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Environmental inventory modelling of the use of compost and peat in growth media preparation

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Abstract

Compost produced from biological treatment of organic waste has a potential for substituting peat in growth media preparation. The Life Cycle Inventories (LCIs) of the two alternatives were compared using LCA-modelling (EASEWASTE) considering a 100 year period and a volumetric substitution ratio of 1:1. For the compost alternative, the composting process, growth media use, and offsetting of mineral fertilizers were considered. For the peat alternative, peat-land preparation, excavation, transportation, and growth media use were considered. It was assumed that for compost 14% of the initial carbon was left in the soil after 100 years, while all carbon in peat was mineralized. With respect to greenhouse gas emissions, the former is considered a saving, while the later is considered an emission, because peat in a peat-land is considered stored biogenic carbon. The leaching during the growth media use was assessed by means of batch leaching tests involving 4 compost samples and 7 peat samples. The compost leached 3-20 times more heavy metals and other compounds than the peat. The life-cycle-assessment showed that compost performs better regarding global warming (savings in the range of 70-150 kg CO_2-eq. Mg^{-1}) and nutrient enrichment (savings in the range of 1.7-6.8 kg NO_3 Mg^{-1} compost), while peat performs better in some toxic categories, because of the lower content of heavy metals.

Keywords: peat, compost, organic waste, LCI, leachate, EASEWASTE

List of abbreviations:
EU: European Union
GHG: Greenhouse gases
GWC: Garden Waste Compost
GWP: Global Warming Potential
KWC: Kitchen Waste Compost
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
PE: Polyethylene

1. Introduction

Growth media is used in horticulture, in professional gardening and landscaping, and in private gardens for lawns, pots and plant beds. Growth media typically consists of an organic component, fertilizer, and sand or sandy soil. The organic component is often peat excavated from natural bogs or fens. Peat is plant debris that in its natural setting is degrading very slowly and thus peat can be considered bound biogenic carbon. However, excavated peat used in a growth media will degrade over a few decades and emit the bound carbon as CO_2. Thus CO_2 released by degradation of peat should be counted as a greenhouse gas (GHG). This is an issue that must be addressed since almost 80 % of growth media used in Europe is constituted of peat materials (IPS, 2007).

Compost produced from organic waste from residential areas could be an alternative to the use of peat in growth media. The organic residential waste, in terms of kitchen organics and garden waste, originates from relative short-term crops and vegetation and thus CO_2 released from its degradation can be considered neutral with respect to GHG (Christensen et al., 2009).

However, comparison of the use of compost and peat in growth media production should also pay attention – in addition to differences in carbon releases - to differences in the need of transport, the fertilizer content, the content of contaminants, and the leaching of nutrients and contaminants into the subsoil. To our knowledge no comprehensive data-set exists to support such a comparison.

This study presents life cycle inventories for compost and peat used in growth media. The inventories include exchanges with the environment from the production, transportation and utilization for a total period of 100 years. Leaching of substances to groundwater was assessed by means of batch leaching tests. The provided inventories can be used in comparison of alternative management scenarios for residential organic waste involving composting and substitution of peat in growth media preparation. As an illustrative example, the life-cycle-inventories (LCI) provided were used in a life-cycle-assessment (LCA) of alternative management of residential organic waste in order to illustrate the importance of detailed LCIs for compost and peat use in growth media production.

1.1. Peat

Peat is an accumulation of organic detritus that forms in anoxic, waterlogged and acidic conditions of bogs and fens. Peat can be excavated and used either as a fuel or as a soil amendment in the plant production industry. In 1999, about 100 million cubic metres of peat were produced worldwide (Joosten & Clarke, 2002), of which 65% was used for energy purposes and 35% in the horticultural sector. The majority of peat is produced in temperate northern countries i.e. the countries of the former USSR, Canada, USA, Scandinavia and Finland. In 2000, Canada produced around $1.3*10^6$ Mg of peat, being the largest producer of peat for horticultural purposes in the world (Cleary et al., 2005).

Peatlands are significant reservoirs of carbon. Carbon in peat in boreal and temperate regions is estimated to be around one third of the carbon stored in the world's soils (Gorham, 1991) or 500 Pg (IPCC, 2003). Carbon accumulation in the form of peat occurs over a long period of time as a result of degradation of plant material under anaerobic conditions and could play a major role in the global carbon cycle.

According to Joosten & Clarke (2002), about 5-10% of the biomass (and thus carbon) produced annually in the peatland area ends up in the peat stock.

The impact of peatlands on climate change is determined by the net emissions of CO_2, CH_4 and N_2O, depending on the environmental (e.g. deepness of the bog) and geographic conditions, type and age of the peatland and land-use (Lappalainen, 1996). For example, fens (a type of wetland), which receive groundwater and are dominated by vascular plant vegetation, emit more CH_4 than bogs dominated by Sphagnum moss (Lappalainen, 1996).

Extraction of peat disturbs the natural cycle of carbon in peatlands. Lowering of the water table due to drainage increases the depth of the aerobic layer and therefore CO_2 emissions are increased. CH_4 emissions generally cease following drainage. The removal of plant cover in areas converted to peat production also terminates the accumulation of plant debris and thence the CO_2 sequestration (Lappi & Byrne, 2004). Degradation of dewatered peat (into carbon containing gases including CO_2) could result in emissions in the order of at least 7.4 Mg CO_2-eq. hectare^{-1} year^{-1} (Reijnders & Huijbregts, 2003).

Transportation and biological decomposition of excavated peat are also contributing to greenhouse gas (GHGs) emissions during the peat life cycle. Being mainly produced in northern areas of the world, peat is often transported very far by different means of transportation. Regarding decomposition, both Smith et al. (2001) and Cleary et al. (2005) report that within 100 years all peat used outdoor is completely degraded and all carbon contained is consequently released to the atmosphere, primarily as CO_2. Release of this CO_2 is accounted as a GHG in this study, because of the long natural cycle (i.e. centuries to millennia) of carbon in peatlands.

1.2. Compost

Various technologies exist to produce compost from residential biowaste such as kitchen organics and garden waste. Composts and compost-containing products are already widely used in different areas, e.g. for agricultural purposes, landscaping, soil reclamation, organic farming, private gardening, erosion control, roadside projects and nurseries. In the European Union (EU) 70-80 % of compost is used for agriculture, landscaping, nurseries etc. while the remaining 20-30 % is used by residential garden owners. Compost is locally produced and thus transportation of the compost is short before use. Beside organic matter, compost also contains nutrients and, depending on its origin, a certain content of contaminants, in particular heavy metals. Nutrients as well as metals may leach into the subsoil when compost is used on land.

2. Materials and methods

For the development of the life-cycle-inventories, data were collected from the literature and supplemented with experimental data regarding the composition of peat and the potential leaching from peat as well as from compost.

2.1. Samples

Four samples of compost were collected at composting facilities in Denmark, and seven samples of peat were collected either at production sites or at commercial sites where peat materials were sold as growth media. Details are presented in Table 1. Both peat and compost were stored shortly in tight plastic barrels before being tested.

Dry matter content of all samples was measured by heating 80-200 g of sample at 55 °C until water evaporation was completed (at least 24 hours). Afterwards, samples were sent to a certified external lab (former Analytica AB, now ALS Scandinavia AB, Luleå, Sweden) for chemical and physical characterization (Table 2).

