A new economic instrument for financing accelerated landfill aftercare*

R P Beaven[1], K Knox[2], J R Gronow[3], O Hjelmar[4], D Greedy[5] and H Scharff[6]

[1]University of Southampton, Faculty of Engineering & the Environment, Highfield, Southampton, SO17 1BJ, UK
[2]Knox Associates (UK) Ltd, Mapperley Park, Nottingham, NG3 5BB, UK; and Visiting Professor at[1]
[3]Centre for Environmental Policy, Imperial College London, South Kensington, London, SW7 1NA, UK
[4]DHI, Agern Allé 5, 2970 Hørsholm, Denmark
[5] ISWA Landfill Group, 34 Birmingham Road, Ansley, Nuneaton, CV10 9PS, UK
[6]NV Afvalzorg Holding, Nauerna 1, Assendelft,1566 PB, The Netherlands

ABSTRACT: The key aspects of landfill operation that remain unresolved are the extended timescale and uncertain funding of the post-closure period. This paper reviews the topic and proposes an economic instrument to resolve the unsustainable nature of the current situation. Unsustainability arises from the sluggish degradation of organic material and also the slow flushing of potential pollutants that is exacerbated by low-permeability capping. A landfill tax or aftercare provision rebate is proposed as an economic instrument to encourage operators to actively advance the stabilization of landfilled waste. The rebate could be accommodated within existing regulatory and tax regimes and would be paid for: (i) every tonne of nitrogen (or other agreed leachate marker) whose removal is advanced via the accelerated production and extraction of leachate; (ii) every tonne of non-commercially viable carbon removed via landfill gas collection and treatment. The rebates would be set at a level that would make it financially attractive to operators and would encourage measures such as leachate recirculation, in situ aeration, and enhanced flushing. Illustrative calculations suggest that a maximum rebate of up to ~€50/tonne MSW would provide an adequate incentive.

---

* NOTICE: this is the author's version of a work that was accepted for publication in Waste Management. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Waste Mangement, Vol 34 Issue 7 (2014), pp1191–1198
DOI:10.1016/j.wasman.2014.03.024

1. INTRODUCTION

Landfill continues to be the mainstay of waste management in many countries and is likely to remain so for several decades. It is recognised as being one of the main technologies that provides a route for the storage of materials in sinks rather than dispersion of materials or their degradation products into the wider environment (Scharff, 2012; Brunner, 2013). Even in regions that are trying to minimise landfill, such as the European Union, landfill may continue to be needed for 10% to 20% of municipal, commercial and industrial non-hazardous waste, either directly or for residues from pre-treatment processes. The volume of wastes present in existing landfills is estimated to be 7 billion tonnes of non-hazardous waste landfilled over a 7 year period between 2004 and 2010 in 27 Countries of the EU (EuroStat, 2013) and 1.4 billion tonnes of MSW alone landfilled in the US between 2002 and 2011(EPA, 2013). This indicates that the perception that societies no longer need to be concerned about landfill, its management and impacts, are misplaced. In particular, it is important that arrangements to manage the environmental impact of landfills after closure are fit for purpose, and that "a*ftercare is an inseparable element of responsible landfill management"* (Scharff and Crest, 2013).

For approximately two decades, proven engineering and operational practices have been available for containment of leachate and gas, restriction of water ingress, and extraction and treatment of leachate and gas, so that landfills have no significant impact on local air and water quality. These techniques have become standard practice in most industrialized countries. As a consequence, most aspects of the potential environmental impacts of landfills are now well controlled. The key issues that remain unresolved are the extended timescale and uncertain funding of the post-closure (aftercare) period. This is a problem applicable to most landfills, not only those that contain biodegradable waste but also a range of largely inorganic waste such as bottom ash, APC residues and treated hazardous wastes. This paper summarizes these problems and presents a proposal for an economic instrument that could resolve these two issues.

2. BACKGROUND

Over the past ~20 years, an increasing awareness has developed that the downside of the impressive containment engineering improvements is that they have created timescales of at least centuries, and possibly millenia, before landfills will reach a point where no active management, monitoring, or inputs of energy or materials are needed, to control the release of contaminants. This point is referred to as Final Storage Quality (FSQ) or Completion. Although there are slightly different interpretations of the meaning of these terms, a commonly accepted view is reflected in guidance published in the UK (Environment Agency, 2005 & 2012) which requires that to reach Completion, operators would have to demonstrate that the flux of contaminants to the environment would still be acceptable under the assumptions of, *inter alia*:

- no active management;
- failure of all engineered containment;
- attainment of hydraulic equilibrium (i.e. water or leachate levels in the site have equilibrated with water fluxes into and out of the site in the absence of active management and failure of some or all of the engineered controls);
- no functioning gas or leachate management systems.

The concept of hydraulic equilibrium is important to the technical debate about aftercare (e.g. Hall et al., 2007). During aftercare, active management and the functioning of engineered controls will result in an imposed hydraulic equilibrium, which, in many sites, will mean the majority of the waste is unsaturated. As active management (e.g. leachate pumping) is discontinued and engineered controls (e.g. the cap and/or liner) deteriorate or fail, then a new hydraulic equilibrium will be established that in many cases may involve the slow filling of the site with leachate. For Completion to occur, the regulator must be satisfied that future fluxes to the environment will be acceptable under a range of hydraulic equilibrium situations.

The long timescales needed to reach FSQ arise partly from the difficulty of achieving sufficient degradation of organic matter and partly from the slow rate of flushing of leachate pollutants that results from low permeability capping or low rainfall infiltration rates (e.g. Knox, 1990; Knox *et al*., 2005). Some technical approaches to managing each of these have been investigated but they remain underdeveloped due to lack of application at full scale. These are discussed below.

2.1 Achieving sufficient degradation

Data from closed landfills and test cells (e.g. Figure 1) show that specific gas generation rates fall fairly rapidly during the first ~10-12 years after closure to <2m^3/tonne per annum, then continue for decades at ~0.5 to 2.0 m^3/tonne per annum with a remaining gas potential from cellulose and hemi-cellulose possibly as high as ~75m^3/tonne (Knox *et al.*, 2011). The dramatic slowing of gas generation rates while so much substrate remains, even under optimised conditions, may be due to the fact that much of the degradable content is only partially accessible to bacterial exo-cellular enzymes because of the presence of the lignin matrix. Lignin is regarded as the most significant factor limiting biodegradability of lignocellulose in anaerobic digestion systems (e.g. Van Soest, 1994).

