-C were measured under high response conditions. When the N fertilizer application rate exceeded the rate of plant uptake, the rate of N utilization dropped by 80–90 % for MF, albeit to lesser degree for MSW-D and MSW-C. The simulations showed that emissions to the environment from organic fertilizers took place over a longer time and omission of the long-term effects could result in underestimation of potential impacts to the environment. As well as the time scope of assessment, local conditions were determining the N emissions. For the N₂O emission, there were very small differences between high and low response conditions for organic fertilizer. The N₂O emission factors varied for 1.8–3.0 % for MSW-D and 1.7–5.1 % for MSW-C. For NO₃⁻ leaching to groundwater, there were large differences between high and low response conditions. For high response conditions, the emission factors varied from 6 to 39, 17 to 68, and 9 to 59 of input N from the application of MF, MSW-D, and MSW-C, respectively. Under low response conditions, much higher leaching emission factors were estimated ranging from 21 to 61 % for MF, 20 to 73 % for MSW-D, and 11 to 66 % for MSW-C.

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A comprehensive substance flow analysis of a municipal wastewater and sludge treatment plant
The fate of total organic carbon, 32 elements (Al, Ag, As, Ba, Be, Br, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Li, Mg, Mn, Mo, N, Na, Ni, P, Pb, S, Sb, Se, Sn, Sr, Ti, V, and Zn) and 4 groups of organic pollutants (linear alkylbenzene sulfonates, bis(2-ethylhexyl)phthalate, polychlorinated biphenyl and polycyclic aromatic hydrocarbons) in a conventional wastewater treatment plant were assessed. Mass balances showed reasonable closures for most of the elements. However, gaseous emissions were accompanied by large uncertainties and show the limitation of mass balance based substance flow analysis. Based on the assessment, it is evident that both inorganic and organic elements accumulated in the sewage sludge, with the exception of elements that are highly soluble or degradable by wastewater and sludge treatment processes. The majority of metals and metalloids were further accumulated in the incineration ash, while the organic pollutants were effectively destroyed by both biological and thermal processes. Side streams from the sludge treatment process (dewatering and incineration) back to the wastewater treatment represented less than 1% of the total volume entering the wastewater treatment processes, but represented significant substance flows. In contrast, the contribution by spent water from the flue gas treatment process was almost negligible. Screening of human and eco-toxicity by applying the consensus-based environmental impact assessment method USEtox addressing 15 inorganic constituents showed that removal of inorganic constituents by the wastewater treatment plant reduced the toxic impact potential by 87-92%. © 2013 Elsevier Ltd. All rights reserved.

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Effects of sewage sludge stabilization on fertilizer value and greenhouse gas emissions after soil application

Application of sewage sludge on agricultural land becomes more and more common in many parts of the world in order to recycle the nutrients from the sludge. A range of sewage sludge stabilization techniques are available to make the sludge more stable prior to storage, transportation, and application. These stabilization techniques include dewatering, drying, anaerobic digestion, composting, and reed bed sludge treatment. However, very few studies have investigated the effect of these techniques after the sludge has been applied to agricultural land. The objective of the current study was therefore to investigate the effect of sewage sludge stabilization techniques on the C and N mineralization and gaseous emissions from soil. A soil incubation was conducted to determine the rate of C and N mineralization and N2O and CH4 emissions of sewage sludge stabilized using different techniques. Unstabilized sludge released up to 90% of their C content as CO2, part of which could be caused by release of CO2 from carbonates. Compared with this, sludge stabilization including

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anaerobic digestion and drying resulted in a reduction of the C mineralization rate of about 40%. Liming reduced C mineralization with around 29%, while treatment in a reed bed system reduced it by 74%. The current study thus clearly demonstrated that stabilization techniques resulted in sludge that was more stable once they were applied to agricultural land. Stabilization also reduced the N immobilization phase, potentially improving the value of the sludge as a fertilizer. Emissions of CH$_4$ were also reduced through sludge stabilization and mainly occurred after application of easily degradable sludge types, which is likely to have enhanced the creation of anaerobic microsites. The stabilization processes also decreased emissions of N$_2$O. The results for both CH$_4$ and N$_2$O indicate that the stabilization tends to reduce the chance of developing conditions where these gases could be produced.