Table 1 – Compost and peat samples

Material		Producer	Country	Collection
Compost	**Kitchen waste (KWC)**	Solum A/S	DK	Composting plant
	Garden waste (GWC)	Solum A/S	DK	Composting plant
		Århus Affaldscenter	DK	Composting plant
		RGS90	DK	Composting plant
Peat	**Sphagnum**	Unimuld	DK	Commercial
	Sphagnum	Sphagnum BG	SE	Commercial
	Peat	Scan Muld	SE	Commercial
	Sphagnum	Moss Peat	LT	Commercial
	Peat	Bord Na Mona	IE	Production site
	White Peat	Vapo	FI	Production site
	Brown Peat	Vapo	FI	Production site
DK: Denmark, SE: Sweden, LT: Lithuania, IE: Ireland, FI: Finland				

2.2. Leaching tests

Leaching tests (on wet material) were performed in 2 litres Polyethylene (PE) bottles, where 200-300 g of test material and water were mixed at a liquid-to-solid ratio (L/S) of 10 l/kg dry material. The bottles were rotated for approximately 24 hours. Liquid and solids were separated through several steps. A first coarse filtration was done with a nylon filter, followed by centrifugation for 8 minutes at 2500 rpm. Finally, filtrations with a GF/C filter and a 0.45 µm filter were performed. Filtrations through the nylon and GF/C filters were enhanced by suction with a vacuum pump. Three samples were taken from the remaining liquid: one 40 ml sample for heavy metals analysis (conserved as 2‰ nitric acid) and two 50 ml samples for organic carbon and anion analysis (conserved in freezer to stop any biological activity). To avoid heavy metals contamination, all equipment used was initially acid washed in a 3 M nitric acid solution and washed again with $1ml-HNO_3/500ml$ water between one sample and the next.

The organic carbon in the leachate was measured as Non-Purgeable Organic Carbon (NPOC). The analysis was performed on a Shimadzu TOC 5000A with auto sampler ASI-5000. Dilution was necessary to measure concentrations within the detection range. Anions measured in the samples comprised chloride, bromide, nitrate and sulphate. The analysis was performed on a Dionex DX-120 Ion Chromatograph. Heavy metal content, both in solids and leachate, was analysed by a certified external lab (ALS Scandinavia AB, Luleå, Sweden).

Reliability of the analysis was assessed. For each of the described methods, two replicates of randomly selected samples were analysed. No significant differences were found.

Table 2 - Chemical composition of peat and compost (kitchen waste compost, KWC, and garden waste compost, GWC).

Parameter	Unit	Peat*	KWC**	GWC***
			Material	
TS	% ww	43.6 ± 4.7	50.4	64.4 ± 7.4
VS	% TS	96.9 ± 1.7	30.9	24.9 ± 2.5
Ash	% TS	3.1 ± 1.7	69.1	75.1 ± 2.5
S	% TS	0.17 ± 0.11	0.45	0.12 ± 0.02
Tot-Cl	% TS	0.06 ± 0.02	0.08	0.05 ± 0.04
F	% TS	< 0.01	< 0.01	< 0.04
Tot-C	% TS	50.4 ± 1.5	19.1	14.3 ± 2.3
H	% TS	5.5 ± 0.1	2.1	1.5 ± 0.26
Tot-N	% TS	1.0 ± 0.3	1.2	0.86 ± 0.07
O	% TS	39.6 ± 2.0	7.2	7.5 ± 1.3
C:N		48 ± 10	15.9	16.6 ± 1.8
Cal. value	MJ/kg TS	19.4 ± 0.9	6.6	4.7 ± 0.39
Cal. value	MJ/kg ww	8.4 ± 0.9	2.8	3.2 ± 0.52
Density	kg/m^3	200 ± 57	726	684 ± 114
As	mg/kg TS	0.9 ± 0.5	6.5	3.7 ± 0.28
Ba	mg/kg TS	18 ± 10	320	343 ± 51
Be	mg/kg TS	0.06 ± 0.06	0.73	0.82 ± 0.1
Cd	mg/kg TS	0.12 ± 0.09	0.62	0.37 ± 0.14
Co	mg/kg TS	0.27 ± 0.09	3.6	3.1 ± 0.32
Cr	mg/kg TS	1.8 ± 1.0	18	29 ± 4.9
Cu	mg/kg TS	1.7 ± 0.8	135	36 ± 12
Hg	mg/kg TS	0.06 ± 0.04	0.53	0.14 ± 0.12
Mo	mg/kg TS	< 0.28	< 4.0	< 4.2
Nb	mg/kg TS	< 0.30	< 4.0	< 5.2
Ni	mg/kg TS	0.8 ± 0.35	13.5	7.2 ± 1.0
Pb	mg/kg TS	10 ± 10	28	34 ± 18
Sb	mg/kg TS	0.13 ± 0.13	0.23	0.08 ± 0.02
Sc	mg/kg TS	0.25 ± 0.22	1.8	2.8 ± 0.77
Sn	mg/kg TS	< 0.85	< 20	< 20
Sr	mg/kg TS	16 ± 7.6	279	140 ± 4.2
V	mg/kg TS	2.2 ± 1.3	24	26 ± 4.5
W	mg/kg TS	< 2.2	< 40	< 42
Y	mg/kg TS	0.90 ± 1.0	8.0	11 ± 1.4
Zn	mg/kg TS	11 ± 6.0	395	154 ± 45
Zr	mg/kg TS	5.5 ± 4.2	124	131 ± 16
Si	g/kg TS	7.8 ± 5.5	187	241 ± 9.2
Al	g/kg TS	1.4 ± 1.2	22	25 ± 3.0
Ca	g/kg TS	2.6 ± 1.4	81	26 ± 2.6
Fe	g/kg TS	1.0 ± 0.56	18	13 ± 3.0
K	g/kg TS	0.57 ± 0.42	11	17 ± 1.4
Mg	g/kg TS	1.1 ± 0.34	3.7	3.1 ±0.20
Mn	g/kg TS	0.002 ± 0.01	0.50	0.33 ± 0.12
Na	g/kg TS	0.38 ± 0.27	4.2	6.5 ± 0.83
P	g/kg TS	0.21 ± 0.05	9.3	1.7 ± 0.24
Ti	g/kg TS	0.01 ± 0.06	1.4	1.4 ± 0.22

* standard deviation calculated on 7 samples of peat

** standard deviation not calculated, because results regard a single sample

*** standard deviation calculated on 3 samples of GWC

2.3. LCI/ LCA-modelling

The life-cycle-inventory modelling was done by means of the EASEWASTE model developed at the Technical University of Denmark for environmental assessment of integrated solid waste management (Kirkeby et al., 2006). The model contains sub-models for transport, composting, and use of compost in agriculture as well as other waste management technologies. The LCIs of compost and peat were compared by the impact assessment available in EASEWASTE, including the EDIP method (Wenzel et al., 1997) and further up-dates (Stranddorf et al., 2005). The impact potentials were normalized by one person-equivalent, which is the annual load from one person from all activities (housing, food, transportation etc.) according to Stranddorf et al. (2005); see Table 3. The developed inventories can be useful in quantitative comparison with a range of other alternatives for organic waste management, for example incineration, composting for use in agriculture, anaerobic digestion and landfilling.

As an illustration two scenarios for organic kitchen waste were compared by means of LCA: (baseline scenarios) landfilling of kitchen organics together with other municipal waste in a landfill with gas recovery and production of electricity substituting for electricity produced from coal burning, and (recycling scenario) source separation and composting of kitchen organics and use of the compost in growth media production as a substitution for peat. The baseline scenario was modelled in EASEWASTE by means of existing default databases, while the recycling scenario was obtained directly from the developed LCIs by considering that 1 Mg of organic kitchen waste results in 430 kg of compost.