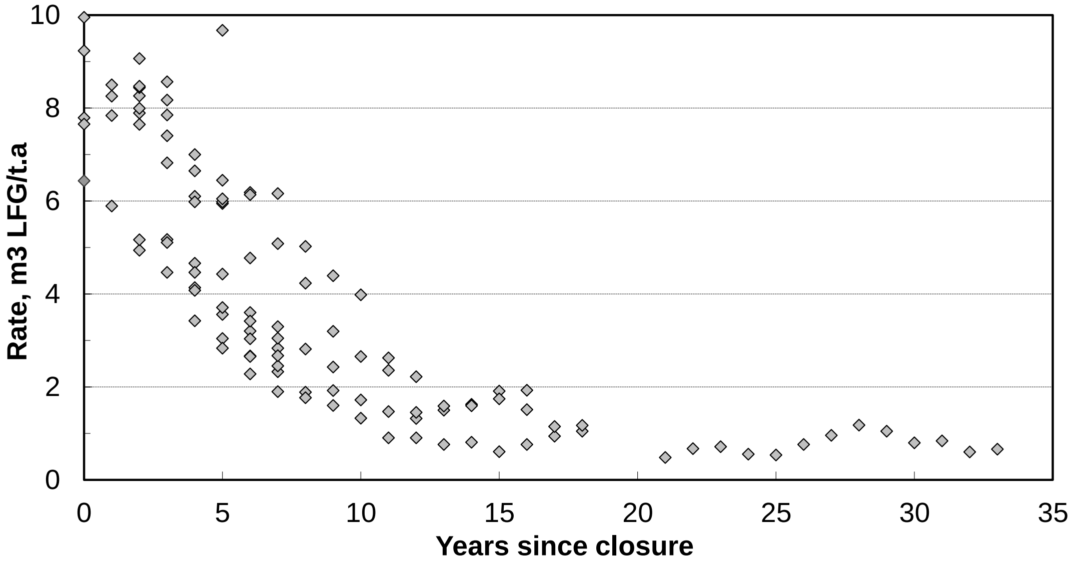

Figure 1. Gas generation rates at twenty closed landfills in Hong Kong and UK (from Knox *et al.*, 2011)

The only process that appears able to achieve any improvement on this 'tail' of the gas curve is *in situ* aeration. An accelerated carbon flux of 2 to 4 times has been reported (e.g. Heyer *et al.*, 2007) during aeration periods that are typically 4 to 6 years. These rates are reported to be accompanied by considerable reductions in leachate NH_4-N and COD concentrations. However, longer term studies of carbon fluxes are lacking and no documented full scale case studies exist that show sustained leachate improvements in typical containment landfills. One study (Oncu *et al.*, 2011) reported increases in leachate COD, BOD, NH_4-N and chloride. Uptake of this promising technology has been limited and there remains a need for full scale case studies to report quantitative data on aspects such as:

- gas generation profiles in the years following cessation of aeration;
- leachate quality profiles, especially NH_4-N, NO_2-N, NO_3-N, TKN, non-degradable (recalcitrant) COD and chloride, both during and after aeration; and
- nitrogen balance including NH_3, N_2O and N_2 in the off-gas and subsequent mineralization of organically bound nitrogen.

2.2 Flushing of soluble leachate contaminants

Test cell and lysimeter studies have shown that flushing of leachate contaminants over time often approximates to an exponential dilution curve in the short to medium term. Over longer timescales in the field, the limited evidence suggests that a simple exponential decline model may actually under predict reality (Woodman *et al.*, 2007). An unpublished (and anonymous) example is shown in Figure 2, together with a published data set for the Vestskoven ash landfill in Denmark (Hjelmar and Hansen, 2004; Beaven *et al.*, 2005). Few monitored full scale examples of flushing a landfill to anywhere near FSQ exist: none of them is the result of deliberately accelerated leaching, rather the consequences of local hydrological conditions and the absence of containment engineering.

