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Environmental modelling of use of treated organic waste on agricultural land: a comparison of existing models for life cycle assessment of waste systems

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Modelling of environmental impacts from the application of treated organic municipal solid waste (MSW) in agriculture differs widely between different models for environmental assessment of waste systems. In this comparative study five models were examined concerning quantification and impact assessment of environmental effects from land application of treated organic MSW: DST (Decision Support Tool, USA), IWM (Integrated Waste Management, UK), THE IFEU PROJECT (Germany), ORWARE (ORganic WAste REsearch, Sweden) and EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies, Denmark). DST and IWM are life cycle inventory (LCI) models, thus not performing actual impact assessment. The DST model includes only one water emission (biological oxygen demand) from compost leaching in the results and IWM considers only air emissions from avoided production of commercial fertilizers. THE IFEU PROJECT, ORWARE and EASEWASTE are life cycle assessment (LCA) models containing more detailed land application modules. A case study estimating the environmental impacts from land application of 1 ton of composted source sorted organic household waste was performed to compare the results from the different models and investigate the origin of any difference in type or magnitude of the results. The contributions from the LCI models were limited and did not depend on waste composition or local agricultural conditions. The three LCA models use the same overall approach for quantifying the impacts of the system. However, due to slightly different assumptions, quantification methods and environmental impact assessment, the obtained results varied clearly between the models. Furthermore, local conditions (e.g. soil type, farm type, climate and legal regulation) and waste composition strongly influenced the results of the environmental assessment.

Keywords: Organic waste, waste management, life cycle assessment, life cycle inventory, environmental impact assessment, modelling, nutrient recycling, soil, wmr 852–1

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Introduction

Composting and anaerobic digestion of organic MSW allow recirculation of nutrients to agriculture, thereby enriching the soil, replacing commercial fertilizers and returning the nutrients from the city to agriculture. Treated organic waste behaves differently to commercial fertilizers with respect to nutrient loss, carbon sequestration and input of heavy metals and other pollutants to the soil. These effects are complex, interacting and greatly dependent on local conditions.

Several agricultural models have been developed to simulate processes in the soil, for example, Bruun *et al.* (2003) and Scholefield *et al.* (1991). These models are, however, often very large and demand detailed input concerning, for example, soil and crop type, spreading methods and climatic conditions. Sub-models for land application of treated organic waste in models for environmental assessment of waste systems constitute only a minor part of a larger model addressing many other aspects of waste management. Therefore, these sub-models are often simplified with relatively few impact categories included in the assessment. In this comparative study the approach to land application of treated organic waste on agricultural land as well as the type and magnitude of the results provided were examined for five models for environmental assessment of waste systems: Decision Support Tool (DST), Integrated Waste Management (IWM), THE IFEU PROJECT, ORganic WAste REsearch (ORWARE), and Environmental assessment of solid waste systems and technologies (EASEWASTE). The EASEWASTE model is currently being developed and one aim of this study was to compare the results from the land application module in EASEWASTE with similar modules in existing models for environmental assessment of waste systems. DST, IWM, THE IFEU PROJECT and ORWARE were chosen for comparison as they are the most frequently mentioned models, in the literature, for environmental assessment of waste systems. Other existing models were omitted from the study (e.g. the Wisard model developed by Ecobilan), mainly due to lack of published literature. The comparison was based on a thorough description of the land application modules in each model and a case study. Differences in results from the five models for environmental assessment of waste systems when performing the same case study of land application of treated organic waste were investigated and discussed.

Two of the five models addressed, DST and IWM, are life cycle inventory (LCI) models. The results from inventory models present all emissions and resource consumptions from the analysed system. THE IFEU PROJECT, ORWARE, and EASEWASTE are life cycle assessment (LCA) models. In these models the inventory data are the basis for further calculations, determining the contributions to defined environmental impact categories (impact assessment). See Box 1 for explanations of common LCA terms. Figure 1 shows the type of result provided by each model.

Resource consumptions and monetary costs are not included in this comparative study.

Model descriptions

Decision Support Tool (DST)

The Decision Support Tool (DST) is a computer-based tool developed by the Research Triangle Institute (RTI), North Carolina State University and the United States Environmental Protection Agency (Office of Research and Development) to evaluate integrated municipal solid waste strategies in the United States with respect to environmental and economic impacts. The tool is meant as a decision support tool for local governments and waste planners and includes waste collection, transfer stations, recovery, compost, incineration and landfill as well as several additional external unit processes (e.g. data from electricity production). The calculations are based on quantities and composition of the waste entering each unit process and the model enables the user to optimize the waste system with respect to different parameters. LCIs are provided for each unit process and can be allocated to the individual waste components (Weiz *et al.* 1999). The full prototype version of the model was completed in December 1999 (final version May 2000).

The submodel for composting organic MSW can produce three compost qualities: high-quality compost (from sorted household waste), low-quality compost (from mixed household waste) and garden waste compost. Land application of the matured compost is relevant only for high- quality compost and composted garden waste. The low-quality compost is landfilled (Komilis & Ham 1999).

Emissions to water from the land application of high-quality compost are derived from the work of Christensen *et al.* (1983, 1984), where leachate from Danish and German compost derived from MSW and sewage sludge was analysed over 30 months in lysimeter experiments (Christensen, 1983, 1984, Christensen & Nielsen 1983, Christensen & Tjell 1984). Emissions of organic matter, nitrogen, phosphorus as well as different ions and metals are included. For garden compost the emissions are based on analysis of compost and leachate from composting experiments. All emissions are expressed per ton produced compost (dry matter) and are thus not dependent on the composition of the incoming waste. The model does not distinguish between emissions to surface water and groundwater.