Table 3 − Normalisation references for environmental impact categories in EDIP1997 (Stranddorf et al., 2005)

Impact category	Geographical scale	Characterisation unit	Normalization reference [Characterisation unit/person/year]
Non-toxic impacts			
Global warming (GW)	Global	kg CO_2-equivalents	$8.7 \cdot 10^3$
Acidification (AC)	Regional	kg SO_2-equivalents	$7.4 \cdot 10^1$
Nutrient enrichment (NE)	Regional	kg NO_3-equivalents	$1.19 \cdot 10^2$
Photochemical ozone formation (POF)	Regional	kg C_2H_4-equivalents	$2.5 \cdot 10^1$
Toxic impacts			
Human toxicity (HT)			
- via air	Local	m^3 air	$6.09 \cdot 10^{10}$
Persistent toxicity (PT), average of:	Regional		
- Human toxicity via water		m^3 water	$5.22 \cdot 10^4$
- Human toxicity via soil		m^3 soil	$1.27 \cdot 10^2$
- Ecotoxicity via water		m^3 water	$3.52 \cdot 10^5$
- Ecotoxicity via soil		m^3 soil	$9.64 \cdot 10^5$
- Spoiled groundwater resources	Local	m^3 groundwater	140

3. Results

The results of the study are presented in terms of the leaching test data, the LCI tables of three growth media (compost from kitchen organics, compost from garden waste, peat), a comparison of the life-cycle impacts associated with the LCI tables, and finally the results of the illustrative example.

3.1. Results of the leaching tests

Table 4 reports average chemical compositions of leachate from peat and compost. The average was calculated aggregating results for samples presented in Table 1. This was done because leachates from different compost samples had similar chemical profiles, indicating that the compost products were more or less similar with respect to leaching, regardless of their origin. The same applied for the peat leachates. Peat leachate had a load of pollutants 3-20 times lower than leachate from compost. In some cases, drinking water limits were exceeded for some compounds.

The conductivity measured in the leachate was approximately 10 times higher in the compost leachate than in the peat leachate. The high salinity of the compost leachate can cause "burning" of the plant roots when compost is used in growth media if not sufficiently diluted by soil and sand.

Table 4 – Chemical composition of peat and compost leachate (L/S 10). (kitchen waste compost, KWC, and garden waste compost, GWC).

Element	Unit	Peat*	KWC**	GWC***
Ca	mg/l	2.2 ± 1.4	132	38 ± 16
Fe	mg/l	0.24[†] ± 0.25	5.1[†]	1.8[†] ± 0.55
K	mg/l	2.4 ± 0.86	212[†]	278[†] ± 19
Mg	mg/l	1.8 ± 1.25	20	8.5 ± 4.6
Na	mg/l	8.7 ± 3.4	42	28 ± 8.6
S	mg/l	3.1 ± 2.7	118	10 ± 8.4
Al	µg/l	224[‡] ± 297	3290[‡]	1897[‡] ± 564
As	µg/l	< 2.3	43[‡]	41[‡] ± 3.8
Ba	µg/l	373 ± 254	380	288 ± 151
Cd	µg/l	< 0.14	0.18	0.44 ± 0.08
Co	µg/l	0.28 ± 0.17	2.2	3.6 ± 1.4
Cr	µg/l	< 0.71	4.1	2.2 ± 0.68
Cu	µg/l	< 1.4	47	40 ± 16
Hg	µg/l	<0.20	<0.20	<0.24
Mn	µg/l	20 ± 22	261[†]	280[†] ± 138
Ni	µg/l	2.8 ± 1.0	24	11 ± 1.3
Pb	µg/l	2.4 ± 1.6	16	19 ± 9.8
Zn	µg/l	486[†] ± 293	450[†]	314[†] ± 51
Mo	µg/l	<0.50	52	10 ± 2.2
Sb	µg/l	<0.11	8.3[†]	1.9[†] ± 0.84
NPOC	µg/l	153 ± 73	200	147 ± 47
Chloride	mg/l	8.2 ± 3.5	99	108 ± 17
Bromide	mg/l	0	0	3.7 ± 6.1
Nitrate	mg/l	2.0 ± 1.5	19	12 ± 13
Sulphate	mg/l	2.1 ± 2.3	99	7.4 ± 7.0

* standard deviation calculated on 7 samples of peat
** standard deviation not calculated, because results regard a single sample
*** standard deviation calculated on 3 samples of GWC
[†] Exceeding Danish drinking water limits
[‡] Exceeding WHO drinking water guidelines

3.2. Life cycle inventory (LCI) for compost

The inventory is built based on the EASEWASTE module for biotechnologies (Kirkeby et al., 2006). Collection and transportation of waste were not included since they could be very variable and the waste should in any case always be collected for treatment.

Figure 1 presents the life cycle inventory boundaries of compost considered. Specific data for the composting process and the use on land were taken from the EASEWASTE database (2008). Relevant parameters are reported in Table 5.
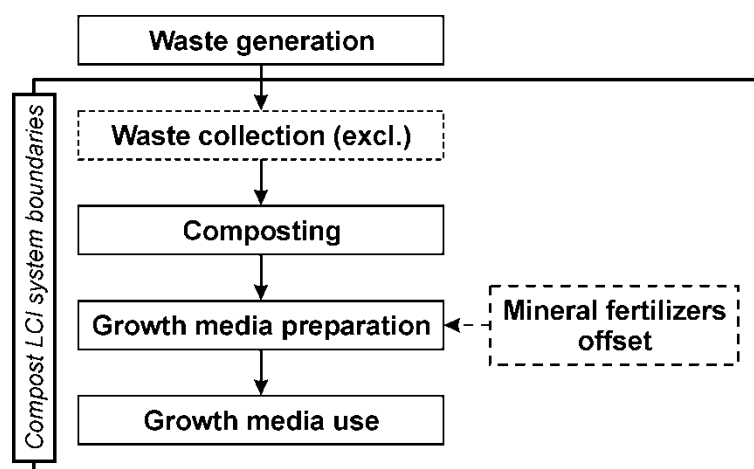

Figure 1 – LCI system boundaries for compost.

Table 5 – EASEWASTE modelling of the composting process and use on land. Data in brackets represent ranges of values found in literature.

Life cycle stage	Parameter	Unit	KWC	GWC
Composting	**N-NH₃**	% of N-loss	0.1	2.4
	N-N₂O	% of N-loss	1.8	1.4 (0.5-1.8)*
	CH₄	% of degraded C	0 (0-3)*	2.1 (2.1-2.7)*
	CO	kg/Mg$_{waste}$	-	0.05
Use on land	**NH₃ evaporation**	% of NH₃	1.6	(1.6-4.5)**
	N-N₂O formation	% total N	1.5	(1.3-2.2)**
	NO₃⁻ leaching	% of NO₃⁻	20	(3-22)**
	NO₃⁻ runoff	% of NO₃⁻	20	(4-30)**
	Carbon binding $_{100\text{-year}}$	% of C	14	(9-14)**

* From Boldrin et al. (2009)
* From Bruun et al. (2006)

Two types of compost were considered: kitchen waste compost (KWC) and garden waste compost (GWC).

Kitchen waste compost (KWC) is assumed to be produced in a closed-building tunnel composting plant, where 1 Mg of compost is produced from an input of 2.33 Mg of green waste. Feedstock to the process is: 50% organic kitchen waste, 30% garden waste, 20% material recirculated from screening. 49% of the N input is lost during the process. Specific air emissions are reported in Table 5. These represent emissions after the biofilter (95% removal of NH₃ and CH₄, no removal of N₂O). The facility consumes 51 KWh of electricity per Mg of waste treated. Both the energy consumption and the emissions are in the mid-upper end of data reported in literature for enclosed composting facilities shown in Boldrin et al. (2009).

Garden waste compost (GWC) is assumed to be produced in an outdoor windrow composting plant, which is the most common treatment for garden waste in many European countries (Andersen et al., 2009). In this facility, 1 Mg of compost is produced from an input of 1.48 Mg of garden waste. Feedstock to the process is: 100% garden waste (although a certain percentage could be recirculated from screening). 3% of the N input is lost during the process. Specific air emissions are reported in Table 5.

No biofilter is installed for treatment of off-gasses. The facility consumes 4.1 litres of diesel per Mg of waste treated. The used dataset - energy consumption and process emissions - is quite typical for open-windrow composting facilities, as shown in Boldrin et al. (2009).