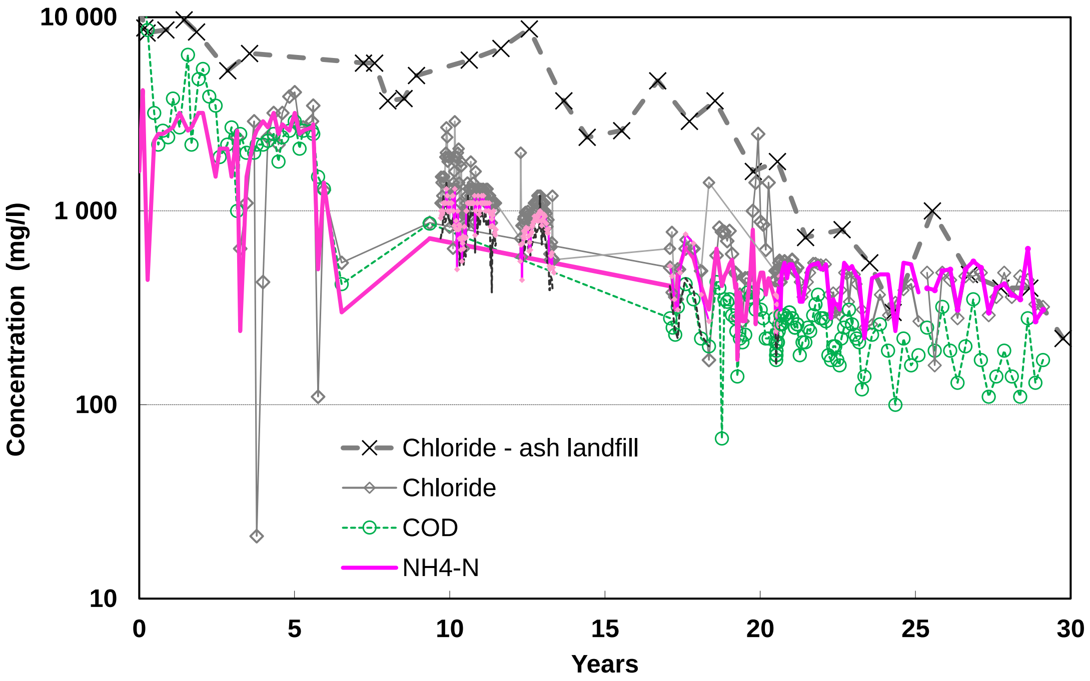

Figure 2. Leachate dilution at full scale landfills with high water inputs

Approximation to exponential behaviour could be considered as a best case and leads to a requirement for flushing by ~3-5m^3 water per tonne of waste (Walker *et al.*, 1997) to achieve the necessary 2-3 orders of magnitude dilution for NH_4-N, recalcitrant COD and chloride to reach FSQ levels. At landfills for inorganic materials, concentrations of some key pollutants, such as heavy metals, may be solubility-controlled and could take much greater volumes to flush to FSQ. At most modern engineered landfills, low permeability top covers, and/or low incident rainfall, means that this will take many centuries, unless positive measures are taken to increase the rate of flushing by adding water, or at least removing the top cover. Legislation and financial considerations both act to discourage or even prevent operators from doing this (see also Section 2.3).

2.3 Methane oxidation

Methane oxidation in top cover layers has been proposed as a means of treating the low rates of gas generation during the prolonged ‘tail’, possibly following in situ aeration. Much useful work (e.g. Huber-Humer *et al.*, 2008 and Scheutz *et al.*, 2009) has been carried out over the last ~20 years to investigate achievable rates and to clarify optimum specifications for restoration layers to maximize methane oxidation. The main factors controlling methane oxidation in landfill top covers are well understood and have led to the development of numerical models to aid design and prediction. For example, CaLMIM (Spokas *et al.*, 2011) is a diffusion controlled model that links oxidation to cover type and depth, organic content of soil, moisture and temperature. It was developed for and tested against data from Californian landfill sites, but is starting to be applied more generally. On the basis of published studies, Stegmann *et al*. (2011) suggested that a well-designed methane oxidation layer that minimises preferential pathways could be relied upon to fully oxidise up to $5m^3$ CH_4 per ha per hour. Such performance might be expected during sub-optimum conditions, which typically occur as the result of either low temperatures (winter) or low soil moisture contents. For a 10m deep column of waste, and landfill gas (LFG) at 50% CH_4, this is equivalent to a specific LFG generation rate of 0.88 m^3LFG/m^3 waste per annum. This is at the lower end of the ‘tail’ generation rates presented in Figure 1. Therefore gas generation rates during the ‘tail’ could exceed the capacity of methane oxidation layers, especially in landfills deeper than 10m.

It remains to be demonstrated by long-term, full scale studies, at what LFG emission rates methane oxidation can offer an effective passive treatment and thereby allow a landfill to be accepted as being at FSQ for gas, year in year out, winter and summer, without further intervention. For both cost and regulatory reasons, many operators would be reluctant to remove a low permeability top cover and replace it with a purpose designed, permeable methane oxidising top cover.

An alternative concept, is to route emitted gas from penetrations such as monitoring wells into purpose designed biofilter zones created at discrete points across a closed landfill surface (e.g. Streese and Stegmann, 2005; Parker *et al.*, 2013). This too is currently at the status of a promising technology, with some useful research studies behind it, but still awaits proven long term full scale case studies.

3. THE DIFFICULTY RESULTING FROM LONG TIMESCALES

Based on a goal of achieving FSQ, the most optimistic expectation for the true duration of aftercare under the status quo of landfill design and operational methods is that gas management will be required for several decades and leachate management for a century or more. Timescales that are so far in excess of 30 years (~one generation) raise two serious issues that have become of increasing concern, namely sustainability and funding.

3.1 Sustainability

Aftercare timescales beyond one generation are incompatible with sustainable development criteria. Even prior to the widespread adoption of the concept of sustainable development following the 1987 Brundtland report, a 1986 Swiss policy was introduced that materials should only be landfilled if they could reach FSQ within one generation, which was defined as 30 years (Belevi and Baccini, 1989).

Leaving behind pollution control burdens for centuries means that the majority of the pollution control activities associated with today's landfilled waste is not dealt with by the generation that created it but is instead passed on to its descendants.

Future generations are unlikely to comprehend the reasons for such flagrant lack of care when history will show that the current generation of policy makers was distinctly aware of sustainable development criteria but still drafted legislation that required containment top covers and water exclusion practices at landfills. In the EU 15 (the 15 member countries of the European Union that agreed the Landfill Directive in 1999) it appears that only Denmark has opted not to fully adopt low permeability top covers, for reasons of sustainability (Golder Europe EEIG, 2005). The moral obligation to future generations and the polluter pays principle remain valid and this should provide some impetus to changing the current set of drivers of landfill operations.

3.2 Funding uncertainty

In the majority of cases, aftercare has to be paid for by the operator of the landfill until FSQ is reached. Where the operator is a commercial company, a fund has to be generated based on setting aside a proportion of the gate fee to create a sum whose value by the time the landfill closes is equivalent to the net present value (NPV) of the long term aftercare costs. Some public bodies who run landfill sites fund aftercare from future taxes rather than from an aftercare fund, but even then it is important that they quantify the liability that will be imposed on future taxpayers.

It is difficult to determine long term costs, when the timescale extends into centuries. Amongst others, the difficulties include:

- uncertainty regarding the true hydraulic equilibrium situation;
- uncertainty regarding the quantity of water that will have to be passed through the landfill to flush out contaminants to an acceptable level (because it has never been achieved at full scale);
- the consequent unpredictability of the engineering costs of obtaining, introducing and abstracting flushing water, and of the costs of treating it prior to discharge;
- uncertainty regarding the final ~30% of the degradation curve for organic matter in landfills (with or without a period of in situ aeration) and of the point at which passive gas controls (e.g. methane oxidation layers) might be relied upon to continue working long term without further monitoring or intervention.