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Influence of data collection schemes on the Life Cycle Assessment of a municipal wastewater treatment plant.

A Life Cycle Assessment (LCA) of a municipal wastewater treatment plant (WWTP) was conducted to illustrate the effect of an emission inventory data collection scheme on the outcomes of an environmental impact assessment. Due to their burden in respect to data collection, LCAs often rely heavily on existing emission and operational data, which are gathered under either compulsory monitoring or reporting requirements under law. In this study, an LCA was conducted using three input data sources: Information compiled under compulsory disclosure requirements (the European Pollutant Release and Transfer Registry), compliance with national discharge limits, and a state-of-the-art emission data collection scheme conducted at the same WWTP. Parameter uncertainty for each collection scheme was assessed through Monte Carlo simulation. The comparison of the results confirmed that LCA results depend heavily on input data coverage. Due to the threshold on reporting value, the E-PRTR did not capture the impact for particulate matter emission, terrestrial acidification, or terrestrial eutrophication. While the current practice can capture more than 90% of non-carcinogenic human toxicity and marine eutrophication, an LCA based on the data collection scheme underestimates impact potential due to limitations of substance coverage. Besides differences between data collection schemes, the results showed that 3-13,500% of the impacts came from background systems, such as from the provisioning of fuel, electricity, and chemicals, which do not need to be disclosed currently under E-PRTR. The incidental release of pollutants was also assessed by employing a scenario-based approach, the results of which demonstrated that these non-routine emissions could increase overall WWTP greenhouse gas emissions by between 113 and 210%. Overall, current data collection schemes have the potential to provide standardized data collection and form the basis for a sound environmental impact assessment, but several improvements are recommended, including the additional collection of energy and chemical usage data, the elimination of a reporting threshold, the expansion of substance coverage, and the inclusion of non-point fugitive gas emissions.

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Sewage sludge management options.

Balance, often included in environmental assessments is vital for accurately evaluating the environmental performance of the non-toxic impact categories. Hence, a depiction of the N balance through the target systems, beyond energy and C emissions of reactive N (NH3, N2O, NH4+, NO3-) into the environment were major contributors to almost all liquid application of sludge. When these emission factors were applied to an LCA comparing sewage sludge treatment over 100 years. Large variations in emission factors, due to local conditions, were observed, especially in the case of the after 25 years, the effect from the application of more stable material such as composted municipal waste persists further to emission factors per unit application of N fertiliser on land by fitting a linear mixed-effect model to the outcome of simulations with varying N application levels. It was evident that the effects of inorganic N fertiliser appear immediately after its application, while improvements in crop yield and emissions of reactive N from organic fertilisers persist over time. The window of emission is dependent on the degree of stabilisation: while the effect from treated sewage sludge ceases after 25 years, the effect from the application of more stable material such as composted municipal solid waste persists over 100 years. Large variations in emission factors, due to local conditions, were observed, especially in the case of the liquid application of sludge. When these emission factors were applied to an LCA comparing sewage sludge treatment alternatives, emissions of reactive N (NH3, N2O, NH4+, NO3-) into the environment were major contributors to almost all of the non-toxic impact categories. Hence, a depiction of the N balance through the target systems, beyond energy and C balance, often included in environmental assessments is vital for accurately evaluating the environmental performance of sewage sludge management options.