Compost is used in preparation of enriched growth media. The N, P, K content of the compost is assumed to replace mineral fertilizers (see Table 2) considering the following substitution coefficient: 20% for N, 100% for P, and 100% for K. LCIs for mineral fertilizers production were defined according to Hansen et al. (2006). Other emissions during 100 years after application to land of the enriched media were calculated according to the coefficients reported in Table 5 (taken from Bruun et al., 2006).

In the assessment, it is considered that 14 % of carbon contained in compost is still bound to soil after 100 years (time horizon of the assessment) and can be considered an avoided emission of biogenic CO_2 (Christensen et al., 2009). The potential for carbon binding in soils by compost amendment is acknowledged in several studies (e.g. Marmo, 2008); the actual value of 14 % of C being sequestered is identical to the binding estimated by agro-ecological modelling of compost use on farm land with a typical Danish crop rotation scheme (see Bruun et al., 2006).

The compost LCI is given in Table 6. Please note that – due to lack of space - some of the resources are not terminated, meaning that the LCI datasets for the production or the use of such resources are not calculated and incorporated in the presented inventory. The leaching of substance to groundwater is calculated according to the leachate composition presented in table 4. Emissions to soil are calculated as difference between the input of substance (Table 2) and the potential leaching to groundwater (Table 6).

3.3. Life cycle inventory (LCI) for peat
The inventory for peat includes the four main phases of the peat life cycle (Cleary et al., 2005), as shown in Figure 2: preparation and use of peat-land, peat extraction and processing, transportation to the growth media manufacturing plant, and decomposition and environmental effects during and after use on land. The complete collection of data can be found in Boldrin & Christensen (2008). The inventory is built with a consequential approach, where LCI data for peat represent the difference between a baseline situation (undisturbed peatland) and a current situation (excavated peatland). This means that the reported emissions are considered as additional emissions occurring when excavating peat from the peatland.

Table 6 – LCI (resource consumption, emissions to air, water and soil) for 1 Mg of compost, originating from 2.33 Mg of waste in case of kitchen waste compost (KWC) and from 1.48 Mg of waste in case of garden waste compost (GWC).

Substance	type	Unit	Composting		Use		Fertilizer offset		Total	
			KWC	GWC	KWC	GWC	KWC	GWC	KWC	GWC
Electricity *	Resource	KWh	51.3	-	-	-	-	-	51.3	-
Diesel *	Resource	l	-	4.08	-	-	-	-	-	4.08
Biogenic CO_2	Air	kg	353	607	339	336	-	-	692	944
Carbon Binding	Air	kg	-	-	14.4	13.7	-	-	14.4	13.7
Methane (CH_4)	Air	kg	-	4.5	-	-	-	-	-	4.5
Nitrous Oxide (N_2O)	Air	kg	0.40	0.01	0.29	0.26	-	-	0.68	0.27
Carbon Monoxide (CO)	Air	kg	-	0.07	-	-	-	-	-	0.07
Ammonia (NH_3)	Air	g	-	4	15	14	-	-	15	18
2-Pentene (Trans)	Air	g	0.60	-	-	-	-	-	0.60	-
Butoxypropylacetate	Air	g	0.45	-	-	-	-	-	0.45	-
Sulphuric Acid (H_2SO_4)	Air	g	0.45	-	-	-	-	-	0.45	-
Nitrate (NO_3-)	Freshwater	g	-	-	12	11	-	-	12	11
Potassium (K)	Groundwater	kg	-	-	2.1	2.8	-	-	2.1	2.8
Chloride (Cl-)	Groundwater	kg	-	-	0.99	1.1	-	-	0.99	1.1
Calcium (Ca)	Groundwater	kg	-	-	1.3	0.38	-	-	1.3	0.38
Sodium (Na)	Groundwater	kg	-	-	0.42	0.28	-	-	0.42	0.28
Magnesium	Groundwater	kg	-	-	0.20	0.09	-	-	0.20	0.09
Sulphate ($SO_4^{(2-)}$)	Groundwater	kg	-	-	0.99	0.07	-	-	0.99	0.07
Aluminum (Al)	Groundwater	g	-	-	33	19	-	-	33	19
Iron (Fe)	Groundwater	g	-	-	51	18	-	-	51	18
Nitrate (NO_3-)	Groundwater	g	-	-	12	12	-	-	12	12
Zinc (Zn)	Groundwater	g	-	-	4.5	3.1	-	-	4.5	3.1
Manganese (Mn)	Groundwater	g	-	-	2.6	2.8	-	-	2.6	2.8
NVOC	Groundwater	g	-	-	199	1.5	-	-	199	1.5
Arsenic (As)	Groundwater	g	-	-	0.43	0.41	-	-	0.43	0.41
Copper (Cu)	Groundwater	g	-	-	0.47	0.40	-	-	0.47	0.40
Lead (Pb)	Groundwater	g	-	-	0.16	0.19	-	-	0.16	0.19
Nickel (Ni)	Groundwater	g	-	-	0.24	0.11	-	-	0.24	0.11
Molybdenum (Mo)	Groundwater	g	-	-	0.52	0.10	-	-	0.52	0.10
Chromium (Cr)	Groundwater	g	-	-	0.04	0.02	-	-	0.04	0.02
Antimony (Sb)	Groundwater	g	-	-	0.08	0.02	-	-	0.08	0.02
Cadmium (Cd)	Groundwater	g	-	-	$2e^{-03}$	0.004	-	-	$2e^{-03}$	0.004
Mercury (Hg)	Groundwater	g	-	-	$2e^{-06}$	0.002	-	-	$2e^{-06}$	0.002
Aluminum (Al)	Soil	kg	-	-	7.3	16	-	-	7.3	16
Iron (Fe)	Soil	kg	-	-	9.3	8.3	-	-	9.3	8.3
Manganese (Mn)	Soil	g	-	-	231	213	-	-	231	213
Zinc (Zn)	Soil	g	-	-	195	96	-	-	195	96
Copper (Cu)	Soil	g	-	-	68	23	-	-	68	23
Lead (Pb)	Soil	g	-	-	13.8	22	-	-	13.8	22
Chromium (Cr)	Soil	g	-	-	9.2	18	-	-	9.2	18
Nickel (Ni)	Soil	g	-	-	6.6	4.5	-	-	6.6	4.5
Molybdenum (Mo)	Soil	g	-	-	1.5	2.6	-	-	1.5	2.6
Arsenic (As)	Soil	g	-	-	2.9	2.0	-	-	2.9	2.0
Cadmium (Cd)	Soil	g	-	-	0.31	0.24	-	-	0.31	0.24
Mercury (Hg)	Soil	g	-	-	0.27	0.09	-	-	0.27	0.09
Antimony (Sb)	Soil	g	-	-	0.03	0.03	-	-	0.03	0.03
N mineral fertilizer *	Res. offset	kg	-	-	-	-	1.2	1.1	1.2	1.1
K mineral fertilizer *	Res. offset	kg	-	-	-	-	5.7	10.8	5.7	10.8
P mineral fertilizer *	Res. offset	kg	-	-	-	-	4.7	1.08	4.7	1.1

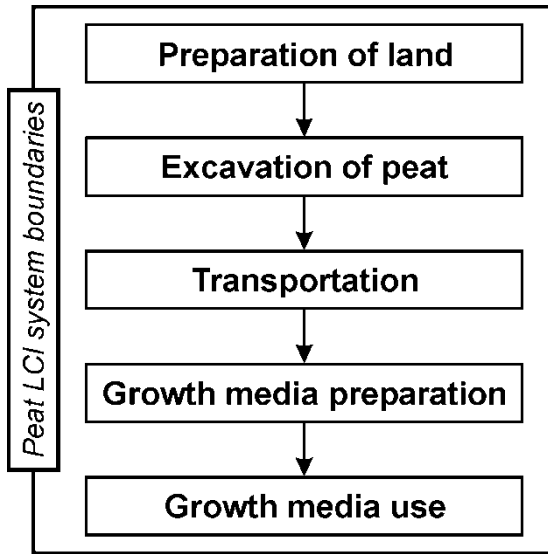* non terminated: refer to LCI datasets since the full dataset is not included.