Even where a long term cost can be defined, there is uncertainty regarding its true NPV. The discount rate used for calculating NPVs has a significant impact, and is a topic that has been debated by social economists for over 50 years. In the 1960s and 1970s it was common for widely different discount rates to be used (Gollier, 2011). In 1972, in order to provide some consistency between the costings of different agencies, the US Government issued a directive requiring the use of a discount rate of

10%, later reduced to 7% in 1992. These levels of discount rates are now considered to be unrealistically high, but at the time represented a global optimism in the economy that did not last. Current thinking (e.g. HM Treasury, 2011; Stern, 2007) is that discount rates tend to reduce according to the period over which they extend and for periods measured in many centuries are probably less than 1% (Figure 3).

During the late 1980s and 1990s the waste industry in many countries moved rapidly towards the use of containment landfills, leading to the realisation among some that aftercare provisions would be needed for timescales measured in centuries. It is perhaps unfortunate that this occurred at a time when accepted discount rates were at unrealistically high levels which reinforced a view that deferring any spend to later years made financial sense. A panel of the UK Institution of Wastes Management (IWM, 1999) discussed how an initial environmental monitoring fee of £10,000 would, in year 50, be reduced to £35 in net present value terms, if a discount rate of 12 percent were applied. The report concluded that either regulatory or financial drivers would be required before the waste management industry started to take measures to deliberately reduce long term aftercare needs.

Currently, operators use a wide range of discount rates (which are often greater than the values in Figure 3) and of assumed aftercare periods. The impact of the range in current use is shown in Figure 4, for example the annual cost of €100,000/yr, is a fairly typical value for many recently closed landfills. For discount rates in excess of 5% there is little increase in the net present value of the total future aftercare costs (of €2M) when aftercare extends beyond 60 years. However for lower discount rates, the time at which future aftercare costs on current NPVs becomes insignificant is longer. For a discount rate of 3% this point is reached at approximately 120 years, for 2% nearer 180 years and for 1% in excess of 300 years.

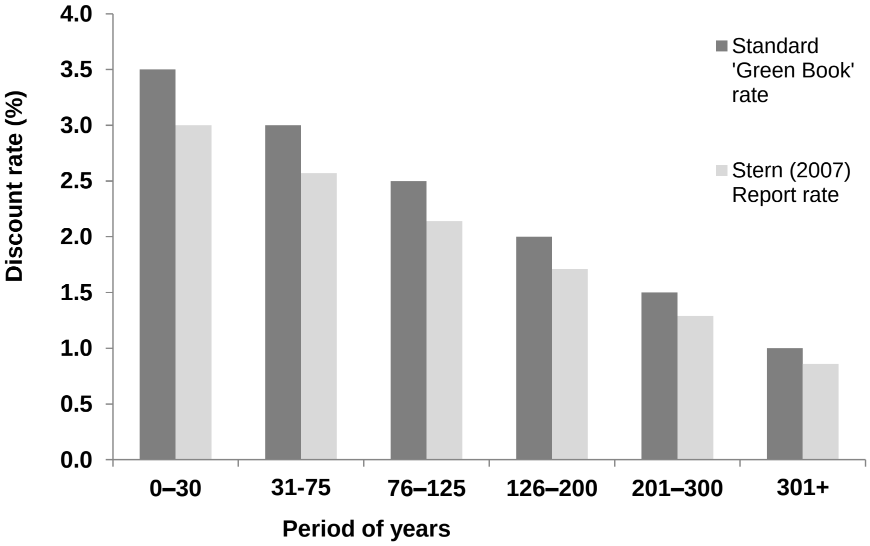

Figure 3 Variation of discount rate with period (HM Treasury, 2011)

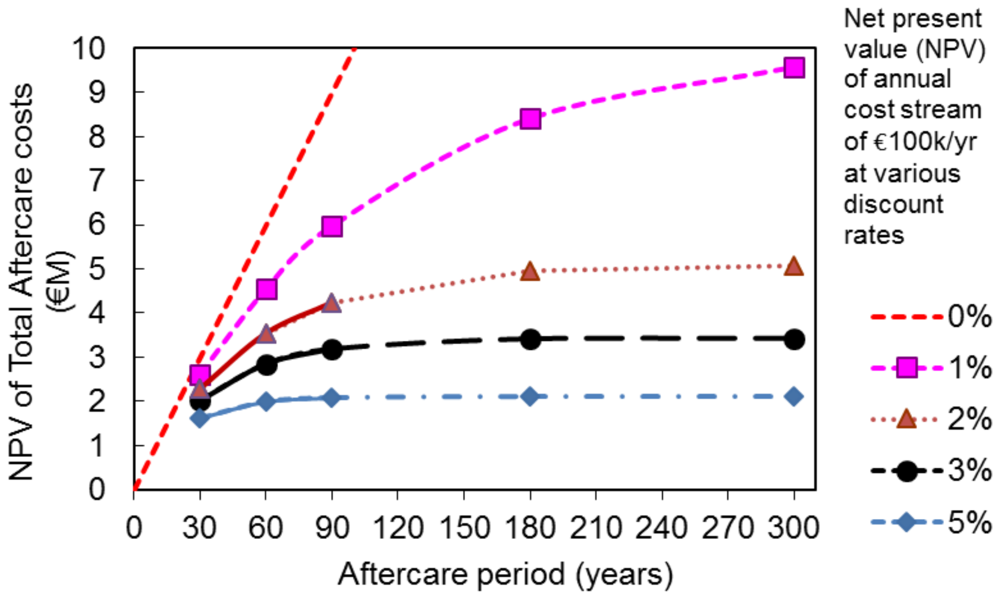

Figure 4. Dependence of NPV on aftercare period and discount rate (solid lines represent typical range of assumptions currently made by landfill operators)

For a 90 year aftercare period, the NPV in this example varies from €2M to €6M. The longer the aftercare period, the greater the range of NPV. Given that decisions on the percentage of the gate fee to set aside have to be made and adjusted throughout an operational period of typically 10-50 years, and given uncertainty over the rate of waste inputs (especially where there is a move to reduce landfilling) and of achievable gate prices, the difficulty for an operator, who is accountable to shareholders or taxpayers, is considerable. In the absence of clear guidance, it is understandable that operators lean towards high discount rates and short aftercare periods (e.g. 30 years) when calculating their funding liability. This is likely to lead to future under-funding of aftercare.

