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NATIONAL TRANSLATION OF THE EU LANDFILL DIRECTIVES—WILL LANDFILLS BECOME SUSTAINABLE?

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ABSTRACT

The key issues of the EU Landfill Directives (1999/31/EC and 2003/33/EC) are elucidated with respect to the directives' objectives towards sustainable waste management. In countries such as Sweden the national translation of the directives' requirements will lead to dryer landfills with relatively more municipal solid waste (MSW) incineration residues. Numerous landfills have been closed before the initially envisaged date. They will not be subject to the advanced closing procedure for landfills according to the translation of the EU directives. Together with former unengineered dumps, these landfills will outnumber the compliant landfills by far. The former are neither subject to the Swedish national translation of the Landfill Directives nor to any other EU or national legislation. Often lacking active and even passive barrier systems, the emission potential of these landfills seems to be able to overshadow that of the reduced number of remaining EU directive-compliant landfills. These landfills will eventually be regarded as contaminated areas. In countries such as Sweden a substitution of MSW landfills by incineration facilities will result in a more rapid and likely increased release of carbon dioxide emissions (among other air pollutants) per tonne of produced waste. Thus, a comparative assessment of the overall impact of waste management options on different timescales for emissions should be done on a country-by-country basis to assess sustainability of the translation of the Landfill Directives. The physical–chemical and microbiological properties of the resulting storage conditions governing the landfills' emission potentials are unknown to a great extent. A prolonged risk of relevant emissions has to be taken into account for compliant landfills due to possible moisture scarcity and subsequent slower degradation rates. On the one hand, leaching of degradation products could be extended, albeit in reduced concentrations. On the other hand, longer contact time with water can enhance leaching of, for example, hydrophilic substances. Concentration and/or mass peaks might be postponed compared to earlier, 'wetter' landfilling with a higher content of easily degradable organic waste. Without addressing and answering these uncertainties, it remains doubtful it the national translation of the Landfill Directives will lead to sustainable waste management in the long run.

Keywords: landfill, legislation, long-term emissions, storage conditions, sustainable waste management.

1 INTRODUCTION

Landfilling can be regarded as the opposite of sustainability. The leftovers from production and consumption are concentrated in a big heap outside settlements, remaining for generations to come. Meanwhile, they produce potentially harmful leachate and generally degas methane and carbon dioxide into the atmosphere for decades. The EU Council Landfill Directive (1999/31/EC) and the Council Decision on Waste Acceptance Criteria and Procedures (2003/33/EC), referred to as 'the Landfill Directives', set technical and quantitative requirements for all EU membership countries regarding the landfilling of waste. This article aims to identify the advantages and disadvantages of the Landfill Directives' requirements, in particular those with importance for long-term pollution potential of landfills. Sweden serves as a case study to discuss whether landfilling and waste management in Europe will become more sustainable. The focus is laid on the changing physical–chemical and biological properties of landfills, as well as on changes in overall waste management practices due to the directives' enforcement.

The objective of the Landfill Directives is 'to provide for measures, procedures and guidance to prevent or reduce as far as possible the negative effects on the environment, in particular the pollution to surface water, groundwater, soil and air, and on the global environment, including the greenhouse effect as well as any resulting risk to human health, from landfilling of waste, during the whole life-cycle of the landfill'. The Landfill Directives intend to inhibit the flow of matter and energy from

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the landfill by enclosing the waste through barriers with low permeability, as well as releasing and collecting liquids and gas at controlled spots (1999/31/EC). The focus is laid on:

- defining landfill classes and minimum requirements for different waste–types;
- banning landfilling of liquid waste;
- reducing biodegradable waste streams to landfills.

Although the Landfill Directive (1999/31/EC) has to be seen as framework legislation, it explicitly defines the design and operation procedures for landfills for all EU membership countries. This generalization is deliberate, as varying landfill standards and resulting differing costs might encourage the long-range transportation of waste through the EU. In combination with the Council Decision on Waste Acceptance Criteria (2003/33/EC), there is scarce room for member states to adjust the outlined criteria to national prerequisites, as can be concluded from Table 1a and b. Still, certain interpretability is granted for the requirements shown in Table 1b.

Exceptions are made for the time span in which countries have to abide by the quantitative restraints on the deposition of organic waste, i.e. biodegradable residues. The general restrictions comprise a reduction of the deposition of biodegradable waste to 75%, 50% and 35% of the total amount of waste produced in 1995 by the year 2006, 2009 and 2016, respectively. The directive defines biodegradable waste as any waste capable of undergoing anaerobic or aerobic decomposition, such as food and garden waste, and paper and paperboard (1999/31/EC). The ground for these reduction quotes was laid by the EU's 5th Framework Action Program on the Environment, accompanied by the ratification of the UN Framework Convention on Climate Change (the Kyoto Protocol) to reduce emissions of greenhouse gases. For the EU, this amounts to a reduction of 8% on 1990 emissions in the period 2008–2012 [1]. Landfilling of biodegradable waste, in particular, has been identified as a major contributor to carbon dioxide and methane emissions in the EU [2].

The prevailing municipal waste situations as well as the geological and climatological prerequisites in the membership and accession countries differ widely, as can be observed from Table 2a and b.

2 ADVANTAGES AND DISADVANTAGES OF THE EU LANDFILL DIRECTIVES

Some of the environmental advantages and disadvantages of the EU Landfill Directives are given in Table 3a and b. The greatest uncertainty regarding the disadvantages lies in the unspecified requirements (see Table 3c).