Box 1: Common life cycle assessment terms

Life Cycle Inventory (LCI). Collection of data for all environmental exchanges (emissions, material- and energy flows) for the defined system.

Impact assessment. Evaluation of the LCI. Might consist of classification, characterization, normalization and weighting.

Impact assessment categories. Environmental impacts to which the emissions from the inventory contribute, e.g. global warming or acidification.

Classification. For each substance in the inventory the relevant environmental impact categories are determined (e.g. CH_4 contributes to global warming).

Characterization. Quantification of the contribution from each substance to the impact categories. Each impact category has a 'reference' substance; all other contributions to the impact category are calculated relative to this substance by 'equivalence' factors. The total impact from the impact category is presented as equivalents of the reference substance. For global warming the reference substance is CO_2 and all other contributions to global warming are counted in CO_2 equivalents calculated by equivalence factors.

Normalization provides a relative impression of the environmental impact or resource consumption compared to the impact from one average person. The yearly contributions from the defined system are divided by the normalization reference, which is the yearly total emissions (global/regional/local) per person (worldwide/regionally/locally). This yields a normalized impact potential in the unit 'person equivalent'.

For resource consumption (non-renewable) the normalization reference is often the known amount of resources divided by the world population. Assuming no further resources are discovered, one 'person equivalent reserve' of resources is thus the amount of resources available for one person and all that person's descendants.

Weighting. To compare the different impact categories, weighting according to seriousness of each category is performed. The weighting factors are based partly on scientific criteria, partly on political priorities.

Ecotoxicity. Quantification of impacts on ecosystems is based on toxicological data and the distribution of the pollutant between the compartments air, water and soil. For each compartment 'the polluted volume' is calculated based on the distribution of the pollutant and the 'predicted no effect concentrations' (PNEC) for ecosystems. This expresses, for example, the number of m^3 soil a certain emission can contaminate to a level corresponding to the PNEC level. Ecotoxicity is therefore expressed in m^3 air, water (acute and chronic impacts) and soil (chronic). In the normalization phase these volumes are compared to the pollution from an average person within a year.

Human toxicity. Pollutants in the environment might cause human toxicity due to exposure through air, water, soil (direct exposure) or intake of polluted food (indirect exposure). The distribution of a certain pollutant between the different compartments (including uptake in plants and distribution to meat and dairy products) as well as exposure from each compartment determines the total human exposure load. Comparing this load with the HRD (human reference dose: a measure for the dose of the specific pollutant assessed not to cause any damage to humans) the 'polluted volume' is defined. Human toxicity is therefore expressed as m^3 air, water and soil. In the normalization phase these volumes are compared with the pollution from an average person within a year.

Toxicity impact categories: In the EDIP system normalized and weighted toxicity impacts are given in three impact categories, persistent toxicity, eco toxicity and human toxicity, reflecting averages of the normalized impacts from the different categories for eco- and human toxicity described above.

The DST model is an LCI model and therefore no actual impact assessment is performed. However, the environmental outputs are divided into different categories: emissions of greenhouse gases (CO_2 equivalents), NO_xs, particulate matter, CO, biological oxygen demand (BOD) and energy consumption. All these categories as well as costs can be used as optimization criteria; that is, the modelling will result in the optimal system with respect to the chosen parameter. A total of 32 substances are followed through the system, but only the mentioned categories are included in the overall evaluation of the results (Barlaz *et al.* 2003b).

Several substances are estimated in the leachate from land application of the compost and therefore appear in the inventory. However, only BOD emissions to water and possible energy consumption from transport and spreading of the compost contribute to the assessment categories.

Barlaz *et al.* (2003a) discuss possible advantages of land application of compost but conclude that the research within this field is yet insufficient to support extension of the model concerning effects from land application of treated organic waste.

Integrated Waste Management (IWM)

The Integrated Waste Management (IWM) model was developed by Procter & Gamble to enable assessment of environmental and economic impacts from changes in waste systems.