Life cycle assessment of sewage sludge treatment and its use on land

Sewage sludge is generated as an end-product of wastewater treatment processes, and its management holds importance in the operation of wastewater treatment plants from both an economic and an environmental point of view. At the same time, the management of sewage sludge is becoming increasingly multi-focused, as renewable energy and nutrient recovery have been added to the list beyond sanitation and stabilisation of sewage sludge. In order to organise and quantify environmental benefits and associated burdens, in order to facilitate an informed decision making process, life cycle assessments (LCAs) have been applied in the field of sewage sludge management for the past two decades. While providing a flexible platform for comparing a range of sewage sludge management options, a knowledge gap has been identified through the review of existing studies, including inconsistencies in pollutant coverage and quantification, the omission of unmetered gaseous emissions and a lack of long-term emission data regarding the land application of sewage sludge. An LCA depends heavily on existing emission and operational data, as generating such data could be prohibitively time- and resource-consuming. Emission and operational data are already collected by wastewater treatment plants for compliance with pollutant discharge requirements, but a part of this pollutant discharge is also reported to a web-based registry (European Pollutant Release and Transfer Registry (E-PRTR)) and is available to the public free of charge. While this data source provides a standardised data collection format, its viability has been questioned due to its limited pollutant coverage and the thresholds regarding reporting requirements. To address this issue, a targeted input data collection campaign was conducted at a municipal wastewater treatment plant. The substance flow analysis of a municipal wastewater treatment plant was conducted to identify the fate of 32 elements, and a reduction in toxicity potential was evaluated by applying USETox. The result was largely confirmative of previous studies, in that wastewater treatment is effective at removing pollutants from wastewater and concentrates them in sewage sludge. Efforts to collect site specific emission data were also expanded to gaseous emission measurements. The tracer dilution method was applied to measure a plant-integrated emission of N2O and CH4 from the wastewater treatment plant. Large variations in emissions were found within and between measurement campaigns, and almost ten times more emissions were found during periods of operational difficulty such as foaming or the malfunction of in-line control systems. The LCA was based on three input data collection schemes: a compulsory environmental information disclosure requirement, a pollutant discharge monitoring requirement and state-of-the-art on-site data collection. While adequately capturing impacts in relation to global warming and marine eutrophication, an LCA based on existing data sources might underestimate impacts associated with wastewater and sludge treatment processes. Finally, the effort to collect emission data was expanded to the use of sludge on agricultural land. The long-term consequences of sewage sludge application on land were evaluated by applying the DAISY dynamic agro-ecosystem model. The C and N mineralisation rates obtained from the 190-day laboratory- scale incubation test for sewage sludge were used to calibrate the DAISY model, and the fates of 32 elements, and a reduction in toxicity potential was evaluated by applying USETox. The result was largely confirmative of previous studies, in that wastewater treatment is effective at removing pollutants from wastewater and concentrates them in sewage sludge. Efforts to collect site specific emission data were also expanded to gaseous emission measurements. The tracer dilution method was applied to measure a plant-integrated emission of N2O and CH4 from the wastewater treatment plant. Large variations in emissions were found within and between measurement campaigns, and almost ten times more emissions were found during periods of operational difficulty such as foaming or the malfunction of in-line control systems. The LCA was based on three input data collection schemes: a compulsory environmental information disclosure requirement, a pollutant discharge monitoring requirement and state-of-the-art on-site data collection. While adequately capturing impacts in relation to global warming and marine eutrophication, an LCA based on existing data sources might underestimate impacts associated with wastewater and sludge treatment processes. Finally, the effort to collect emission data was expanded to the use of sludge on agricultural land. The long-term consequences of sewage sludge application on land were evaluated by applying the DAISY dynamic agro-ecosystem model. The C and N mineralisation rates obtained from the 190-day laboratory- scale incubation test for sewage sludge were used to calibrate the DAISY model, and the fates of C and N in the agricultural field were simulated over a 100-year period. The outcome of the simulation was deduced further to emission factors per unit application of N fertiliser on land by fitting a linear mixed-effect model to the outcome of simulations with varying N application levels. It was evident that the effects of inorganic N fertiliser appear immediately after its application, while improvements in crop yield and emissions of reactive N from organic fertilisers persist over time. The window of emission is dependent on the degree of stabilisation: while the effect from treated sewage sludge ceases after 25 years, the effect from the application of more stable material such as composted municipal solid waste persists over 100 years. Large variations in emission factors, due to local conditions, were observed, especially in the case of the liquid application of sludge. When these emission factors were applied to an LCA comparing sewage sludge treatment alternatives, emissions of reactive N (NH3, N2O, NH4+, NO3-) into the environment were major contributors to almost all of the non-toxic impact categories. Hence, a depiction of the N balance through the target systems, beyond energy and C balance, often included in environmental assessments is vital for accurately evaluating the environmental performance of sewage sludge management options.