3 LANDFILLING IN SWEDEN

Sweden, a member of the EU since 1995, has a population of 9 million inhabitants, as of August 2004, and a GNP of about 26,000 US$ [13]. It covers 450,000 km^2 with a length of 1600 km and a width of 500 km. The average population density is 20 km^{-2}, but municipalities in the northern part have a population density of less than 1 km^{-2}. The climate is humid to subarctic. Due to its geographic position, precipitation occurs in the north to a great extent as snow. The number of days with snow cover varied between under 25 and 225 in the period 1961–1990 [14].

Sweden is administratively divided into 21 counties, governed by county administrative boards, called 'länsstyrelsen'. These counties comprise 289 municipalities with their own municipal councils. Either the county administrative boards or the municipal councils through their delegations function as the controlling competent authority for landfill operators. The sources of permits for the landfills in operation vary from site to site due to size differentiation and legislative amendments, especially since the inauguration of the new national environmental directive as of 1 January 1999. The majority of landfills in operation in 2002 had a permit granted by the former environmental law through the

Table 1: (a) Minimum EU Landfill Directive criteria; (b) EU Landfill Directive criteria with interpretability.

(a) Criteria without or with little interpretability by membership countries

Landfill design and operation

- Accepted conditioning plan for existing landfills to be kept operational
- After-care phase $\geq$30 years, monitoring and maintenance through operator
- Geological barrier underneath the landfill and in the vicinity, thickness and permeability of base and sides, preferably clay of low permeability or comparable artificial layers
- Collection and treatment of contaminated leachate
- Collection and treatment of gas emissions from biodegradable waste landfills
- Top soil cover >1 m
- General principles for waste acceptance procedures and required information on waste prior to deposition
- Monitoring procedures including frequency and certain parameters

Waste classification

- Definition of three landfill classes (inert, non-hazardous, hazardous)
- Criteria on limited co-disposal of hazardous waste on non-hazardous waste landfills
- Exclusivity of inert waste for inert waste landfills
- Non-acceptance of liquid, explosive, corrosive, oxidizing, highly flammable or flammable, infectious waste and whole used tyres, waste not fulfilling the laid down acceptance criteria and waste not pretreated
- Prohibition of mixing of waste in order to meet the acceptance criteria

Waste properties

- Leaching and organic content limit values for inert waste, granular non-hazardous waste for co-disposal with hazardous wastes and hazardous waste for co-disposal with non-hazardous waste
- Leaching limit values for hazardous waste
- Exception from testing requirement for wastes included in Chapter 20 of the European Waste List
- Test methods for waste prior to deposition, where already existing

(b) Criteria with certain interpretability by membership countries

Landfill design and operation

- Definition of 'control water from precipitations entering into the landfill body'
- Definition of 'sufficient attenuation capacity' of the geological barrier
- Control of gas emissions and migration

Waste classification

- Definition of 'pretreatment of waste'
- Definition of acceptance criteria for landfills containing substantial amounts of organic, non-hazardous wastes
- Sampling of waste

county administrative board, for landfills with an annual waste flow of 50 tonnes to 75 ktonnes. They majority of landfills were established during the 1970s. The area covered by landfills in Sweden is 27 km^2. Figure 1 shows the waste amounts going to landfills in Sweden from 1998 to 2002 and extrapolated until 2007.

Table 2: Landfills and climate in the (a) EU and (b) accession countries.

Country	MSW (ktonne)[a]	MSW to landfill[a] (%)	Population density (km^{-2})	Precipitation[b] (mm/a)	Potential evaporation[c] (10^3 mm/a)	Landfills/non-hazardous landfills[a] after 1997
(a) EU						
Austria	3100	<50	97	500–2500	0.5–1	773/97[d,e]
Belgium	5492	25	337	800–1100	0.5–0.7	212/n.d.
Denmark	3121	7[f]	125	550–850	0.5–0.7	100/34[f]
Germany	50,085[g]	27[g]	233	500–1100	0.5–1	2412/1877[h]
Greece	3900	>80	81	500–1100	1–1.25	1550/n.d.[i]
Finland	2510	>80	15	300–700	n.d.	359/n.d.
France	37,800	>60	109	600–1800	0.7–1.25	452/n.d.
Ireland	1933	>80	55	750–1600	0.5–0.7	126/n.d.
Italy	26,846	>75	192	500–1600	0.7–1.25	789/n.d.
Luxembourg	184	<40	173	700–800	0.5–0.7	n.d.
Netherlands	9359	<20	387	700–900	0.5–0.7	38/n.d.
Portugal	4364	>75	109	380–1800	1–1.25	120/n.d.
Spain	24,470	>60	79	300–1800	0.7–1.25	195/n.d.
Sweden	3177[j]	26[k]	20	300–2100	0.1–0.5	237/200[j]
UK	30,000	>80	244	550–2500	0.5–0.7	3489/536[i]
EU 15 (sum)	206,341	47	n.d.	n.d.	n.d.	>10,852/≫2744
Czech Republic	3365	>75	130	500–1000	0.5–1	347
Cyprus	369	>80	83	600–800	1–1.25	n.d.
Estonia	569	>90	31	550–850	0.5–0.7	261
Hungary	4376	>80	108	550–900	0.5–1	729
Latvia	292	>90	37	550–750	0.5–0.7	550
Lithuania	1.236	>90	55	550–700	0.5–0.7	n.d.
Malta	n.d.	n.d.	1260	n.d.	1–1.25	n.d.
Poland	12,317	>90	124	500–1000	0.5–1	1401
Slovak Republic	1700	>75	111	550–1100	0.5–0.7	277
Slovenia	1.024	>90	95	800–1100	n.d.	168
(b) Accession countries						
Bulgaria	3197	>90	69	500–1000	0.5–0.7	n.d.
Romania	5699	>90	91	300–1100	0.7–1	765
Turkey	n.d.	n.d.	86	200–2200	n.d.	n.d.

n.d., no data available or not found.
[a]Eurostat [3], column 2: data from 1998 to 2002, except Cyprus from 1993 and Slovenia from 1995, column 7: 'mostly controlled sites', data from 1997 to 1999 if not otherwise quoted; [b]National meteorological institutes; [c]Estrela *et al*. [4]; [d]Austrian EPA [5], reference year 2001; [e]according to Perz [6]: 53 MSW landfills; [f]Danish Environmental Ministry [7]; [g]German EM [8], reference year 2000; [h]German EM [9], reference year 1996; [i]Hjelmar *et al*. [10], data from 1994, except Greece from 1987, data based on questionnaire responses; [j]RVF [11]; [k]Swedish EPA [12].