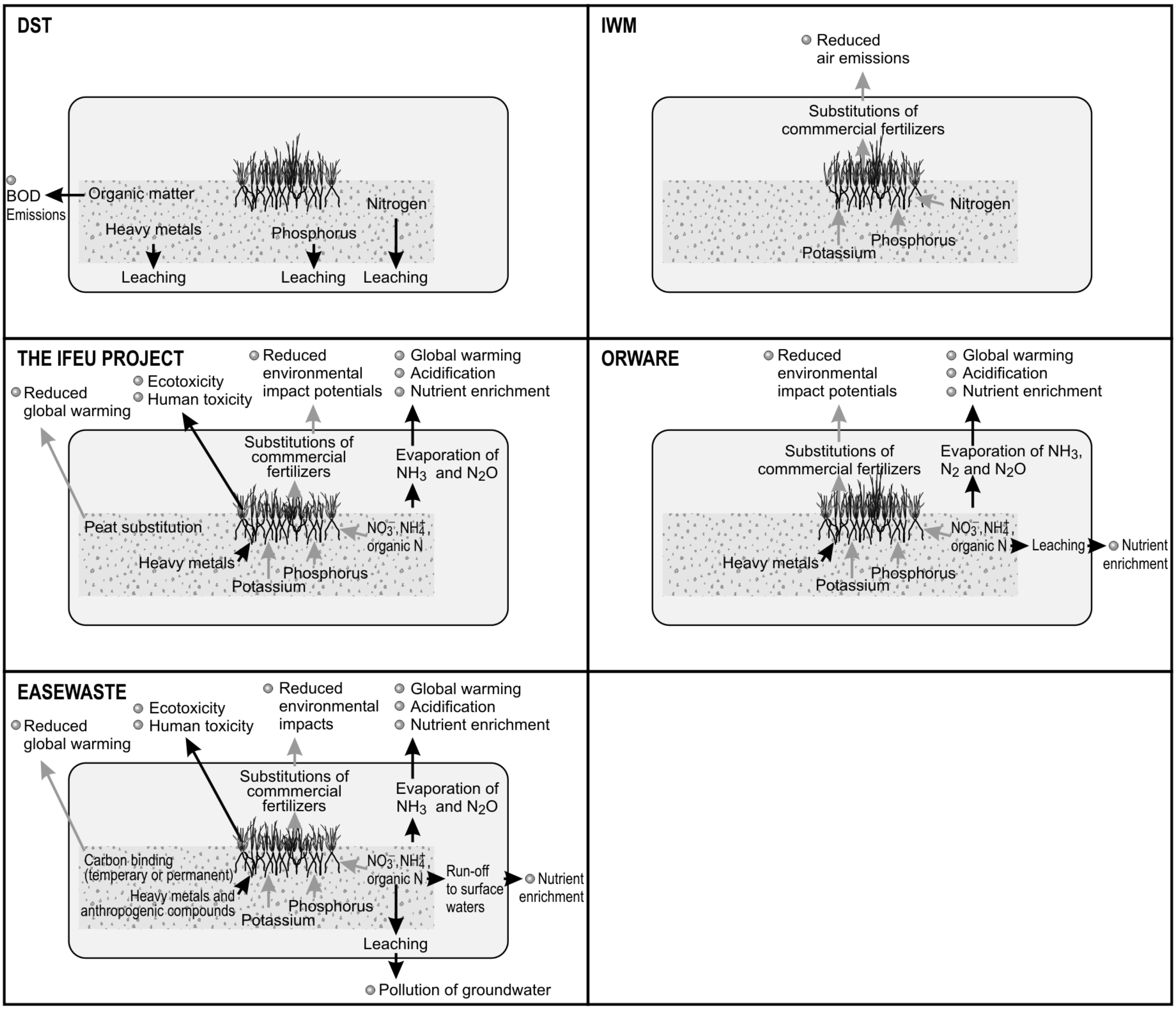

Fig. 1: Potential environmental impacts from application of treated organic waste on agricultural land in the five models investigated. Only the impacts in the outer box contribute to the final results.

The goal was to support a scientifically based development within the area of integrated waste management by applying LCA principles by summing up inventories for whole waste systems (collection, sorting, different treatment methods and final disposal). The first version was developed in 1995; the second version was published in 2001 (McDougal *et al.* 2001).

Biological treatment is defined as composting and anaerobic digestion. Different pre-treatment methods are included for mixed waste and source-sorted waste prior to biological treatment. The final use of the compost depends on its quality. Land application in agriculture is included.

The nutrient content of the mature compost is defined from an average of different references and therefore does not depend on the composition of input waste. Full substitution of commercial fertilizers (N, P_2O_5 and K_2O) is considered and the substituted amount is determined. Only air emissions from the production of commercial fertilizers are included (including production of the energy used in the process).

Since this model is an LCI model, no impact assessment is performed. The inventory is presented in tables divided into costs, fuels, final solid waste (landfilled waste), air emissions and water emissions. Air emissions from saved fertilizer production are thus the only contribution from land application of treated organic waste in the IWM model.

THE IFEU PROJECT (UMBERTO)

UMBERTO is software (developed and distributed by the IFU-Institute in Hamburg) for modelling costs, process optimization, environmental management and life cycle assessment. The software determines mass and energy flows and contains a library containing single modules, including some modules for waste treatment (www.ifu.de, 2004). The official library does not contain a model for land application of treated organic waste. However, for a specific project assessing different treatment methods for organic waste, a module for land application was developed (Vogt *et al.* 2000, 2002). This module (and not the official version of the software) is described in the following paragraphs.

The biological wastes examined in the project were different types of industrial organic waste as well as organic household waste and garden-, park- and cemetery waste. Different treatment methods were considered for each waste type; for example, composting and anaerobic digestion followed by land application in different areas, such as agriculture and private gardens. The substitution effect depends on the final use of the product (e.g. composted garden waste might substitute peat, whereas composted household waste might substitute commercial fertilizers).

The degradation rate of the treated organic matter determines the emission of organic carbon dioxide and nutrients after application. The degradation rate was set to 50%, resulting in 50% of the applied carbon released as carbon dioxide (biogenic), whereas the rest remains in the soil bound in humus (Vogt *et al.* 2000).

Loss of nitrogen to air is quantified from the composition of the treated organic waste. Ammonia loss is calculated as 37% of the ammonia content and 4% of the organic nitrogen in the composted organic waste. These values are based on assessment of a range of European field studies concerning loss of ammonia from spreading of different fertilizer types under different conditions (Vogt *et al.* 2002). The emission coefficients are strongly dependent on local conditions, fertilizer type and spreading methods. The chosen emission coefficients represent land application of treated organic waste under average German conditions. Formation of nitrous oxide is calculated as 1.25% of the total nitrogen applied (Vogt *et al.* 2002) as recommended by the IPCC (IPCC 2001). The actual emission depends strongly on specific conditions, but setting more case-specific values is not considered reasonable with the current level of knowledge.

Emissions of nitrogen to surface water and groundwater are not included in the model, even though they are discussed in the model description.

Heavy metals from the treated waste are included in the assessment. It is assumed that the total content of heavy metals in the waste is retained during composting. For anaerobic digestion a minor fraction of the heavy metals is assumed to be routed to the wastewater from the digester.