Figure 2 – LCI system boundaries for peat.

Before harvesting, the peatland is dried, cleared of vegetation and levelled. The inventory accounts for alteration of the net GHG emissions during this phase, as calculated in Cleary et al. (2005).

Extraction and processing is performed by means of fossil-fuelled heavy machineries. Emissions (runoff) to water of eutrophying pollutants could occur during this phase. Therefore, the inventory includes air emissions during production and combustion of fuel and emissions of organic matter, nitrogen and phosphorous nutrients, and soluble metals to watercourses (Koskela et al., 2004; Cleary et al., 2005). Being produced mainly at northern latitudes, peat is often transported for long distances with different transportation means. The inventory includes air emissions from production and combustion of fossil fuel used for transportation. Amounts and provenience of peat used in Denmark have been calculated for 2006, using data from Statistics Danmark. In average, it was estimated that peat is transported for 500 km by ship, 120 km by train, 110 km by lorry in highways and 50 km on local roads. The complete dataset can be found in Boldrin & Christensen (2008).

When used on land, peat decomposes and may release some pollutants. The inventory includes emissions to air of all the fossil carbon content of peat and leaching to groundwater of different substances. Peat LCI is presented in Table 7. Leaching of substances to groundwater is calculated according to the leachate composition reported in Table 4. Emissions to soil are calculated as done for compost. Peat-based growth media are often used for indoor horticulture and the generated leachate is collected and recirculated. Such a case could be studied by excluding leaching values in Table 6 from the LCI of peat.

Table 7 – LCI for 1 Mg of peat (resource consumption, emissions to air, soil and water).

Substance	type	Unit	Preparation and use of peatland	Production	Transportation	Use on land	Total
Peat	Resource	kg	-	-	-	-	1000
Diesel	Resource	kg	-	5.7	3.7	-	9.4
LPG	Resource	kg	-	2.1	-	-	2.1
Gasoline	Resource	kg	-	0.73	-	-	0.73
Light fuel oil	Resource	kg	-	0.02	-	-	0.02
Natural gas	Resource	kg	-	$3.69e^{-06}$	-	-	$3.7e^{-06}$
$CO_{2\ fossil}$	Air	kg	108	34	12	815	969
NO_x	Air	kg	-	0.48	0.21	-	0.68
CH_4	Air	g	197	1.8	-	-	199
N_2O	Air	g	-	14	-	-	14
CO	Air	g	-	171	27	-	198
HC	Air	g	-	70	-	-	70
Partic.	Air	g	-	50	7.1	-	57
SO_2	Air	g	-	38	-	-	38
VOC	Air	g	-	-	21	-	21
Cr	Air	g	-	-	$1.8e^{-04}$	-	$1.8e^{-04}$
Cu	Air	g	-	-	$3.7e^{-04}$	-	$3.7e^{-04}$
Hg	Air	g	-	-	$3.7e^{-06}$	-	$3.7e^{-06}$
Cd	Air	g	-	-	$3.7e^{-05}$	-	$3.7e^{-05}$
Pb	Air	g	-	-	$3.7e^{-04}$	-	$3.7e^{-04}$
Ni	Air	g	-	-	$3.7e^{-03}$	-	$3.7e^{-03}$
Se	Air	g	-	-	$3.7e^{-05}$	-	$3.7e^{-05}$
Zn	Air	g	-	-	$3.7e^{-03}$	-	$3.7e^{-03}$
Org. matter	Water	kg	-	3.0	-	-	3.0
COD_{Mn}	Water	kg	-	1.8	-	-	1.8
Susp. solids	Water	kg	-	1.7	-	-	1.7
Nitrogen	Water	g	-	180	-	-	180
NH_4-N	Water	g	-	86	-	-	86
Phosphorus	Water	g	-	5.8	-	-	5.8
Sodium (Na)	Groundwater	g	-	-	-	26	26
Chloride (Cl-)	Groundwater	g	-	-	-	23	23
Potassium (K)	Groundwater	g	-	-	-	6.7	6.7
Calcium (Ca)	Groundwater	g	-	-	-	6.3	6.3
Sulphate (SO4(2-))	Groundwater	g	-	-	-	5.9	5.9
Nitrate (NO3-)	Groundwater	g	-	-	-	5.7	5.7
Magnesium	Groundwater	g	-	-	-	5.5	5.5
Zinc (Zn)	Groundwater	g	-	-	-	1.3	1.3
Iron (Fe)	Groundwater	g	-	-	-	0.68	0.68
Aluminum (Al)	Groundwater	g	-	-	-	0.64	0.64
NVOC	Groundwater	g	-	-	-	0.44	0.44
Manganese (Mn)	Groundwater	g	-	-	-	0.06	0.06
Nickel (Ni)	Groundwater	g	-	-	-	0.008	0.008
Lead (Pb)	Groundwater	g	-	-	-	0.007	0.007
Arsenic (As)	Groundwater	g	-	-	-	0.007	0.007
Copper (Cu)	Groundwater	g	-	-	-	0.004	0.004
Chromium (Cr)	Groundwater	g	-	-	-	0.002	0.002
Molybdenum (mo)	Groundwater	g	-	-	-	0.001	0.001
Mercury (Hg)	Groundwater	g	-	-	-	$6e^{-04}$	$6e^{-04}$
Cadmium (Cd)	Groundwater	g	-	-	-	$4e^{-04}$	$4e^{-04}$
Antimony (Sb)	Groundwater	g	-	-	-	$3e^{-04}$	$3e^{-04}$
Aluminum (Al)	Soil	g	-	-	-	177	177
Iron (Fe)	Soil	g	-	-	-	126	126
Manganese (Mn)	Soil	g	-	-	-	2.4	2.4
Lead (Pb)	Soil	g	-	-	-	1.2	1.2
Chromium (Cr)	Soil	g	-	-	-	0.22	0.22
Copper (Cu)	Soil	g	-	-	-	0.21	0.21
Arsenic (As)	Soil	g	-	-	-	0.10	0.10
Nickel (Ni)	Soil	g	-	-	-	0.09	0.09
Zinc (Zn)	Soil	g	-	-	-	0.04	0.04
Molybdenum (Mo)	Soil	g	-	-	-	0.03	0.03
Antimony (Sb)	Soil	g	-	-	-	0.02	0.02
Cadmium (Cd)	Soil	g	-	-	-	0.02	0.02
Mercury (Hg)	Soil	g	-	-	-	0.01	0.01

3.4. LCI comparison

Dilution of peat with compost could be done at different ratios (up to 50%, Prasad & Maher, 2006), depending on the type of compost and the desired characteristics of the growth media. The substitution is done on a 1:1 volume basis (Mathur & Voisin, 1996). The inventories presented in Table 6 and Table 7 have been compared, using as a reference 1 Mg of compost and an equivalent volume of peat, used as bulking components in preparation of enriched growth media to be used on land. Densities of compost and peat reported in Table 2 have been used to convert volumes into masses. The life cycle inventory boundaries for compost and peat are presented in Figure 1 and Figure 2. Compost is presented in two alternative scenarios, depending on the type of waste (i.e. green waste or garden waste) that it is produced from. The reason for including mineral fertilizers offsetting in the compost system boundaries is twofold. First, the assessment can focus on the material (compost, peat) rather than on the growth media. Second, the peat LCI remains the same no matter the type of compost it is compared to. In fact, including mineral fertilizers in the peat life cycle would have required definition of two different inventories for peat, depending on the nutrient content of the compost that the peat was compared to. Environmental loads from the technical processes of growth media preparation are not calculated, as it is assumed to be the same in both scenarios and therefore could be left out according to the consequential LCA principles.