For the year 2002 the total amount of material put into non-private waste management sites amounted to 6175 ktonnes, of which 100 ktonnes were deposited in so-called 'plan reactors' (especially biocell deposition in pilot scale or with scientific character). Of the landfills 84% had a residual operation time of over 5 years in 2002; 37% of the landfill sites were supplied with over 70% of the waste amount landfilled.

Table 3: (a) Advantageous environmental aspects, (b) disadvantages and (c) unspecified requirements, with expected impact, of the enforcement of the EU Landfill Directives.

(a) Advantages

Directly

- reducing the amount of methane and carbon dioxide produced by landfills
- reducing the amount of methane and carbon dioxide released by landfills
- reducing leachate emission by geological and hydrological requirements during the technical lifetime of the landfill sites
- better control of incoming waste
- minimum control of gas and leachate emissions during operation
- minimum monitoring requirements during after-care phase
- maximum leachable contents are to be measured and restricted for certain waste groups

Indirectly

- reducing the risk of long-range waste transport

(b) Disadvantages

- possible delay of emission peaks beyond after-care phase
- accelerated filling and closing of landfills before 2001 with lower demands for capping and monitoring
- intensified reactor landfilling is not addressed
- no provisions are taken to account for carbon sequestration on behalf of the Kyoto protocol
- storage after unloading or storage prior to recovery up to 3 years and storage before landfilling up to 1 year is not subject to the Landfill Directives
- no provisions are taken to control and reduce the leaching of the resulting waste mixture, e.g. synergetic effects are not taken into account
- landfills serving isolated settlements can be granted exemptions

(c) Unspecified requirements, with expected impact

- definition of ‘control water from precipitation entering the waste’
- definition of ‘after-care phase’
- quality of conditioning plans accepted on a national basis
- extent of granted exceptions
- definition of acceptance criteria for organic waste
- closing date for compliant landfills

Landfilling represented the major waste management option until the year 2002. The extrapolation after the year 2004 in Fig. 1 was done according to the following assumptions:

- incineration and thus incineration residues increase due to the realization of new incineration plants which are either planned or in a feasibility study status in 1999 (see also SNV [16]);
- 20% (weight) of the combusted waste becomes bottom ash, 5% (weight) becomes fly ash, both of which are landfilled due to the lack of alternative full-scale management options [15];
- the amount of waste for landfilling is slightly increasing due to the deposition of larger amounts of municipal solid waste (MSW) incineration residues;
- waste for private landfilling increases steadily due to economic growth (4% per year) over a 8-year period and due to the subsequent effects of growth on different industries;
- the overall amount of waste produced increases as it is connected to economic growth.

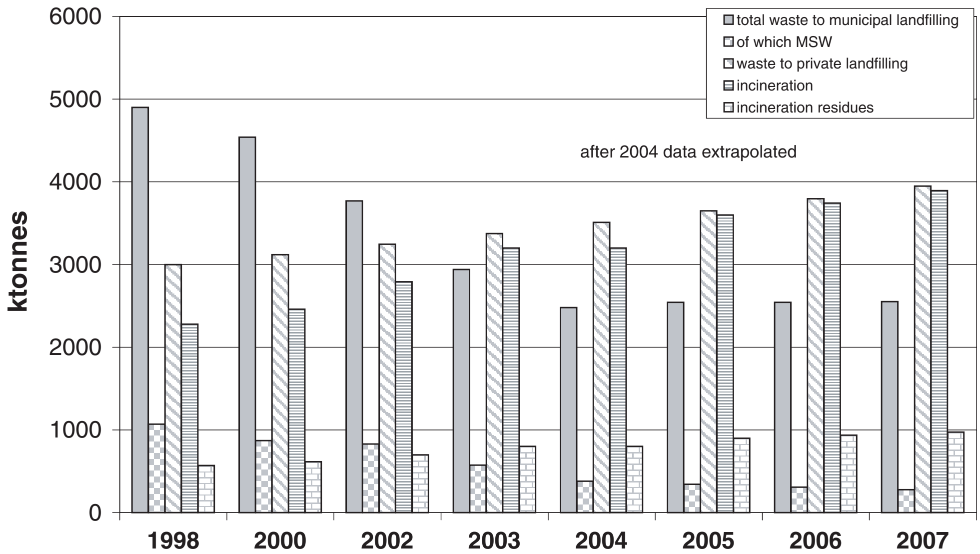

Figure 1: Waste production in Sweden from 1998 and until 2007 (data until 2002 from RVF [15] and SNV [16]).

Sweden has no emission limit values for effluents. Emission limits are set by the competent authorities on a case-by-case basis, depending on the recipient. An exception is, among others, the recommended maximum value for certain parameters (especially heavy metals) for treatment of effluents in municipal wastewater treatment plants.

On behalf of the Swedish Environmental Protection Agency (EPA) a suggestion for a sampling programme for leachates has been developed [17]. The characterization of a number of landfill leachates according to this programme is listed in Table 4. The detected values are rather on the lower end of the ranges summarized for numerous German landfills of different age and content [18].