General information
Plant-integrated measurement of greenhouse gas emissions from a municipal wastewater treatment plant

Wastewater treatment plants (WWTPs) contribute to anthropogenic greenhouse gas (GHG) emissions. Due to its spatial and temporal variation in emissions, whole plant characterization of GHG emissions from WWTPs face a number of obstacles. In this study, a tracer dispersion method was applied to quantify plant-integrated, real-time emissions of methane and nitrous oxides. Two mobile cavity ring-down spectroscopy sampling devices were used to record downwind gas concentrations emitted from a municipal WWTP situated in Copenhagen, Denmark. This plant is equipped to remove biological nitrogen and employs anaerobic digestion for sludge stabilization. Over the course of nine measurement campaigns, a wide range of emissions were detected: methane from 4.99 kg·h⁻¹ up to 92.3 kg·h⁻¹ and nitrous oxide from below the detection limit (0.37 kg·h⁻¹) up to 10.5 kg·h⁻¹. High emissions were observed during periods experiencing operational problems, such as during foaming events in anaerobic digesters and during sub-optimal operation of biological nitrogen removal in the secondary treatment of wastewater. Methane emissions detected during measurement campaigns corresponded to 2.07-32.7% of the methane generated in the plant. As high as 4.27% of nitrogen entering the WWTP was emitted as nitrous oxide under the sub-optimal operation of biological treatment processes. The study shows that the unit process configuration, as well as the operation of the WWTP, determines the rate of GHG emission. The applied plant-integrated emission measurement method could be used to ease the burden of quantifying GHG emissions from WWTPs for reporting purposes and could contribute to the development of more accurate depictions of environmental performance of WWTPs. © 2014 Elsevier Ltd.
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The Role of Time Dependency in Life Cycle Assessment of Landfills – Accounting for Sinks and Releases

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Life cycle assessment of sewage sludge management: A review
In this article, 35 published studies on life cycle assessment (LCA) of sewage sludge were reviewed for their methodological and technological assumptions. Overall, LCA has been providing a flexible framework to quantify environmental impacts of wastewater and sewage sludge treatment and disposal processes for multiple scales, ranging from process selection to policy evaluation. The results of LCA are, in principle, unique to the goal and scope of each study, reflecting its local conditions and comparison between different LCAs is not intended. Furthermore, the assessments are limited by the methodological development of the life cycle impact assessment (LCIA) and the advancement of research in quantifying environmental emissions associated with wastewater and sewage sludge treatment processes. Thus, large discrepancies were found in the selection of the environmental emissions to be included and how they were estimated in the analysis. In order to reduce these choice uncertainties, consolidation of the modelling approach in the following area are recommended: quantification of fugitive gas emissions and modelling of disposal practices. Besides harmonization of the key technical assumptions, clear documentation of the modelling approach and the uncertainties associating with each assumption is encouraged so as to improve the integrity and robustness of assessment.

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Development of substance flow based Life Cycle Assessment tool for sewage sludge treatment and disposal

Life Cycle Assessment (LCA) is a method to quantify environmental impacts of products or systems. It is often done by correlating material and energy demands with certain input characteristics. An attempt was made to evaluate the robustness of the substance flow based LCA for wastewater and sludge treatment processes. Operational data of a conventional wastewater treatment plant over 12 years was collected. A cluster analysis was conducted to determine the relatedness of each input and output characteristic at the whole plant level. The results indicate that the output from the wastewater and sludge treatment processes correlate sufficiently with the solids content of wastewater influent, while energy use correlates with the total input volume. However, the correlations appeared to be stronger when individual treatment processes were separately analysed.

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