For application of composted organic household waste the substitution of commercial fertilizer is included. For other applications and other organic waste types substitution of peat is also included. Peat is considered a fossil reserve and substitution of peat thus results in saved carbon dioxide emissions from degradation of the peat (Vogt *et al.* 2002).

Of the treated organic waste, 50% of the nitrogen is assumed to be accessible for the plants. For P, K, Ca and Mg 100% utilization is assumed. Substitution effects are calculated as environmental impacts from production of N, P_2O_5, K_2O, CaO and MgO based on Patyk & Reinhardt (1997), which is a comprehensive data collection of emissions and resource consumptions from production of commercial fertilizers in Europe (especially Germany).

Saved impacts from use of substituted commercial fertilizers consist of input of heavy metals to soil. The heavy metal content in commercial fertilizers is mainly derived from Boysen (1992).

The impact assessment used is very similar to the impact assessment in the EDIP method (Hauschild & Wenzel 1998), but it has been revised by the IFEU institute to better reflect the impacts from waste treatment. The impact categories used are: global warming, photochemical ozone formation (summer smog potential), nutrient enrichment, acidification, human toxicity (carcinogenic risk + smaller particles, PM_{10}), ecotoxicity and input of cadmium and lead to soil. Furthermore, resource depletion is included in the impact assessment (not included in the present case study).

The equivalence factors, describing the contribution of each substance to the impact categories, used in THE IFEU PROJECT are similar to the EDIP equivalence factors (Hauschild & Wenzel 1998). However, there are minor differences; for example, the nutrient enrichment potential is calculated in phosphorus equivalents instead of nitrate equivalents. This means only a factor in difference (in the case study the equivalence factors from EDIP were therefore used). The carcinogenic risk potential (human toxicity) is counted in arsenic equivalents; determined by equivalence factors based on toxicity data from the US EPA (www.epa.gov/iris). The particulate matter less than 10 pm (PM_{10}) is counted in PM_{10}-equivalents (kg). Ecotoxicity focuses on emissions of heavy metals to water. No such emissions occur due to land application and the ecotoxicity is therefore not represented in the final assessment. Inputs to soil are not included in the ecotoxicity; however, input of cadmium and lead to soil are included as separate categories (Vogt *et al.* 2002). No further aggregation is performed before the assessment.

ORganic WAste REsearch (ORWARE)

ORWARE is a model originally developed for environmental assessment of biodegradable liquid and solid waste. The model can, however, also handle treatment of mixed waste and therefore enables comparisons between different waste systems including treatment of mixed and source-sorted waste. The model is developed by a co-operation of the Swedish Institute of Environmental and Agricultural Engineering, the Swedish University of Agricultural Sciences, the Royal Institute of Technology and the Swedish Environmental Research Institute and was financed by the Waste Research Council and the Swedish Environmental Protection Agency (Dalemo 1999).

ORWARE contains a sub-model for the nitrogen cycle in the soil and the environmental impacts from use of treated organic waste substituting commercial fertilizers. The first description of the land application sub-model was given by Dalemo *et al.* (1997). The impacts from the soil system are calculated as the differences between use of commercial fertilizer and organic fertilizer and both first-year and long-term emissions are accounted for in Dalemo *et al.* (1998).

The proportion of organic nitrogen fertilizer lost through leaching was determined by simulations in the model SoilN for nine regions in Sweden, characterized by varying climate and production- and fertilization conditions. The leachate was defined as nitrate leaving the root zone and therefore no longer accessible to plants (Johnsson & Hoffmann 1997). For every region 'normal emissions' based on combinations of nine crops (typical of the region), three soil types and two different fertilization schemes were determined. Thus, the emission coefficients depend mainly on region, soil type and crops. The emissions were simulated for use of commercial fertilizer only and combined commercial fertilizer and manure (Johnsson & Hoffmann 1997). To represent pure organic fertilizer, these simulated emission coefficients were recalculated based on the ratio between increased nitrate emissions and the content of organic nitrogen in the manure (Dalemo *et al.* 1998). ORWARE does not determine the total losses but only the additional impacts from use of organic fertilizers. As the additional loss of nutrients from leaching is assumed to originate from the organic nitrogen, the unit of the emission coefficients is kg NO_3^-–N/kg organic N added.

Loss of ammonia is quantified as a fraction of the ammonia-nitrogen in the spread treated organic waste and should be set according to the time of spreading, spreading technique and dry matter content in the waste. Coefficients are suggested based upon simulations in STANK; a model for calculating ammonia losses (Jordbruksverket 1997). Simulations of the coefficients are based on typical Swedish conditions and measurements of ammonia losses from agriculture in Sweden for several years. The coefficients vary between 0.03 and 0.50 with typical values around 0.10 (Dalemo *et al.* 1997).

Coefficients for loss of nitrogen gas (N_2) are based on Scholefield *et al.* (1991), who determined the total loss through leaching and denitrification as a difference between input nitrogen, other losses and output nitrogen in the crops. To determine the fraction of this nitrogen loss evaporated as nitrogen gas, factors were determined for different soil types and drainage conditions (Scholefield *et al.* 1991). In ORWARE the factors from Scholefield *et al.* (1991) are used to calculate the nitrogen gas as a fraction of the nitrogen lost through leachate (Dalemo *et al.* 1998). The magnitude of the factors was verified against Audsley *et al.* (1997) which stated percentages of nitrogen lost by denitrification and leachate respectively for loss of nitrogen gas from sandy and clayey soils.