4. CURRENT APPROACHES TO MANAGING AFTERCARE

Laner *et al.* (2012) published a review of various countries' approaches to (i) the technical evaluation of when FSQ or Completion may be judged to be reached, and (ii) regulatory approaches to setting out the financial obligations of landfill operators during the aftercare period. Some approaches were based on fixed numerical standards, e.g. for waste characteristics or pollutant flux. Others were more performance based or risk assessment based.

Included in the review was an initiative referred to as the Evaluation of Post Closure Care (EPCC) Methodology (Morris and Barlaz, 2011). This envisaged a possibility that the operator might be freed from waste regulatory controls, transferring from aftercare into what the authors called Custodial Care, at some point prior to reaching FSQ: this is based on achieving a condition referred to as Functional Stability (FS), a point at which some active management and monitoring is still needed but at a *de* *minimis* level. Some aspects of the EPCC approach are similar to a risk based approach such as that used in the UK (EA, 2005; 2012). This allows prudent trimming of the intensity of controls and monitoring, as the level of risk from the landfill diminishes. However, a difficulty with the removal of waste regulatory control lies in the judgement needed to determine what can be accepted as being a *de minimis* level of risk and what additional costs may still remain, after an operator has been freed from regulatory control, given the uncertainty in characterizing deposits of waste. For this reason, it is possible that many would resist this approach, if it were based solely on the flux of contaminants, without considerations of waste pollution potential and the achievement of hydraulic equilibrium.

By and large, none of the approaches reviewed by Laner *et al.* (2012) achieved, or set out as an objective, a shortening of the time needed to reach FSQ, though some required the aftercare fund to be transferred after a fixed period to the public authority, who then take on the long term management burden. Therefore, the major issues of funding and sustainability remain unresolved.

In practice, the universal approach adopted by operators remains one of reducing the annual cost as much as possible and as soon as possible, by adopting the dry tomb approach encouraged by legislation. The risk remains that at some point in the future, funds may run out, organizations may fail and the costs will then devolve to the public purse. Neither a diffuse private-sector waste industry nor a straitened public sector waste industry can make the necessary changes towards shortening the timescales, without an effective driver, and no such driver currently exists.

A new financial incentive is proposed below, that would encourage operators to bring as much as possible of the pollution control burden forward in time by applying accelerated degradation and flushing techniques. This would promote technical and engineering development of these techniques.

5. AN ALTERNATIVE APPROACH

Here an economic instrument is described that would stimulate engineering development and widespread application of acceleration techniques. It could be accommodated within existing regulatory and tax regimes in many countries. It depends on there being a landfill tax or a financial security system, and on a portion of it being hypothecated for expenditure on a stepping up of post-closure measures beyond those an operator would currently take and/or more stringent financial securities for aftercare. In existing implementation of the Landfill Directive aftercare is often not limited to a timeframe. Nevertheless, in reality most operators provide financial security for only 30 to 60 years of aftercare. This will be insufficient for other than inert wastes, in the large majority of cases. Financial security should be for a period of time measured in centuries rather than decades. Rebates would be paid on two bases: (i) a payment for every tonne of nitrogen (or other agreed leachate marker, for example at landfills for mainly inorganic wastes) whose removal is enhanced via leachate extracted from the site (Beaven and Knox, 2000); and (ii) a payment for every tonne of non-commercially viable carbon (i.e. degradable carbon that is not economically exploitable for energy generation) removed via LFG collection and treatment. The rebates would be set at a level that would make it financially attractive for operators to implement acceleration techniques and would encourage engineering improvements of technologies such as recirculation, in situ aeration, and accelerated flushing.

Costs would be more certain, and financial provision could be calculated with greater confidence, if the bulk of the aftercare burden were brought forward to within ~20 years of closure. This might not fully achieve FSQ but it would be closer to sustainability. It might allow sites to be switched to largely passive control systems (e.g. methane oxidising soil layers for gas control and artificial wetlands for leachate treatment) at an early stage.

A driver based on a landfill tax or financial security rebate has the following major attractions.

- It provides a clear financial incentive for operators to apply acceleration methods in the shortest possible time (it will be in operators interest to recoup their rebate as early as possible).
- The system is equitable and would be applied equally to all operators.
- The cost would be passed on to customers, just like present landfill taxes and financial provisions, thereby ensuring that the polluter pays, i.e. the costs of managing the pollution potential of the wastes are borne by the people who generate the waste.
- The principle and operation of the measure is clear: there is a direct link between the cost of the measure and the benefit to society.
- Technical innovation would be encouraged, as operators seek more efficient ways of accelerating degradation, flushing sites and treating leachate.

Choice of parameters and funding level on which to base rebates

For ***accelerated flushing***, leachate nitrogen is proposed as the primary measure for calculating a rebate: nitrogen removal represents the main cost element of leachate treatment at most MSW and similar landfills; flushing of NH_4-N is widely recognized as the likely controlling parameter in reaching FSQ for leachate quality (e.g. Knox, 2005); NH_4-N and other nitrogen species are already widely monitored in regulated effluent discharges and would be simple to adopt as a reliable basis for calculating rebates.

Alternatives that could be considered are non-degradable (recalcitrant) COD and chloride. This might become desirable in any case if in situ aeration proves to have achieved a significant reduction in NH_4-N.

For landfills that receive predominantly inorganic wastes (e.g. some hazardous waste landfills) it is likely that some other parameter, such as sulphate or perhaps one of the heavy metals, may be the component that dictates the flushing requirement. For some of these, leachate concentrations are controlled mainly by solubility rather than by availability (contrasting with NH_4-N and chloride at MSW landfills) and further work is needed to characterize the long term flushing behaviour of such sites. Economic instruments might have to be modified for such sites.

The rebate should be based on the cost of flushing and treating the potential pollutants from landfills, with a premium to provide the financial incentive and to cover uncertainties. Table 1 shows an indicative calculation of how the leachate rebate could be set for a MSW landfill, based on the amount of nitrogen actively removed from the site.