Figure 3 presents results for the normalised potential non-toxic impacts. Composts (both green and garden waste) have better environmental performances in three out of four categories. Figure 4 presents contributions to Global Warming category from different gases, expressed in kg CO_2-eq. Peat has a large emission of "fossil"-CO_2, while compost is only generating biogenic-CO_2, which is neutral (GWP = 0) with respect to global warming (Christensen et al., 2009). Savings of using compost instead of peat are estimated to be 69 kg CO_2-eq. Mg^{-1} of green waste and 148 kg CO_2-eq. Mg^{-1} of garden waste. N_2O formation from use of compost is a relevant potential contributor to global warming. Values used (see Table 5) for N_2O formation are quite precautionary, so in different situations impact on global warming could be expected to be lower than those presented in Figure 3 and 4. Taking into account N_2O emissions during composting process is the reason for lower GHG savings estimated in this study, compared to other studies (e.g. Kranert & Gottschall, 2007) where this factor has not been taken into account.
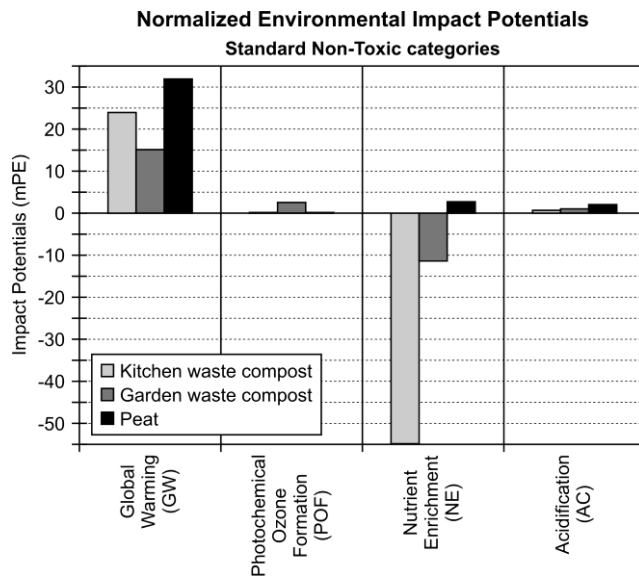
Normalized Environmental Impact Potentials

Standard Non-Toxic categories

Figure 3 – Potential non-toxic impacts from use of compost (1 Mg) and peat (285 kg) as bulking materials in growth media preparation.

Global Warming Potential category
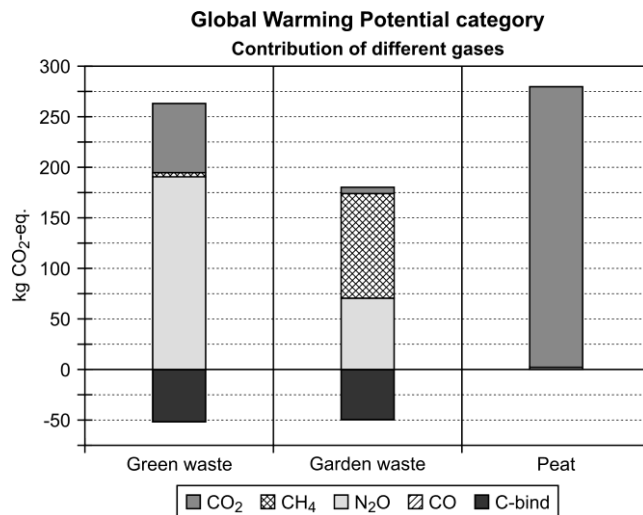
Contribution of different gases

Figure 4 – Contribution of different gases to Global Warming Potential.

Large savings in terms of nutrient enrichment (eutrophication) for compost are mainly due to the replacement of phosphorous fertilizer. In fact, during the production of commercial P fertilizers, consistent amounts of phosphate are discharged into freshwater, contributing to eutrophication. Potential detrimental effects of peat on nutrient enrichment and acidification are mainly due to emissions of NO_x from the combustion of fossil fuels in heavy machineries (e.g. for excavation) and transportation means. Potential impacts on Photochemical Ozone Formation (Smog) are quite small. Garden waste compost has the most detrimental effect in this category, mainly because of the methane emissions from the windrows. Methane is a potential precursor of smog formation.

Figure 5 presents results for the normalised potential toxic impacts. The graph should be considered as a qualitative assessment rather quantitative, meaning that the three options can be compared within one category, but categories should not be compared to each other in an attempt to estimate the overall impact. Harmonization of the toxicity characterization factors as well as a consensus on how to normalise and

aggregate the individual impacts are still needed and under debate (Christensen et al., 2007). Compost performs worse than peat in Human Toxicity via Water and Human Toxicity via Soil because of the higher content of heavy metals. Kitchen waste compost has a larger impact on Human Toxicity via Water than garden waste compost because of the higher content of mercury (Table 2), which is the main contributor to this impact category. Arsenic (As), chromium (Cr) and mercury (Hg) are the main contributors to Human Toxicity via Soil for both types of compost. The larger environmental load attributed to garden waste compost is due to the higher content of chromium as can be seen in Table 2. Green waste compost has a potential beneficial effect with regards to ecotoxicity in water due to the avoided emissions of Cd associated with P fertilizer.

The impact category called spoiled groundwater resources is directly related to the leaching properties of the materials. The higher load of metals in leachate (Table 4) results in a bigger impact for compost.
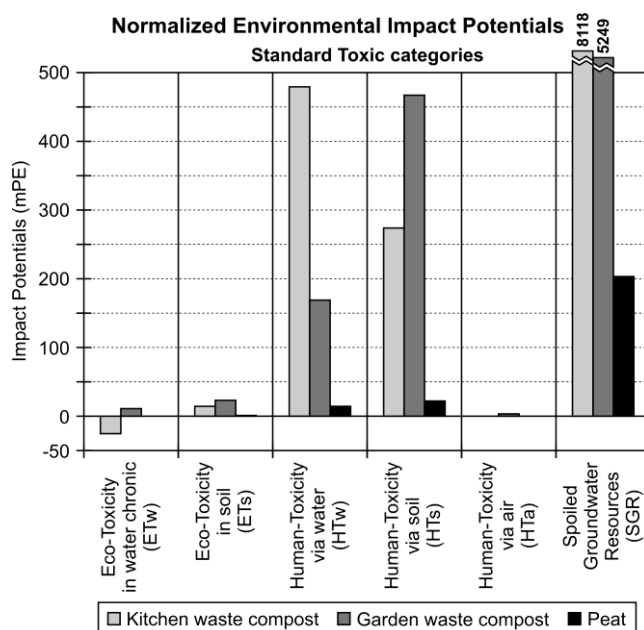
Figure 5 – Potential toxic impacts from use of compost (1 Mg) and peat (285 kg) as bulking materials in growth media preparation.

3.5. Uncertainty and sensitivity analysis

Uncertainty important analysis (Björklund, 2002) was carried out to determine how the uncertainty is related to different factors. This kind of analysis includes an assessment of the relevance of different parameters on the results, an evaluation of their uncertainty, and a sensitivity test.

A number of parameters were selected and their relevance (Table 9, second column) on the results was determined based on the results previously presented (Figures 3 to 5). The uncertainty related to each factor/parameter was qualitatively evaluated:

• Densities of compost and peat can fluctuate quite relevantly (Table 2), determining important variations in the peat compost substitution ratio, which is therefore considered highly uncertain.

- Electricity requirements for tunnel composting. According to Boldrin et al. (2009), the used data is an average value for this type of composting technology. The uncertainty is considered medium.
- Carbon binding within 100 years time horizon. It depends on local conditions, such as soil type, climate, farming practices, etc. The value used in the LCI is in the high end of the range modelled by Bruun et al. (2006) and its uncertainty is thus considered medium.
- Methane emissions from garden waste compost. The data used is in the typical range reported in literature (Boldrin et al., 2009). The uncertainty is considered low.
- Methane emissions from peat. The data used originate from literature. The uncertainty is precautionarily considered high.
- Chemical composition of peat and compost. Determined by means of chemical analysis. Standard deviation is small for most parameters. The uncertainty is considered low.
- Leaching properties of peat and compost. Determined by means of leaching test. Results (Table 4) show that variation across samples is in some case relevant. The uncertainty is considered medium.