Loss of nitrous oxide (N_2O) is quantified according to the Intergovernmental Panel on Climate Change (IPCC) guidelines stating that approximately 1.25% of the fertilizer-nitrogen added will be lost as nitrous oxide. Since ORWARE calculates only the additional losses from use of organic fertilizers, the loss of nitrous oxide is calculated as 1.25% of the additional losses of nitrate and nitrogen gas.

Plant utilization of the organic soil amendment is based on literature review. For phosphorus, potassium and mineral nitrogen, utilization similar to commercial fertilizer is assumed. For organic nitrogen, 30% utilization is assumed during the first year and an additional 30% utilization of the nitrogen pool in the soil (determined as the difference between nitrogen input, plant uptake and losses during the first year) is assumed during the following years. Based on the utilization rates the amount of commercial fertilizer substituted is quantified.

In different studies different references for environmental impacts from production of commercial fertilizers were used depending on the scenario investigated; for example, Baky & Eriksson (2003) and Davis & Haglund (1999).

The amount of heavy metals and other pollutants emitted to soil by spreading of the treated organic waste depends on the content in the organic waste and the removal through the collection and treatment system.

Land application of treated organic waste contributes in ORWARE to three impact categories: global warming (CO_2 equivalents), nutrient enrichment (O_2 equivalents) and acidification (SO_2 equivalents). The categories were chosen due to relevance to environmental impacts from waste treatment and a certain scientific consensus about equivalence factors for different substances within each category. The equivalence factors for all included substances build on Lindfors *et al.* (1995) and are similar to the factors used in EDIP (Hauschild & Wenzel 1998). Later studies have discussed human and ecotoxicity and documented the heavy metal flow to soil (Sundqvist *et al.* 2002). Other impact categories (stratospheric ozone depletion, photochemical ozone formation, resource consumption and economics) are also included in later studies (Baky & Eriksson 2003); (Sundqvist *et al.* 2002). However, these impact categories are not addressed here, since they are not included in the description of the land application module (Dalemo *et al.* 1998).

Environmental Assessment of Solid Waste Systems and Technologies (EASEWASTE)

EASEWASTE is a model for environmental assessment of waste systems developed by the Technical University of Denmark. The model considers environmental impacts from waste generation, collection, treatment and disposal, including a sub-model for assessment of environmental impacts from land application of treated organic waste (Hansen *et al.* 2005). The sub-model builds largely on specific emission coefficients derived from field experiments and simulations. The inherent default data are based on 'typical Danish scenarios', but data for different conditions can be entered.

Ammonia loss is determined as a fraction of the ammonia nitrogen in the treated organic waste. For organic fertilizers, 15% of the added ammonia is assumed lost. This average default value is based on two field experiments conducted by the Danish EPA and covers large variations (Sommer *et al.* 2001). For commercial fertilizer no significant ammonia loss is assumed.

Nitrate loss to ground- and surface water as well as nitrous oxide formation is defined as a fraction of the nitrogen in the treated organic waste. Comprehensive simulations in the agroecosystem model Daisy has yielded default data for these emissions for 'typical Danish conditions': 3–87% of the applied nitrogen leached to groundwater, 0–30% were lost through drains to surface waters and 1.3–2.2% of the nitrogen was lost as nitrous oxide (Bruun *et al.* 2005). Daisy is a relatively complex model describing the water, heat, C and N dynamics in the soil–plant–atmosphere system. A further description can be found in Hansen *et al.* (1991).

Phosphorus emissions to ground- and surface waters were not included in the model, since these emissions depend strongly on the soil properties and actual phosphorus content and less on the amount of phosphorus fertilizer applied to the field.

The treated organic waste is assumed to substitute commercial fertilizers, which is the case for marginal substitution in Denmark. The amount of substituted fertilizer is determined by the utilization ratios describing the crop-availability of the nutrients in the organic waste compared to commercial fertilizers. The utilization ratios symbolize the accumulated effect over time, since the impact from organic fertilizers does not only occur during the first year after spreading. In reality, legislation might influence the actual amount of commercial fertilizer substituted. In the Daisy simulations two types of utilization rate for nitrogen in the organic waste are therefore included: one rate for the actual availability of nitrogen to the plants to simulate uptake and emissions and one rate for substitution of commercial fertilizer; the former depending on chemical and physical parameters, the latter controlled by legal regulations. The default utilization rates in EASEWASTE are based on the Danish regulations for nutrients in organic fertilizers: 40% for nitrogen in anaerobically digested MSW, 20% for nitrogen in composted MSW and 100% for phosphorus and potassium (Plantedirektoratet 2003). This means that the farmer's quota for commercial nitrogen fertilizer for the respective year will be decreased by 40 or 20% of the nitrogen content in the applied treated organic waste, depending on the waste type.

The heavy metal input to soil from spreading of the treated organic waste is determined from the content of heavy metals in the input waste, whereas the heavy metal content of the substituted commercial fertilizers is obtained from Audsley *et al.* (1997). Heavy metal input to soil has a potentially toxic impact on humans and ecosystems, contributing to the impact categories human toxicity and ecotoxicity (via effect factors calculated in EDIP).

Carbon sequestration is represented as a percentage of the added carbon in the treated organic waste permanently bound in the soil. Generally, quantification of the impacts from the land application model consists of accumulating yearly contributions until no further effect can be identified. Using this approach for carbon sequestration will result in no effect, since all added carbon from one specific application will eventually be released (thus, the default value is zero). However, if the land application of organic waste is seen as part of a changed farming practice resulting in a generally increased carbon level in the soil (due to frequently repeated applications) this will represent an actual removal of carbon dioxide from the atmosphere (until a new equilibrium has been reached) and therefore a negative contribution to the global warming impact. The release of carbon from applied organic waste has been simulated under Danish conditions for a 100-year period by Daisy (Bruun *et al.* 2005).