3.1 The national translation of the Landfill Directives

In Sweden the translation of the Landfill Directive 1999/31/EC has resulted in the ordinance SFS 2001:512 and is accompanied by General Guidance (NFS 2004:5), whose content can be regarded as a more specified guide comparable to the German 'Technische Anleitung Siedlungsabfall' (Technical Guidance on Household Waste), TASI for short. The Council Decision on Waste Acceptance Criteria 2003/33/EC is translated into the provisions NFS 2004:10. The management of organic and combustible waste is enforced by the Swedish EPA's 'Provisions and guidance on management of organic and combustible waste, NFS 2004:4'.

Table 5 shows the Swedish translation of the main criteria from Table 1b.

3.2 Consequences of the national translation

In the following sections the key issues of the expected impacts on landfilling and waste management are summarized.

3.2.1 Operation and closure

The number of landfills closed during the years prior to 2001 was greater than in preceding years. A survey done by the Swedish EPA revealed that operators expected higher costs especially for

Table 4: Analyses of untreated leachate from Swedish landfills according to a single sampling programme (Öman *et al*. [15]).

Parameter	Unit	Minimum	Maximum	Average	Standard deviation	No. of landfills	German landfills[b]
pH	–	6.4	8.5	7.5	7	11	5.4–8.7
T_{water}	°C	2	25	16	41	11	n.d.
T_{air}	°C	−14	14	4	200	11	n.d.
EC	mS/m	490	2730	1210	60	6	691–109,000
SS	mg/l	9	210	53	110	10	n.d.
BOD_7	mg O_2/l	4	110	28	110	10	7–64,880[c]
COD_{Cr}	mg O_2/l	250	1300	760	46	11	22–29,150
Chloride	mg/l	360	4900	1730	89	11	13–11950
$N\text{-}NH_4$	mg/l	93	870	370	71	11	0.4–7000
N-tot	mg/l	98	860	360	74	12	n.d.
EOX	mg/l	0.001[a]	0.030	0.009	108	11	n.d.
PAH (16)	mg/l	0.03[a]	11	2.9	145	18	n.d.
Ni	μg/l	9.8	91	30	73	14	3–1400
Cu	μg/l	5.8	80	22	90	14	2.5–40,000
Cr	μg/l	1.5	45	17	94	13	5–2570
Zn	μg/l	16	340	63	128	14	10–125,000

n.d., no data available or not found.
[a]Detection limit; [b]Kruempelbeck and Ehrig [18]; [c](BOD_5).

closing procedures due to the Landfill Directive 1999/31/EC. They chose to cease landfilling before the compliance date. According to this survey, there were 339 landfills in operation at the date of the survey [19]; of these 137 served wastes from industrial production, the remaining were regarded as MSW landfills. According to the same source, about 300 MSW landfills were in operation in 1994. About 15% of the total 339 landfills operating in 2002 will be closed by 2008 and thus are subject to the EU Landfill Directive's closing procedure but not the conditioning requirements; 30% of the landfills operating in 2002 will be closed by 2020. In 2004 there were only 175 landfills left that received amounts of MSW exceeding 50 tonnes per year.

3.2.2 Isolated settlements

In terms of the population there is a south–north inclination for the number of landfills. In the four northernmost counties there were 38 landfills in 2003 [19] and 108 in the four southernmost counties. Still, only two landfills would fulfil the requirements of serving 'isolated settlements' according to the Landfill Directive's Article 3 (1999/31/EC) and could be granted exemption from key requirements. However, these have not been applied for.

3.2.3 Gas and leachate control and treatment

In 2002 only 16% of the operating landfills in Sweden had some form of gas collection system. An additional 5% of the operators had taken the decision to employ a gas collection system at that time [19]. In 2004 gas was collected at 60 landfills in operation and an additional 10 closed landfills had gas collection systems. This appears to be a rather small number, considering that the already placed organic waste fraction has to be taken into account to enable a decision for or against a gas collection

Table 5: Swedish translation of the EU Landfill Directives.

EU Landfill Directive requirement	Swedish translation	Reference
Organic waste	Definition Organic waste: Waste that contains organic carbon, such as biological waste and plastic waste.	SFS 2001:1063
	Landfill prohibits. Separated combustible waste is not to be landfilled. Organic waste is not to be landfilled.	§ 9 SFS 2001:512
	Exceptions The above constraints are not valid for: 1. Bottom and fly ash, APC-residue sludge with a TOC $<18\%$ dry weight.	§ 10 since 1 January 2001
	2. Composted WWT sludge. 3. Animal waste which is permitted to be buried due to other legislation. 4. Other waste with homogenous content which contains $<10\%$ TOC. 5. Waste with a heterogeneous content and $<10\%$ per volume combustible waste.	§ 12 NFS 2004:4
	6. Waste whose physical or chemical properties after pretreatment are such that the waste should not be recycled or disposed of in a different way than by landfilling. Operators have to consult the competent authority before landfilling such waste.	§ 13 NFS 2004:4
	In case of shortage of other waste management capacities under certain conditions, operators can apply for dispensing with the prohibition of landfilling organic or combustible waste for 1 year.	§ 15–20 NFS 2004:4
Definition of 'pretreatment of waste'	'…use of physical, thermal, chemical or biological methods, including sorting, which alters the waste's properties in the way that its amount or hazardousness reduces, handling is eased or recycling is favoured'.	§ 14 SFS 2001:512
Definition of 'control water from precipitations entering into the landfill body'	It is the operator's responsibility to cover the landfill with a final cap … constructed in order to restrict the amount of leachate which passes through the cap such that it does not (or can be expected to not) exceed $5\,l/m^2$/year for landfills accepting hazardous waste and $50\,l/m^2$/year for landfills accepting non-hazardous waste.	§ 31 SFS 2001:512
	The competent authority can, in special cases, permit loosening or exception of the control requirements if this is without risk of damage or negative effects on either human health or environment.	