A number of other factors/parameters were not tested in the uncertainty analysis. The reason for that is either their small influence on the results or the fact that varying these values would enlarge the differences shown by the results, thereby strengthening the conclusions:
- Emissions of N_2O. The emission factor for N_2O during compost degradation was chosen in a precautionary perspective and in reality it is expected to be lower than what previously used. Thus, from a global warming perspective, the benefits of using compost instead of peat are expected to be even bigger than presented in the results.
- Transportation of peat. Transportation of peat from the excavation site to the market has been estimated considering commercial flows of peat to and from Denmark. Precise data were not available, but the results show that transportation contributes marginally to the environmental footprint of peat.
- Energy requirement for garden waste composting. The used datum can be considered as a typical value (Boldrin et al., 2009). Furthermore, results show that energy consumption has a marginal influence on the results.

A sensitivity test, aiming to determine how a result is influenced by a parameter, was performed by varying the different parameters in selected scenarios, according to Table 8. The quantitative results of the test are shown graphically in Figure 6 and Figure 7 by means of variation intervals, showing the consequences of the changes mentioned. A qualitative indicator describing the sensitivity of each parameter relative to the different impact categories was then defined according to the following considerations. For a specific impact category, high sensitivity was assigned if the variation interval was large relatively to the impact in itself or if the variation interval was larger than the absolute (numerical) difference found between the analysed scenarios. The results are reported in Table 9.

Table 8 – Sensitivity test for different parameters and scenarios.

Test name	Tested scenario	Parameter changed	Change	From	To	
Substitution factor	Peat	Compost/peat substitution factor	± 25 %	285 kg	214 kg	356 kg
Electricity requirements	KW compost	Electricity use	± 50 %	51 kWh	26 kWh	76 kWh
Carbon binding	KW compost	Carbon binding	- 50 %*	14 %	7 %	-
Methane from GW	GW compost	Methane emission	± 50 %	2 %	1 %	3 %
Methane from peat	Peat	Methane emission	± 50 %	199 g/Mg	100 g/Mg	300 g/Mg
Chemical comp. GW	GW compost	Chemical composition	± St.dev.	Table 3	Table 3	Table 3
Chemical comp. peat	Peat	Chemical composition	± St.dev.	Table 3	Table 3	Table 3
Leaching GW	GW compost	Leachate composition	± St.dev.	Table 4	Table 4	Table 4
Leaching peat	Peat	Leachate composition	± St.dev.	Table 4	Table 4	Table 4

* according to Bruun et al. (2006), in Danish condition carbon binding does not exceed 14 %.

Table 9 – Qualitative results of the uncertainty importance analysis.

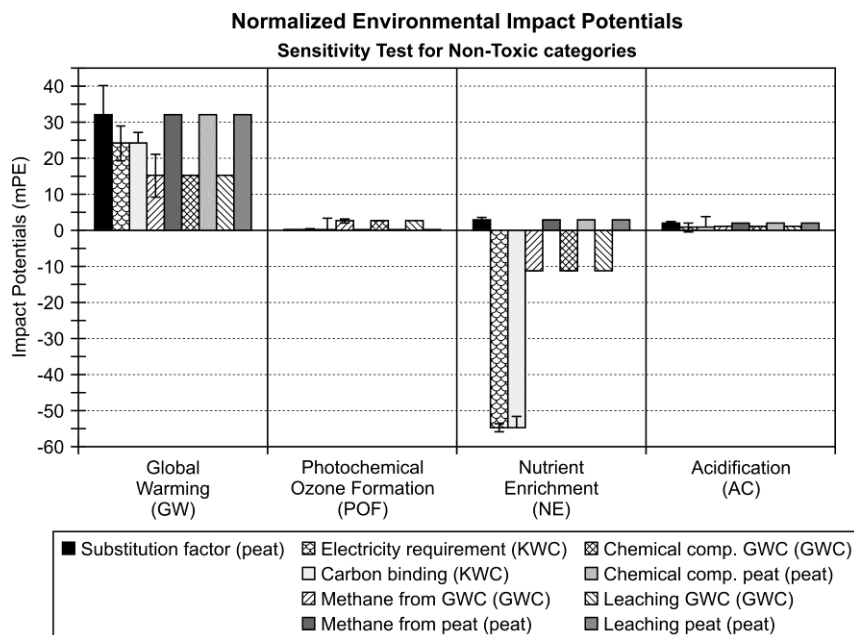| Parameter	Relevance on the results	Uncertainty	Sensitivity
Substitution factor	High	High	High
Electricity requirements	Low	Medium	Low
Carbon binding	Medium	Medium	Low
Methane from GW	High	Low	Low
Methane from peat	Low	High	Low
Chemical comp. GW	Medium	Low	Medium
Chemical comp. peat	Low	Low	Low
Leaching GW	Medium	Medium	Low
Leaching peat	Medium	Medium	Low

Figure 6 - Results of the sensitivity test for non-toxic impact categories.
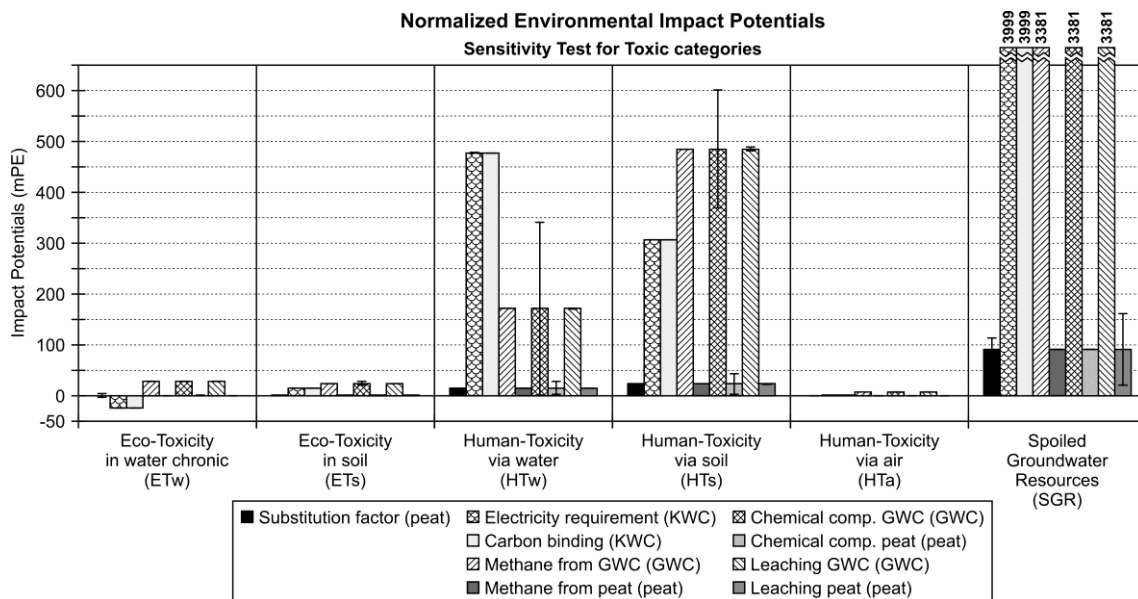
Figure 7 - Results of the sensitivity test for toxic impact categories.

The qualitative results of the uncertainty analysis are shown in Table 9 and they indicate that the most problematic parameter is the substitution factor between compost and peat. Some uncertainty is also introduced in the modelling by the chemical composition of garden waste - mainly due to variability in Hg content affecting human toxicities and spoiled groundwater impact categories. However, the results also reveal that the conclusions of the assessment might not be altered, because in most of the cases the differences seen between scenarios are larger than the uncertainty related to the results.