The impact assessment from the EDIP system developed by Wenzel *et al.* (1997) was used. Eight environmental impact categories are included in this assessment: global warming, stratospheric ozone depletion, photochemical ozone formation, acidification, nutrient enrichment, toxicity (persistent toxicity, ecotoxicity and human toxicity). Furthermore, resource consumption is assessed in the model (however, not included in this study).

Case study

The approach to land application of treated organic MSW differs between the five models assessed. Table 1 summarizes the environmental processes quantified in the five investigated models. To illustrate differences and similarities between the different models, a case study of environmental assessment of land application of 1 ton of composted organic household waste was performed. The composition of the compost is shown in Table 2.

Table 1: Contributions to environmental effects from land application of treated organic waste in the investigated waste models for environmental assessment of waste systems.

	DST	IWM	THE IFEU PROJECT	ORWARE	EASEWASTE
Run-off to surface waters	Fixed amount of BOD, N and P per kg compost[1]	–	–	$k_1 \cdot N_{org} + N_{pool,\ eventually}$	$k_1 \cdot N_{tot}$
Leaching to groundwater					$k_2 \cdot N_{tot}$
Loss of ammonia	–	–	$k_1 \cdot N_{org} + k_2 \cdot N_{am}$	$k_2 \cdot N_{am}$	$k_3 \cdot N_{am}$
Formation of nitrous oxide	–	–	$k_3 \cdot N_{tot}$	$k_3 \cdot N_{leaching}$	$k_4 \cdot N_{tot}$
Heavy metals to soil	Fixed amount of heavy metals per kg compost[2]	–	Metals from waste	Metals from waste[4]	Metals from waste
Carbon binding	–	–	Peat substitution[3]	–	$k_5 \cdot C_{tot}$
Commercial fertilizer production	–	Saved air emissions included	Substitution (defined ratio)	Substitution (defined ratio)	Substitution (defined ratio)
Commercial fertilizer use	–	–	Saved heavy metal input to soil included	Calculated emissions represent additional emissions	Emission coefficients represent additional emissions

[1]Only BOD emissions contribute to the final results.
[2]Not contributing to the final results.
[3]For some combinations of organic waste and applications, substitution of peat is included to represent increased soil quality in terms of higher carbon content, better water capacity and draining conditions. Peat is assessed as fossil carbon source and substitution of peat therefore 'saves' CO_2 emissions.
[4]Only included in the final results in a few studies.

Table 2: Composition of composted source sorted municipal organic waste.

	Composted MSW
Dry matter (DM), % of ww	62.3[c]
Volatile solid (VS), % of DM	70.0
N total, % of DM	1.15[a]
Ammonia-N, part of N_{tot}	0.06[b]
Nitrate N, part of N_{tot}	0.01[b]
Nitrogen, organic, part of N_{tot}	0.93[b]
P (tot) , % of DM	0.27[a]
K(tot) , % of DM	0.84[a]
C, % of DM	38.0
Cd, mg kg^{-1} DM	0.12[c]
Cr, mg kg^{-1} DM	3.3[c]
Cu, mg kg^{-1} DM	21.2[c]
Hg, mg kg^{-1} DM	0.05[c]
Ni, mg kg^{-1} DM	18.6[c]
Pb, mg kg^{-1} DM	4.0[c]
Zn, mg kg^{-1} DM	61.0[c]

[a]Fricke & Vogtmann 1994
[b]Sonesson 1996
[c]Vogt *et al.* 2002.

For the two LCI models the results depend on the weight of the treated waste applied to agricultural land. Thus, the results are not influenced by the input composition or the agricultural conditions in the actual area. In the three LCA models the choice of constants (depending on local conditions), substituted commercial fertilizers and energy type will influence the results. For THE IFEU PROJECT only one set of constants for compost is available, so this was used. For EASEWASTE emission coefficients based on Daisy simulations of application of composted organic waste on a crop farm in western Denmark on loamy soil were used (Bruun *et al.* 2005). For ORWARE the adjustable emission coefficients were defined identically to the coefficients in EASEWASTE. For all three models, environmental production costs for commercial fertilizers were based on Patyk & Reinhardt (1997) including specified impacts from production of German electricity. Table 3 shows the input data for the case study.

Fuel consumption for spreading the treated organic MSW was not included in the analysis. Transportation is relatively standardized within LCA (mainly resource consumption and emissions from burning of fuels) and other studies have shown this fuel consumption to have only minor influence on the potential environmental impacts from soil application of treated organic waste (e.g. Hansen *et al.* 2005).

Results

The results from land application of 1 ton of composted organic MSW in the five models are shown in Tables 4–6. In DST and IWM no actual impact assessment is performed; thus the impacts were presented in inventory categories specified in each model. For DST most of the emissions represented in the inventory did not contribute to the final categories presenting the results. Only BOD emissions to water were included in the final assessment (see Table 4). For

Table 3: Input data for the case study.