Continued

Table 5: *Continued*

EU Landfill Directive requirement	Swedish translation	Reference
Definition of ‘sufficient attenuation capacity’ of the geological barrier	A landfill has to be located such that all leachate after the operation phase, and not collected leachate during the operation phase, passes through a geological barrier, which fulfils the following requirements: The transport time for leachate through the barrier is not to be shorter than 200 years for hazardous waste landfills, 50 years for non-hazardous waste landfills and 1 year for inert waste landfills. Comment: The bottom seal can be included in the calculation of travel time, vertical transport time as well.	§ 19 SFS 2001:512
Control of gas emissions and migration	The operator is obliged to collect gas from landfills that are filled with biologically degradable waste. Landfills and landfill cells which are not filled with waste any longer but that do not have a final cap are to be covered with a methane oxidizing layer to take care of leaking gas and prevent methane losses if the landfill is not protected with a final cover within 5 years. This is valid for all landfills regardless of whether they have a gas collection system. The methane oxidizing potential of the chosen material is to be shown either through preceding experiments [by a third party] or through genuine experiments. Landfills supplied with organic waste have to collect landfill gas. If no gas is produced, there is no need to install a gas collection system. The methane oxidizing layer put on top of a landfill awaiting final capping is not regarded as disposal if the layer has a thickness of less than 0.5 m.	§ 25 SFS 2001:512 NFS 2004:5
Acceptance criteria for landfills containing substantial amounts of organic, non-hazardous waste	Stable, non-reactive hazardous waste is not to be landfilled together with biodegradable waste.	§ 31 NFS 2004:4
Sampling of waste	prEN 14899: Characterization of waste	Appendix NFS 2004:10
Leaching limit values	C_0 with percolation test prCEN/TS 14405 L/S 10 for total release with SS-EN 12457-3.	§ 15–16 NFS 2004:10

APC, air pollution control; TOC, total organic carbon; WWT, wastewater treatment.

system (according to the legislation). An investigation of landfill gas emissions through soil covers on landfills, comprising MSW sites in Northern Sweden and Finland showed two distinct seasons for gas emissions: winter, when the soil is frozen and snow covered, and comparatively cold summers, in which spring and autumn might be included [20]. The highest methane emission rates were observed during dry summer months and cold winter months, when microbial methane oxidation was believed to be restricted by moisture deficit and low temperatures, respectively.

Leachate was collected from 148 landfills in 2002. As the landfills without leachate collection only received a fraction of the total amount of waste deposited, ca. 90% of the waste was placed at a site with leachate collection [15]. This percentage is unchanged for the year 2004. A total of about 10 million m^3 leachate was collected annually in recent years; 60% was treated in community wastewater treatment plants and the remaining 4 million m^3 was treated locally. The only requirement for leachate treatment is given as the recommendation that infiltration into a soil-based filter or a wetland without a specific outlet is not allowed (NFS 2004:5). Natural attenuation of landfill leachate, e.g. through irrigation on short rotation coppices or soil filters as well as recirculation, mostly accompanied by storage in sedimentation ponds are the dominating leachate treatment methods [15]. The favoured leachate treatment options are partly dependent on biological production and microbiological turnover rates, which are a function of temperature (among other parameters). One might expect, therefore, differences in leachate quality for the same treatment method, when comparing a landfill in the far south with a landfill in the far north, which has been found in a Norwegian investigation [21]. To the knowledge of the authors, no comprehensive summary and comparison has been made on the leachate parameters after treatment described in Table 4. The amount of leachate after operation is likely to be reduced for compliant landfills, as can be observed from Table 6.

3.2.4 Management of organic and combustible waste

The amount of organic and combustible waste landfilled has been decreasing in the last few years and explains to a great extent the reduction in landfilled amounts (compare with Fig. 1). Still, it can be expected that organic and combustible waste, which is prohibited in landfills, has been and still is landfilled in Sweden. Table 7 shows the amount of waste that has been granted exemption by the council administrative boards (taken from SNV [22]).

In 2004 there were 29 MSW incineration plants in operation in Sweden [15]. If planned incineration plants are realized by 2005, there will be an increase in the combustion capacity of 1600 ktonnes compared to 3100 ktonnes in 2003. This is expected to meet the demand for organic and combustible

Table 6: Leachate production from Swedish landfills prior to and after legislation amendment.

Leachate production as national average	370 mm
Values for Sweden (Hjelmar *et al.* [10])	250–300 mm
New legislative requirements for capped landfills	50 mm/5 mm non-hazardous/hazardous

Table 7: Amount of organic and combustible waste granted landfilling exemption (ktonnes).

Year	MSW	Other waste	Total
2002	600	990	1600
2003	535 (440)*	939 (870)*	1470 (1,300)*
2004	174	204	378

*Realized amount.

sorted waste, according to the Swedish EPA [22]. There is a lack of reliable data on the total amounts of waste produced, especially with regard to industrial waste. A different study estimates a capacity shortage for the alternative management of sorted organic and combustible waste [23]. The fraction of organic waste put into so-called 'plan reactors' (100 ktonnes in 2002) has to be accounted for in some way. The Swedish Association of Waste Management (RVF) regards these sites with advanced gas collection systems and water recirculation as a treatment method and not as deposition systems, as subsequent mining of the degraded material is 'planned' [15].