Table 1. Calculation of indicative tax rebate for accelerated flushing of leachate

	Value	**Unit**
Calculate level of rebate to be attractive to operators		
Cost of basic biological treatment (N/DEN[1]/BOD removal)[2]	7	€/kgN
Cost for installation, operation and maintenance of flushing infrastructure[3]	2	€/m^3 leachate
Estimated flushing volume required to reach Completion[4]	3	m^3/t MSW
∴ lifetime cost for installation, operation and maintenance of flushing infrastructure	6	€/t MSW
Releasable nitrogen via leachate, for MSW and equivalent wastes[5]	2	kgN/t MSW
Cost for installation, operation and maintenance of flushing infrastructure[3]	3	€/kgN
Combined cost for flushing and treatment	10	€/kgN
Suggested level of rebate to allow for uncertainty, profit etc.	15	€/kgN
Potential liability to tax authority (per tonne MSW):		
Releasable nitrogen via leachate, for MSW and equivalent wastes[5]	2	kgN/t MSW
Cost of rebate at proposed level per tonne of MSW	30	€/t MSW

[1] N/DEN = nitrification/denitrification

[2] based on the authors' extensive experience of designing and operating biological leachate treatment plants

[3] costs based on authors' estimates

[4] based on the flushing of 7 bed volumes (Knox, 1990) with a bed volume ~40%

[5] Beaven and Walker (1997); Ehrig and Scheelhaase (1993); Heyer and Stegmann (1995)

Table 2. Calculation of indicative tax rebate for acceleration of degradation

	Low cost	**High cost**	**Unit**
Calculate level of rebate to be attractive to operators			
Cost of in situ aeration (Heyer *et al.*, 2007)[1]	1	3	€/m^3 waste
Aeration period	3	3	years
Assume equivalent LFG emission rate achieved during aeration	4	2	m^3 LFG/t.a
Equivalent LFG released over 3 year aeration period	12	6	m^3 LFG/t
Carbon content of 3 year gas release [12gC per 22.4 litres]	6.4	3.2	kgC/t
Assumed in situ density of waste at time of aeration	1.3	1.3	t/m^3
Cost of in situ aeration, per tonne of carbon released	120	718	€/tC
Proposed rebate, allowing for uncertainties in performance etc.	500	500	€/tC
Potential liability to tax authority (per tonne MSW):			
Remaining gas potential at start of rebate period (start of ‘tail’)[2]	75	75	m^{3}LFG/t MSW
Carbon equivalent of gas in 'tail' [12gC per 22.4 litres]	40	40	kgC/t MSW
Cost if rebate claimed at proposed rate for whole of 'tail'	20	20	€/t MSW

[1] Heyer et al (2007) quoted 0.5-1.0 €/m^3 under favourable conditions to 2-3€/m^3 under unfavourable conditions for equipment and 3 years operation

[2] Value for remaining gas potential in ‘tail’ taken from Knox et (2011)

For degradation, carbon release of non-commercially viable carbon measured in collected gas emissions is proposed as the primary measure of accelerated degradation. Table 2 shows an indicative calculation of how the rebate per tonne of carbon released could be set. It uses high and low values for the costs of acceleration by *in situ* aeration, and for the degree of acceleration achievable, based on the limited information in the public domain. The table also shows what the potential rebate liability might be to the landfill tax authority if all of the poorly degradable carbon in the ‘tail’ of the gas curve were released and claimed for.

It would be necessary to define a threshold at which sites became eligible to claim the degradation rebate: it would be counter-productive to pay rebates until sites have reached the point where it is uneconomical for the operator to generate electricity from landfill gas (i.e. they already have a commercial incentive to accelerate anaerobic degradation, up to a point). Stegmann *et al.* (2011) reported a whole site generation rate of 25m^{3}CH$_4$/hour as a criterion below which sites might be classed as entering a passive management phase. This rate was proposed partly on the basis of the capability of methane oxidizing soil layers. Currently this is also the approximate lower limit for the commercial viability of electricity generation. It may therefore be a suitable threshold for eligibility of the rebate.

Hupe *et al.* (2013) reported that a further benefit of encouraging operators to oxidise carbon *in situ* is its value in terms of carbon capture and abatement of GHG emissions. They estimate that the cost of *in situ* aeration of every m^3 of landfilled waste is ~€ 1 and results in a saving of ~100kg CO_2 equivalent per m^3, due to reduced fugitive methane emissions. The abatement costs of landfill aeration are hence approximately €10 per tonne CO_2 equivalent. This can be compared with cost estimates for CO_2 capture and storage at a range of industrial processes (Rubin *et al.*, 2012): these costs range from 30 to 150 USD/tCO_2 avoided (~€20 to €110/tCO_2 avoided). CO_2 avoidance costs associated with other technologies such as photovoltaics and wind power may be as high as €200 per tonne CO_2 equivalent (Hupe *et al.*, 2013). Consequently, landfill aeration may be one of the cheapest GHG avoidance technologies available, to the extent that it oxidises what would otherwise be fugitive methane, and on this basis has been endorsed by the German Federal Environment Ministry through its 2012 climate protection programme (BMUB, 2012).

Tables 1 and 2 indicate a maximum exposure to the tax authority of €50/t, if both leachate and gas acceleration measures were implemented to the full, although in reality this is unlikely to be achieved. This level of refund of collected tax is not unreasonable in the context of landfill taxes that are generally rising across EU countries. In 2012 landfill tax rates for some types of non-hazardous wastes in Austria, Belgium, Denmark, Ireland, Sweden, and the UK were at or above €49/tonne: the 2013 tax rate is already at €75/tonne in Ireland and will be ~€90/t in the UK from April 2014 (European Commission, 2012). The highest landfill tax rates in the EU were previously seen in The Netherlands, where a rate of €108/tonne for combustible waste was applicable in 2011. However, this tax was revoked in 2012 as no revenues were being collected due to its success in preventing the landfilling of combustible wastes. A new €17/tonne landfill tax will be introduced for all wastes in April 2014.

6. DISCUSSION

The easiest application of the system we propose would be to new landfills, where a clear link could be established between landfill tax revenues raised at the site and the proportion of these used to fund accelerated remediation. The scheme would also lend itself to some large full scale trials to demonstrate its viability.

There is also an argument that this type of scheme could be applied retrospectively to old landfills. This could include recently closed sites that have made financial provisions. Retrospective funding would need to come from current landfill tax revenues so there would obviously be some restriction on the amount available for this purpose, but this has to be balanced against the potential future costs of inaction. Funding could also come from recognition that landfill aeration may be one of the cheapest carbon abatement technologies currently available (Hupe *et al.*, 2013).