Compost	DST 1 ton	IWM 1 ton	ORWARE 1 ton	IFEU 1 ton	EASEWASTE 1 ton
Run-off, NO_3^-					0.08 kg N kg^{-1} N_{tot}
Leaching, NO_3^-			(0.15 + 0.17) kg N kg^{-1} N_{org}*		0.07 kg N kg^{-1} N_{tot}
Ammonia loss			0.15 kg N kg^{-1} Nam	0.37 kg N kg^{-1} N_{am} + 0.04 kg N kg^{-1} N_{org}	0.15 kg N kg^{-1} N_{am}
Nitrogen gas			0.45 kg N kg^{-1} $N_{leaching}$		
Nitrous oxide formation			0.0125 kg N kg^{-1} $N_{loos(NO3 + N2)}$	0.0125 kg N kg^{-1} N_{tot}	0.014 kg N kg^{-1} N_{tot}
Carbon binding			0	0	0
Substitution ratio, N (org/mineral)		7.1 kg N ton^{-1} compost	0.3/1	0.5/0.5	0.2/0.2
Substitution ratio, P		1.8 kg P ton^{-1} compost	1	1	1
Substitution ratio, K		4.7 kg K ton^{-1} compost	1	1	1

*First year and long-term leaching. The nitrogen not taken up by plants or lost through other emissions is assumed eventually to be lost through leaching. In this case the long-term leaching is calculated to 0.17.

Table 4: Contributions to the defined impact categories from land application of 1 ton composted organic waste in the DST model.

Impact assessment	Unit	DST
Energy consumption	MJ	
Green house gas	kg CO_2 eqv.	
NO_X	kg	
Particles	kg	
CO	kg	
BOD	kg	135.6

IWM, the inventory was directly presented in the category 'air emissions' (see Table 5). Applying the impact assessment from the LCA-models, the savings from the production of commercial fertilizers avoided become comparable to the savings obtained by THE IFEU PROJECT, ORWARE and EASEWASTE (global warming –43.5 kg CO_2 eqv., nutrient enrichment –0.24 kg NO_3 eqv., acidification –0.82 kg SO_2 eqv.).

The results from THE IFEU PROJECT, ORWARE and EASEWASTE were divided into impacts originating from direct land application, avoidance of production of commercial fertilizers and energy consumption (from fertilizer production avoided), see Table 6 and Figure 2. The impacts from land application depend on the waste composition and the local agricultural conditions, whereas the impacts from avoided production of commercial fertilizers are determined by the product chosen and the geographical location of the production (electricity production).

The impact on global warming directly from land application and avoided production of commercial fertilizer differ with a factor of two between the three models. The global warming impact from land application mainly originates from formation of nitrous oxide. For the avoided production of commercial fertilizers the contribution to global warming mainly originates from emissions of carbon dioxide, methane and nitrous oxide.

Table 5: LCI data for land application of one ton composted organic waste in the IWM model.

Impact assessment	Unit	IWM
Air emissions	kg	
CO_2	kg	–21.3
CH_4	kg	–0.003
N_2O	kg	–0.07
SO_2	kg	–0.06
CO	kg	–0.02
NO_X	kg	–0.09
Particles	kg	–0.0003
HCl	kg	–0.001
NH_3	kg	–0.04
Dioxins	kg	–1.03E–11

ORWARE showed a significantly higher contribution to nutrient enrichment from land application than the two other models due to long-term leaching of nitrate (nitrogen not lost within the first year enters a nitrogen pool in the soil, which is eventually lost to the environment if not taken up by plants).

Contributions to acidification were one magnitude larger for THE IFEU PROJECT than for the two other models due to the assumption that ammonia loss occurs from both organic nitrogen and ammonia in the compost. EASEWASTE and ORWARE assume ammonia loss only from the content of ammonia-nitrogen. Since the ammonia content in compost is low compared to the content of organic nitrogen, ammonia formation from organic nitrogen strongly influences the

Table 6: Impact assessment for land application of one ton composted organic waste in the three investigated LCA models.

Impact assessment		THE IFEU PROJECT				ORWARE				EASEWASTE			
Impact category	Unit	LA	FP	EP	Total	LA	FP	EP	Total	LA	FP	EP	Total
Global warming	kg CO_2 eqv.	43.6	–34.1	–4.5	5.0	22.9	–22.1	–2.4	–1.5	50.4	–14.6	–2.2	33.6
Nutrient enrichment	kg NO_3 eqv.	1.6	–0.16	–0.005	1.4	10.0	–0.11	–0.003	9.9	2.82	–0.07	–0.003	2.8
Acidification	kg SO_2 eqv.	0.8	–0.12	–0.006	0.69	0.15	–0.09	–0.003	0.05	0.15	–0.06	–0.003	0.08
Persistent toxicity	Person eqv. (DK)									0.044	0.000	0.000	0.044
Eco toxicity	Person eqv. (DK)									0.000	0.000	0.000	0.000
Human toxicity	Person eqv. (DK)									0.000	–0.002	0.000	–0.002
CRP	kg As	–0.004	–1.1E–07	–0.08	–0.09								
PM_{10}	kg particles	0.07	–0.02		0.05								
Cd to soil	mg to soil	64	–9.9		54								
Pb to soil	mg to soil	2188	–304		1884								

CRP, carcinogenic risk potential; LA, direct impacts from the land application; FP, impacts from the avoided production of commercial fertilizer; EP, impacts from the avoided energy production (commercial fertilizer production).