3.2.5 Changes due to other legislation

Additional waste legislation (taxes on landfilling), the prohibition of landfilling untreated waste and expanded producer responsibilities (Ordinance 1994:1205 on recycling paper, 1997:185 on packaging, 2000:208 on electrical and electronic equipment) has led to increased sorting and diverting of waste streams. This is reflected in an ascending amount of masses that are stored and sorted at waste management sites. The total amount has risen continuously from 889 ktonnes in 1995 to 1575 ktonnes (including 95 ktonnes of hazardous waste in 2002), plus an additional 800 ktonnes waiting to be supplied to incineration plants [15]. These activities produce different types of residues. A study on cell deposition of metal and sorting residues resulted in higher copper and zinc, higher sulphate and nitrate, but lower total organic carbon (TOC) and ammonium–nitrogen values in the leachate [24].

3.2.6 After-care phase

A minimum of 30 years is required for after care in Sweden (SFS 2001:512). If necessary, competent authorities can demand a prolonged period. This implies that operators have to provide for the necessary financial resources to fulfil monitoring and sampling, which is accounted for in the price for waste deposition.

4 DISCUSSION AND CONCLUSION

The inside of a municipal waste landfill can be regarded as a heterogenic, mixed, anaerobic reactor, as long as there is biodegradable material present. Parts of the organic waste fraction serve as substrate for microbial populations. The products of the microbiological activities can be found in the liquid and gaseous emissions from MSW landfills. The translation of the Landfill Directives will cause an overall reduction of the amount of landfilled waste, especially organic waste. As a consequence, a reduction of methane emissions from landfills will occur after a certain time lag. The amount of (time restricted) deposited waste and of landfilled waste incineration residues is likely to increase, totally as well as relatively. Due to the concentration of MSW to a reduced number of larger landfills with mostly gas collection systems, the environmental effects of gas emissions from landfills are regarded to be small on a total scale, according to the National Environmental Agency [19].

Dryer waste fraction will enter the landfills, as the moisture supplied by organic waste is redirected. Requirements for intermediate capping of methane oxidation, and especially final capping will further reduce water infiltration. An overall reduction in landfill emissions is to be expected. A relative change in emission ratios, i.e. carbon released through the leachate (as TOC or dissolved organic carbon) to carbon released as carbon dioxide and methane in the gas phase, can lead to relatively higher emissions through the leachate path. Dryer storage conditions and less infiltrating water will have implications on the fluxes of substances transported out of the landfill, as discussed in van Praagh and Persson [25]. The time to reach an environmentally acceptable final storage quality might be postponed, although concentrations of degradation products resulting from easily degradable carbon sources will be lower. For soluble substances such as salts, the opposite might be true, and longer contact time due to less infiltration might lead to enhanced leaching.

On an overall basis, the increase in intermediate storage and sorting activities has implications on storm water (or rather) leachate quality from the storage sites. Until a certain portion of waste is capped inside a landfill, either with other waste or with an intermediate or final cover, there is no apparent difference in storing it intermediately and storing it permanently (if it is not stored inside). This means that the collection and treatment costs for the leachate produced by this waste portion will not differ apart from the fixed cost differences in installation.

The EU Landfill Directives lead to a reduction in landfilled organic waste. In the US and Canada, both the 'dry-tomb' landfill and the 'reactor' landfill are accepted landfill technologies. Full-scale landfills are filled with primarily biologically degradable waste to function as 'bioreactors' [26]. The goal is to achieve an inexpensive, more rapid degradation of organic matter. Theoretically, this results in higher gas yields, shorter half-life periods and thus shortened after-care phases. The disadvantages are, among others, greater primary and secondary settlement problems, and the necessity of advanced gas collection and irrigation systems to maintain optimal conditions for the methanogenesis. This waste management option is included in the landfilling options of the EU Landfill Directive (1999/31/EC); however, strict restrain on water infiltration limits (such as in Sweden) might put an end to bioreactor landfilling due to a lack of moisture or prolong the necessary treatment time. Leaching limit acceptance criteria for organic waste landfills or landfills with a high content of organic waste are to be set by membership countries. Research has not focused on the environmental impacts of this form of organic waste 'treatment' compared to other 'pretreatment' methods (mechanical–biological pretreatment, incineration) and the subsequent disposal of their residues. Therefore, it remains questionable whether landfilling is outdated as a treatment method.

Emissions are to be controlled and restricted according to the EU Landfill Directives. Gas quantity and quality from compliant landfills will change. Gas production might decrease per tonne dry waste due to a lack of moisture, but possibly more gas will be captured due to tighter capping. The possibilities of using/selling the collected methane gas will depend on the resulting quality and quantity.

The question remains whether the new types of MSW landfills will be contaminant sinks or sources? What is left after the after-care phase and what can be done with it? For a discussion about landfills as carbon sinks, see Smith *et al*. [1]. Instead of the final storage quality, a term for the 'final product quality' might be more accurate.

Will landfills become more sustainable?

The EU Landfill Directives lead to a reduction in the total deposited amounts of waste. This in turn will reduce the speed with which land areas are used for disposal. It promotes separate collection or separation of wastes. Through this, certain objectives of the EU's 6th Environmental Action Program might be met (Article 8: '[…] a significant reduction in the quantity of waste going to disposal […]', [27]). The most rapidly growing pretreatment for biodegradable waste is incineration. It is likely to become the major method in the EU in the long run, especially if strict TOC limits are not accompanied by alternative limit parameters and thus do not allow other treatment methods than incineration (2003/33/EC, Annex). Waste incineration compared to landfilling is expected to give a net decrease in climate gas fluxes, as calculated by Smith *et al*. [1]. A comparative summary of different assessments of waste management options envisaged advantages of incineration compared to landfilling for MSW in Sweden [28]. In these assessments, incineration is operated with combined heat and power recovery and is favoured over landfilling, as the replaced fossil fuel's emissions are subtracted. There is an underlying paradox hidden in this method, though. Due to the high investment per tonne waste, incineration plants have an inherent 'craving' for fuel, i.e. waste, as the investment only pays off after a calculated amount of years of continuous operation. The EU waste hierarchy prefers reduction of waste before recycling (even thermal) and landfilling. As a consequence, it remains questionable whether replacement of landfill capacity by incineration in return will result in decreasing amounts of waste produced and thus to the envisaged 'more sustainable production and consumption patterns' and 'decoupling the use of resources and the generation of waste from the rate of economic growth' [27].