3.6. An illustrative example

According to consequential LCA principles, the system boundaries of peat should be expanded to include an alternative option for handling of organic waste (Finnveden, 1999; Ekvall & Weidema, 2004). In fact, composting functions primarily as a waste managing service and the peat scenario should therefore consider the consequences of not using compost in growth media (i.e. compost is used for other purposes or the organic waste is treated in a different way). System expansion was not included in the LCIs and in the comparison of them, because of the variety of possible alternative treatments for the organic waste. The LCIs are as tables the main out-come of the study and can be used when performing LCA studies where local specific situations are analysed in detail against local alternatives.

An hypothetical case including two scenarios have been developed to show the use of the presented inventories and the consequences of implementing consequential LCA principles. In the "green waste" scenario, 1 Mg of green waste is composted and the produced compost is used in substitution of peat during preparation of growth media (mineral offsetting is included). The inventories for the different processes were obtained are the above-presented inventories. In the "peat" scenario, 1 Mg is landfilled in a conventional landfill (bottom liner, leachate collection system, leachate treatment, gas collection system, soil topcover) with energy recovery (40% of the generated gas is collected and sent to CHP, where the produced energy substitutes 100% for energy production at a coal-fired power plant), while the growth media is

produced by using peat. In both scenarios, the environmental consequences of the use of growth media are modelled. The boundaries of the compared scenarios are presented in Figure 8 and Figure 9.

The results of the hypothetical case are shown in Figure 10 with respect to the non-toxic impact categories and in Figure 11 for the toxic impact categories. For most of the impact categories, the results show that the scenario based on composting of green waste is preferable to the scenario where green waste is landfilled and growth media are produced using peat materials, thus strengthening the conclusions previously drawn. Along with the benefits described during the LCIs comparison, avoiding landfilling of organic waste results in important benefits with respect to spoiled groundwater resources.
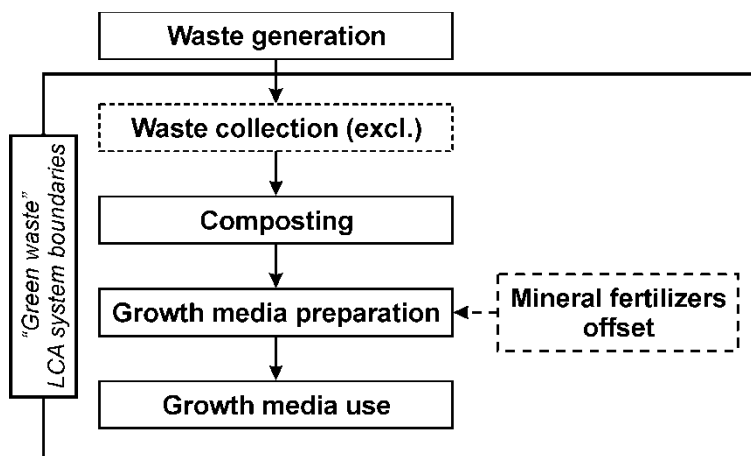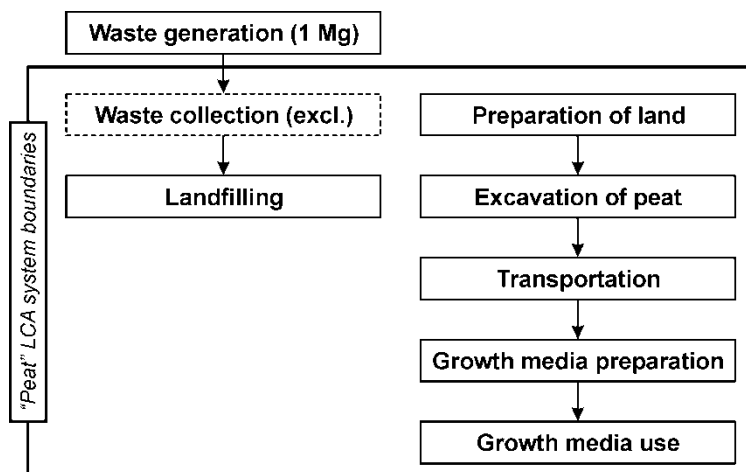

Figure 8 – "Green waste" scenario system boundaries.

Figure 9 – "Peat" scenario system boundaries.

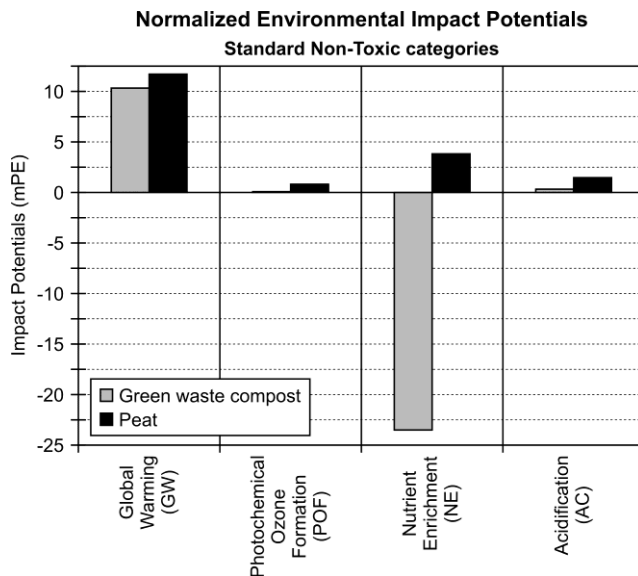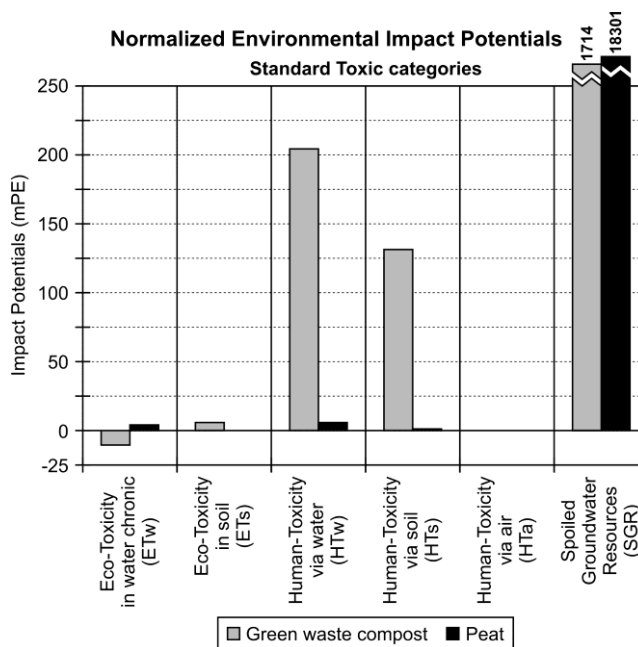**Figure 10 – Potential non-toxic impacts from the hypothetical scenarios.**

Figure 11 – Potential toxic impacts from the hypothetical scenarios.

4. Conclusion

The substitution of peat with compost in growth media has some potential environmental benefits. Compost has a lower impact on global warming because of the biogenic origin of the carbon contained. The savings are in the order of 9-17 mPE Mg^{-1} compost corresponding to 70-150 kg CO_2-eq. Mg^{-1}. Further relevant improvements could be achieved by:

- reducing methane emissions from windrows by proper management;
- increasing energy efficiency in the composting plant;
- reducing N_2O from use on land (although it is not clear how).

NO_x emissions from use of heavy machineries during peat excavation are prevented, with benefits in terms of eutrophication and acidification.

Compost has also a potential for substituting commercial mineral fertilizers, with consequent benefits on eutrophication in the order of 14-57 mPE Mg^{-1} compost.

It was found that especially avoiding the productions of N and P fertilizers have a big impact on the environment. Potential impacts from compost could come from its content of heavy metals, which could either leach to groundwater or accumulate in soil (especially with repeated application, Amlinger et al., 2004).

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