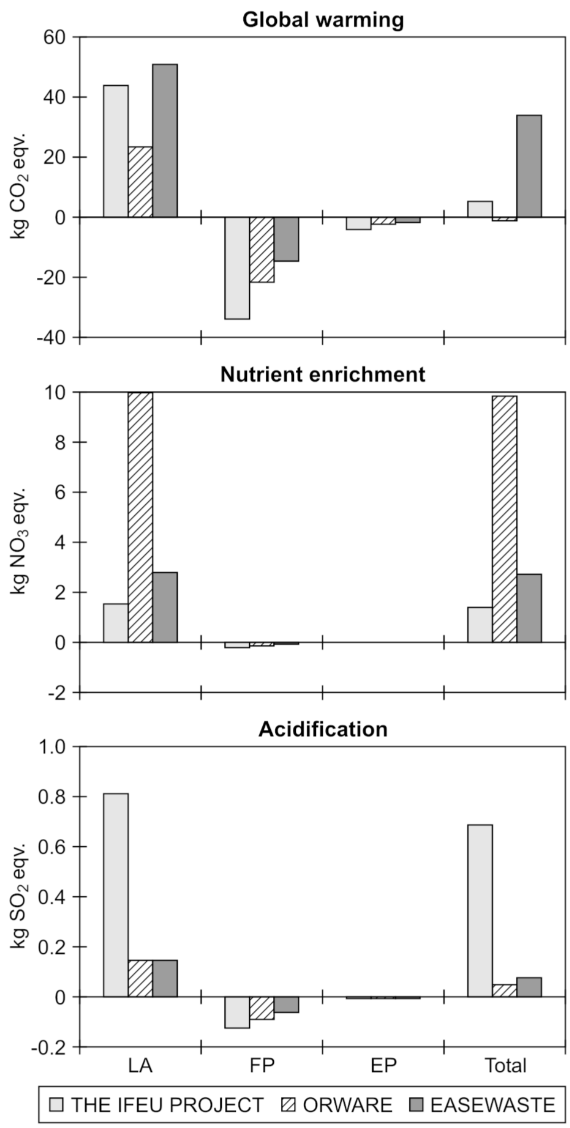

Fig. 2: Impacts on global warming, nutrient enrichment and acidification from application of 1 ton of composted organic MSW in the three investigated LCA models. LA, Land application (direct); FP, fertilizer production; EP, energy production.

ammonia loss (thus acidification) even though the percentage of organic nitrogen lost as ammonia is low (4%).

The toxicity categories are not comparable between the models (and not included in ORWARE). They are shown in Table 6 only to illustrate that this aspect is included in the final assessment of the land application in EASEWASTE and THE IFEU PROJECT.

Discussion

The investigated models were all developed for environmental assessment of waste systems. The level of detail in the submodels for land application of treated organic waste is a compromise between including all relevant information and keeping the amount and details of input data on a reasonable level. The LCI models were developed for overall assessment of whole waste systems including all waste types and consider use of treated organic waste in agriculture in a relatively simple way with very few scenario-specific results. The LCA models were all developed with special focus on organic waste: ORWARE was originally developed for environmental assessment of organic waste, the land application module in THE IFEU PROJECT was developed specifically for assessing different treatment technologies for organic waste, and the development of EASEWASTE was influenced by a strong debate in Denmark concerning treatment of organic waste. These LCA models have therefore included many more details in the land application module. Nevertheless, there are still environmental effects from land application, which are not included in any of the models, since they cannot be quantified reasonably with respect to the chosen categories for environmental impact potentials. These effects include conditions such as improved soil quality and increased crop resistance towards certain diseases.

The environmental impacts from land application in the two LCI models depend only on the weight of the input material. Thus the composition of the treated organic waste and the local agricultural conditions have no influence on the results. For the three LCA models detailed site-specific information can be included in the emission coefficients, possibly estimated using specified agricultural models. This was the case in both ORWARE (SoilN) and EASEWASTE (Daisy). Furthermore, the composition of the organic waste, the choice of substituted commercial fertilizer and electricity influence the resulting impacts due to differing environmental 'production costs'. The actual formula for calculation of the impacts vary slightly between the models, causing varying results for assessment of the same scenario.

THE IFEU PROJECT, ORWARE and EASEWASTE can model land application of compost, anaerobic digestion residue, sludge from wastewater treatment plant or other organic waste types. In DST and IWM, however, the land application is developed specifically for composted organic waste and application of other waste types therefore will not make sense.

For further comparison of the results (within and between the models) normalization and weighting of the obtained environmental impact potentials are necessary. Normalization often uses regional or even local references while the weighting is partly political. These calculations are not included in this study, since the aim was comparison of the quantification of the environmental impacts from land application of treated organic waste in different models. Furthermore, the only model offering normalization and weighting of the results as an integrated part of the assessment is EASEWASTE, where the user can choose between four different levels of results: LCI, LCIA, normalized data and weighted data. ORWARE and THE IFEU PROJECT all present the environmental impact categories separately. However, in some ORWARE studies a monetary price has been defined for the resulting impacts, which must be considered as weighting of the results (e.g. Sundqvist *et al.* 2002).

Conclusion

The five studied models for environmental assessment of waste treatment systems have different approaches to land application of treated organic MSW, regarding both the choice of impacts to include and how to include them. DST and IWM are LCI models including only a limited part of effects from the land application. The results are presented as inventory results divided into certain categories which differ for each model: comparison of the results is therefore difficult. The three LCA models, THE IFEU PROJECT, ORWARE and EASEWASTE, use the same overall approach for quantification of the environmental impacts. However, small differences in assumptions, calculation methods and impact assessment caused variations in the results when the same scenario was simulated in the three models. Therefore, the resulting environmental impacts from the system are affected by the choice of model. Furthermore, the impacts are strongly affected by the local agricultural conditions and the composition of the waste. Due to the many factors influencing the results, the interval for environmental impacts from land application of treated organic waste is very broad.

All five models investigated are applicable for general environmental assessment of waste systems. However, if focus is on organic municipal waste and especially on effects from land application of treated organic waste, the level of detail in the investigated LCI models (DST and IWM) is insufficient to support decisions within this field, since no specific conditions can be included in the assessment.

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