Methane and carbon dioxide are released faster through incineration than by landfilling and no carbon is sequestered through incineration. As a consequence, the positive environmental impact of emission reduction of climate gases due to minimization of deposited biodegradable wastes might be outweighed by increasing waste incineration. If the reduction of climate gases from landfills has to be taken seriously, future investigations should focus on the differences in emissions between landfills operating under present and future conditions, as well as on the time periods when emissions are to be expected.

Higher amounts of salts and heavy metals (measured as concentrations) deposited as MSW incineration residues could lead to higher overall emission fluxes through the leachate. As long as there are no holistic comprehensive Environmental Impact Assessments on different waste management options, it is doubtful whether the necessary pretreatment methods and future landfills will actually result in 'avoiding an increase of emissions to air, water and soil' [27]. Separate collections, recycling of packaging, incineration as a favourable pretreatment method and especially the deposition of its residues as hazardous waste lead to higher waste treatment costs. It remains questionable if these in return will result in decreasing amounts of waste produced.

The precaution principle together with a lack of knowledge on long-term emission from landfills complying with the Landfill Directives require consideration of the fact that even the 'new' landfills might become potentially contaminated sites. Remediation technology might become obligatory in the future. This is valid even for landfills still in operation, which will be closed by 2008. The long-term behaviour of wastes has to be known 'as precisely as possible' (1999/31/EC, Annex II), including not yet described toxicity and risk analyses in particular for wastes showing a threefold leaching of certain parameters compared to the limit values (2003/33/EC, Annex). Reliable, straightforward tools have to be still developed.

Only a few studies have focused on the emissions of 'old', i.e. abandoned for a long time, landfills (see e.g. Kjeldsen and Christophersen [29] in their study of leachate quality of old landfills in Denmark). To the knowledge of the authors, there are no comprehensive investigations of the cumulative remaining emission potential of these older landfills, neither for Sweden nor for any other country. In many cases these 'dumps' lack sophisticated active and often even passive barrier systems (Table 2). Until now, contaminated sites are administratively and legally disconnected from waste management in many countries, and only a few initiatives at a European level have been taken to quantify and qualify contaminated sites [30]. Today, there is no reliable, straightforward method to monitor new or old landfills. In countries such as Sweden, where emission restriction is decided on a case-by-case basis with reference to the recipient, reliable investigations of landfill emissions and their future development are a must. Studies of new, totally compliant landfills could be more intensively used for the identification of potentially hazardous old landfills. As these outnumber technically advanced landfills by far, they pose a greater potential emission risk. From a global or regional environmental protection point of view, financial resources might be allocated more efficiently through concentration on remediation and upscaling of presently operating or medium–old landfills than on the establishment of 'modern' new landfills. This more holistic approach is necessary to enable a net gain for the regional and global environment alike.

Although the implementation of the EU Landfill Directives is likely to have positive environmental effects, there is still an urgent need for research on certain possible consequences. Research in the European landfill sector towards more sustainable waste management should take into account:

- The development of reliable monitoring tools, which enable the estimation of a landfill's emission potential over a long time scale.

- The definition of the 'after-care phase' length for different types of landfills with respect to 'final storage quality' and the hydrological prerequisites. The possible risk of postponing high emission phases of 'new landfills' beyond the technical after-care-phase.
- The environmental impact of pretreatment options, including the leachate and gas emissions produced and including the landfilling of their residues, compared to untreated landfilling.

Without the above proposed tools and calculations, the remaining questions on the impact of altered landfilling conditions and waste compositions on the long-term behaviour and emission potential of landfills cannot be answered properly. An uncertainty prevails whether the EU Landfill Directives' objectives can actually be met for the 'whole life cycle' of a landfill and thus whether landfills as well as waste management as such will become sustainable. This is especially true for countries such as Sweden, where the national translation of the EU Landfills Directives leads to significantly different storage conditions.

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REFERENCES

[1] Smith, A., Brown, K., Ogilvie, S., Rushton, K. & Bates, J., *Waste Management Options and Climate Change*, Final report to the European Commission, Final Report ED21158R4.1, Office for Official Publications of the European Communities: Luxembourg, 2001.

[2] Anonymous, Report for DGXI, *Options to Reduce Methane Emissions (Final Report)*, AEAT-3773, Issue 3, 1998.

[3] Eurostat, *Treatment of Municipal Waste*. Eurostat/New Cronos, http://europa.eu.int/

[4] Estrela, T., Marcuello, C. & Iglesias, A., *Water Resources Problems in Southern Europe—An Overview Report*, Topic Report No. 15/1996, 1996.

[5] Austrian EPA, Federal Statistic on Contaminated Areas, http://www.umweltbundesamt.at/umwelt/altlasten_start/statistik/, 2003.

[6] Perz, K., *Waste Generation, Treatment and Recovery and Disposal in Austria* (Aufkommen, Verwertung und Behandlung von Abfällen in Österreich, Materialien zum Bundes-Abfallwirtschaftsplan 2001, in German), Federal Environmental Agency-Umweltbundesamt GmbH, Monographien Band 138, Klagenfurt, Austria, 2001.