In many ways, the adoption of this type of financial incentive would be most beneficial to countries that have both the gross domestic product (GDP) to support such an initiative and whose waste management policies continue to incorporate landfill to underpin other waste management technologies. This would certainly include many countries within the G-20 economies. Such a scheme encourages resource efficiency, provides a truer cost of the externalities of landfilling such that comparison with other technologies becomes more transparent and, most importantly, ensures the sustainability of landfills according to the definition that the burden of problems created today should not be passed on to future generations.

There are also strong arguments for implementing this type of scheme in Europe, even though existing waste management policy is towards minimising the use of landfills. Rapidly increasing landfill taxes to encourage diversion of waste to other technologies will not eliminate problems associated with landfills. The principles behind this proposal would have the same impact as the landfill tax, of encouraging resource efficiency and diverting waste from a long term storage option, but have the added benefit that it will start to address with the pollution legacy of landfills.

A report for the European Commission on the use of economic instruments (EIs) in waste management (European Commission, 2012) set out some general principles for the implementation of various policy options, most notably:

- *"Allowing some flexibility for Member States (MS) to implement EIs in the most appropriate way for their own particular conditions (i.e. respect of the subsidiarity principle);*
- *Ensuring an appropriate balance between regulatory instruments (e.g. targets, technical standards, bans) and EIs;*
- *Considering carefully what should be done with revenues generated from EIs;*
- *Providing a clear policy framework for the foreseeable future within which the waste management industry can operate, to allow rational investment in infrastructure;*
- *Fully taking into account the economics of the waste management sector, allowing the development of EIs to rest on rational cost analysis; A full understanding by MS of the external costs and benefits of various waste management options; and*
- *Requiring better reporting by MS on waste generally and on the use of EIs specifically."*

The use of the landfill tax to provide a mechanism to shorten the aftercare period concurs with many of the above principles. The costs associated with shortening landfill aftercare periods and reducing pollution liabilities are not excessive when compared with other waste processing and treatment options (e.g. WRAP, 2013) and are within the envelope of landfill tax levies charged in many countries.

The European Commission report (2012) considered opportunities for moving towards a common European approach for the use of EIs in relation to waste management, and recommended as the first of three main options, the use of a minimum level of landfill tax. Although it was suggested that “a reasonable minimum level for a landfill tax for untreated MSW may be around €40 per tonne” the report concluded that setting a common rate for all Member States in the EU would not be appropriate, but recommended within future rewrites of the Landfill Directive (European Council, 1999) the adoption of a common method for calculating a minimum tax level, where taxes would be more strongly encouraged in poorly performing Member States. Obtaining the required acceptance of Member States for regulations relating to tax is difficult, but there is a precedent for EU action on minimum rates of taxation, with the Energy Tax Directive (European Parliament & Council, 2003).

A less politically sensitive opportunity within the Landfill Directive (LFD) may be via its requirement regarding financial security. At present Article 10 requires only that the estimated costs for the closure and after-care of the landfill site for a period of at least 30 years from its closure are covered by the disposal price charged. Article 10 could be amended to require cover for a much longer stipulated minimum period of time (probably centuries) and specify that a common discount rate would be used, to be proposed by the Technical Adaptation Committee (Waste Framework Directive, (2008/98/EC) Article 39). Article 10 of the LFD could also include an option to allow Member States to implement less stringent financial provision regulations if they choose to adopt a landfill tax regime that covers these costs and encourages operators to shorten the timescale of aftercare via a rebate scheme.

There will inevitably be objections to the use of tax revenues to assist private and commercial landfill operators to clean up their long-term liabilities from existing sites. However, whilst these companies have undoubtedly made money out of past landfilling activities, the reality may be that many may never have properly accounted for, nor charged appropriate gate fees for, removing long term pollution loads in a short timescale, because guidance and regulation was too imprecise. Consequently, society may have benefited from these cheaper prices and it is not unreasonable that some burden for any shortfall should be borne by society. Furthermore, the uncertain financial viability of private institutions over timescales measured in centuries has already been mentioned. If these companies should fail, the burden of long term liability may come back to society anyway. It may be less costly to address this now while the institutions are still in place and infrastructure still in serviceable condition.

If, rather than simply acting as long term repositories, a major objective of landfills becomes the removal of contaminants within a relatively short period of time, to what extent might their design and operation change?

7. CONCLUSIONS

It is now widely understood that landfills create very long term pollution liabilities. However, there have been few policy initiatives anywhere which have attempted to address this problem other than by the indirect means of diverting wastes away from landfill.

The purpose of this paper is to highlight the impasse that has been reached and to stimulate debate about realistic and achievable policy initiatives that address the problem of landfill liabilities. The proposal outlined here suggests the use of an economic instrument to encourage the application and further development of rapid removal and treatment of long term contaminants in leachate and, to a lesser extent, gas. This approach should lead to technical and engineering innovation, not only in the development of cheaper and more efficient clean up technologies, but perhaps more importantly in the whole approach to landfilling

DISCLAIMER

The views expressed in this paper are those of the authors only, and are not intended to represent those of any other person or organization.

REFERENCES

Beaven, R. P. and Walker A.N. (1997). Evaluation of the total pollution load of MSW. Proceedings Sardinia 97 - Sixth International Landfill Symposium, Cagliari; Italy, CISA. Vol I: 57-71

Beaven, R.P. and Knox, K. (2000) The use of nitrogen tax as a driver towards more sustainable landfills. pp401-410 in Proceedings of Waste 2000, Coventry: The Waste Conference Ltd.

Beaven, R.P., Woodman, N. and Barker, J.A. (2005) End-member flushing models for 'saturated' waste. In proceedings of Sardinia 2005: Tenth International Waste Management and Landfill Symposium,. Cagliari: CISA.

Belevi, H. and Baccini, P. (1989) Long term assessment of leachates from municipal solid waste landfills. pages XXXIV-1 to XXXIV-8. in Vol I of Proceedings of Sardinia 1989: Second International Landfill Symposium. Cagliari: CISA.

BMUB (2013) Merkblatt Investive Klimaschutzmaßnahmen German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, http://www.ptj.de/klimaschutzinitiative-kommunen/investive_massnahmen accessed 4 March 2014

Brunner, P. H. (2013) Editorial, Waste Management and Research, **31** 10, Supplement 1-2.