[7] Danish Environmental Ministry, *Waste Statistics 2002* (Affaldsstatistik 2002, in Danish), Orientering fra Miljøstyrelsen, Miljøministeriet, http://www.mst.dk, 2003.

[8] German EM, Contaminated sites—situation and mitigation procedures, http://www.bmu.de/, German Environmental Ministry, 2003.

[9] German EM, Provisions on cross-border waste disposal into the 10 accession countries after ratification of accession treaties, http://www.bmu.de/de/, German Environmental Ministry, 2003.

[10] Hjelmar, O., Johannessen, L.M., Knox, K., Ehrig, H.-J., Flyvbjerg, J., Winther, P. & Christensen, T.H., *Management and Composition of Leachate from Landfills*, Final Report for the Commission of the European Communities, DGXI A.4, Waste 92, VKI: Hørsholm, Denmark, 1994.

[11] RVF, *Waste Management in Sweden 2003*, The Swedish Association of Waste Management (RVF), http://www.rvf.se, 2003.

[12] Swedish EPA, *Waste Management/Household Waste* (Avfallsteknik/hushållsavfall, in Swedish), Swedish Environmental Protection Agency, http://www.naturvardsverket.se, 2003.

[13] SCB, *National Economic Data*, Swedish Statistical Database, http://www.scb.se, 2003.

[14] Brandt, M., Eklund, A. & Westman, Y., *Snow in Sweden, Snow Depth and Water Content in Snow* (in Swedish), Fakta nr. 2, Swedish Meteorological Institute (SMHI): Stockholm, Sweden, 1999.

[15] RVF, *Waste Management Sites with Landfilling, Statistics 2002* ('Avfallsanläggningar med deponering, statistic 2002', in Swedish), RVF report 203:8, The Swedish Association of Waste Management (RVF), ISSN 1103-4092, 2003; RVF, *Swedish Waste Management 2003, 2004, 2005*, The Swedish Association of Waste Management (RVF), www.rvf.se.

[16] SNV, *Governmental Request—Map of Municipal Waste Management Plans* (Regeringsupp drag—kartläggning av hur kommunerna planerar att omhänderta sitt avfall, in Swedish), Swedish Environmental Protection Agency: Stockholm, 2000.

[17] Öman, C., Malmberg, M. & Wolf-Watz, C., *Manual for Characterization of Leachate* (Handbok för lakvattenbedömning, in Swedish), RVF report 00:7, IVL, Swedish Environmental Institute: Stockholm, 2000.

[18] Kruempelbeck, I. & Ehrig, H.-J., Long-term behaviour of municipal solid waste landfills in Germany, Sardinia 99, *Proc. of the Seventh International Landfill Symposium*, CISA, Cagliari, Italy, I, pp. 27–36, 1999.

[19] SNV, *Evaluation of the Consequences of the Landfill Directive's Implementation* (Utvärdering av genomförandet av deponeringsdirektivet, in Swedish), Dnr NV 641-592-02, Swedish Environmental Protection Agency: Stockholm, 2003.

[20] Maurice, C. & Lagerkvist, A., LFG emission measurements in cold climate conditions: seasonal variations and methane emissions mitigation. *Cold Regions Science and Technology*, **36**, pp. 37–46, 2003.

[21] Roman, E. & Haarstad, K., North-south gradient in leachate quality in Norway, Sardinia 2003, *Proc. of the Ninth International Landfill Symposium*. CISA, Cagliari, Italy, 2003.

[22] SNV, *Follow Up of Landfill Prohibit* ('Uppföljning av deponeringsförbud', in Swedish), Report Nr. 5383, Swedish Environmental Protection Agency: Stockholm, 2004.

[23] Sundberg, J., *Capacity for Combustible and Organic Waste* ('Kapacitet för omhändertagande av brännbart och organiskt avfall', in Swedish), RVF rapport 1103-4092; 02:02, The Swedish Association of Waste Management (RVF): Malmö, 2002.

[24] Fällmann, A.-M., Larsson, L., Myrhede, E. & Sundberg, J., *Leachate from Special Waste, Metal Waste and Sorting Residues* ('Lakvatten från specialavfall, metal- och restavfall (MRA) och sorteringsrester', in Swedish), Report Nr. 1 2000, The Swedish Association of Waste Management (RVF): Malmö, 1999.

[25] van Praagh, M. & Persson, K.M., Estimating and predicting actual landfill emissions by flux measurements in different scales—theory and practice, manuscript, 2004.

[26] USA EPA, *Bioreactors, What is a Bioreactor Landfill*, US Environmental Protection Agency. http://www.epa.gov/epaoswer/non-hw/muncpl/landfill/bioreactors.htm, 2003.

[27] EU, Decision No. 1600/2002/EC of the European Parliament and of the Council of 22 July 2002 laying down the Sixth Community Environment Action Programme, OJ L 242/1, 2002.

[28] Sundqvist, J.O., Sundberg, J., Granath, J., Olofsson, M. & Ljunggren Söderman, M., Synthesis of system analyses in waste management—environmental aspects (in Swedish), IVL, Stockholm Environmental Institute, 2001.

[29] Kjeldsen, P. & Christophersen, M., Composition of leachate from old landfills in Denmark, Sardinia 99, *Proc. of the Seventh International Landfill Symposium*, CISA, Cagliari, Italy, II, pp. 105–112, 1999.

[30] Prokop, G., Schaman, M. & Edelgaard, I., *Management of Contaminated Sites in Western Europe*, Topic Report No. 13/1999, European Environmental Agency: Copenhagen, 2000.