Ehrig, H. J. and T. Scheelhaase (1993). Pollution potential and long term behaviour of sanitary landfills. Proceedings Sardinia 93. Fourth International Landfill Symposium. CISA vol II: 1203-1225.

European Council (1999) Directive 1999/31/EC on the landfill of waste *Official Journal L 182, 01 – 19.*

European Parliament & Council (2003) Directive 2003/96/EC restructuring the Community framework for the taxation of energy products and electricity *Official Journal L 283, 51 – 70.*

European Parliament and Council (2008) Directive 2008/98/EC on waste and repealing certain directives. *Official Journal L312, 3 – 30.*

Environment Agency (2005) LFTGN 09: Guidance on Landfill Completion and Surrender. Bristol: The Environment Agency for England & Wales.

Environment Agency (2012) How to surrender your environmental permit: The Landfill Sector (EPR 5.02) and other permanent deposits of waste. Bristol: The Environment Agency for England & Wales.

EPA (2013) Municipal Solid Waste Generation, Recycling, and Disposal in the United States http://www.epa.gov/epawaste/nonhaz/municipal/msw99.htm . [accessed 12/11/13].

European Commission (2012) Use of Economic Instruments and Waste Management Performances http://ec.europa.eu/environment/waste/pdf/final_report_10042012.pdf . [accessed 13/11/13].

EuroStat (2013) Environmental Data Centre on Waste, Waste generation and treatment statistics http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/waste_generation_management/management/disposal . [accessed 12/11/13].

Golder Europe EEIG (2005) Implementation of the Landfill Directive in the 15 Member States of the European Union. A report for The European Commission Markets Team (DG ENV.F.2 (BU-5 00/120). Report Ref: REF ENV.A.2/ETU/2004/0016. On line available from http://ec.europa.eu/environment/waste/landfill_index.htm. [accessed 05 July 2012.]

Gollier, C (2011) Pricing the future: The economics of discounting and sustainable development. Princeton University Press (http://idei.fr/display.php?a=24040 accessed 12 Feb 2014)

Hall, D.H., McDougall, J., Drury, D., Blakey, N., Braithwaite, P. and Rosevear, A. (2007) Sustainable landfill: the role of fail-safe engineering for landfill aftercare In: *Proceedings Sardinia 2007, Eleventh International Waste Management and Landfill Symposium*, Cagliari, Italy; 1-5 October, CISA.

Heyer, K.U. and Stegmann, R. (1995). The long term behaviour and residual emission potential of landfills. Proceedings of Sardinia 95 Fifth international landfill symposium. 2-6 Oct, S. Margherita di Pula - Cagliari, Italy. CISA. Vol I: 149-161.

Heyer, K-U., Hupe, K., Koop, A. and Stegmann, R. (2007) Aerobic in situ aeration of landfills: long-term experience and new developments, Paper no 723 in proceedings of Eleventh International Waste Management and Landfill Symposium, Cagliari: CISA.

Hjelmar, O. and Hansen, J.B. (2004) Towards final storage quality in landfilling: an example. In Proceedings of Waste 2004.. Coventry: The Waste Conference Ltd.

HM Treasury (2011) THE GREEN BOOK Appraisal and Evaluation in Central Government (https://www.gov.uk/) [accessed July 2013].

Huber-Humer, M., Gebert, J. and Hilger, H. (2008) Biotic systems to mitigate landfill methane emissions Waste Manag Res 26: 33-46 doi:10.1177/0734242X07087977

Hupe, K., Heyer, K-U. and Stegmann, R. (2013) Landfill aeration as a contribution for climate protection: developments and experience. In Proceedings of Sardinia 2013, Fourteenth International Waste Management and Landfill Symposium, Cagliari: CISA.

IWM (1999) The role and operation of the flushing bioreactor. Report of the Institution of Wastes Management Sustainable Landfill Working Group. Pub: IWM Business Services Ltd.

Knox, K. (1990) The relationship between leachate and gas. pp367-386 in proceedings, International Conference Landfill Gas: Energy and Environment Conference, Didcot: ETSU. ISBN 0-7058 1628-1.

Knox, K. (2005) Characterizing waste stabilization effects in the Brogborough test cells. Environment Agency research contract P1-448; ESART project no B/010. Bristol: the Environment Agency for England and Wales.

Knox, K., Braithwaite, P., Caine, M. and Croft, B. (2005) Brogborough landfill test cells: the final chapter. A study of landfill completion in relation to final storage quality (FSQ) criteria. In Proceedings of Sardinia 2005, Tenth International Waste Management and Landfill Symposium. Cagliari: CISA.

Knox, K., Cheng, K. and Hayward-Higham, S. (2011) Uncertainties in understanding and measuring the completion of waste degradation. Paper no 168 in Proceedings of Sardinia 2011, Thirteenth International Waste Management and Landfill Symposium, Cagliari: CISA

Laner, D., Crest, M., Scharff, H., Morris, J. W. F. and Barlaz, M. A. (2012) A review of approaches for the long term management of municipal solid waste landfills. Waste Management 32: 498-512.

Morris, J.W.F. and Barlaz, M.A. (2011) A performance-based system for the long-term management of municipal waste landfills. Waste Management 31: 649–662 doi:10.1016/j.wasman.2010.11.018

Öncü, G., Reiser, M. and Kranert, M. (2011) Aerobic in situ stabilization of landfill Konstanz Dorfweiher: leachate quality after one year of operation. Paper no 583 in Proceedings of Sardinia 2011, 13th International Waste Management and Landfill Symposium, Cagliari: CISA.

Parker, T., Childs, A., Pointer, P., *et al.* (2013) Lessons learned from first full size methane oxidation biofilter in the UK. In Proceedings of Sardinia 2013, Fourteenth International Waste Management and Landfill Symposium, Cagliari: CISA.

Rubin, E.S., Mantripragada, H., Marks, A., Versteeg, P. and Kitchin, J. (2012) The outlook for improved carbon capture technology. Progress in Energy and Combustion Science, 38(5) 630-671, ISSN 0360-1285, doi:10.1016/j.pecs.2012.03.003.

Scharff, H. (2012) Landfills as sinks for (hazardous) substances Waste Management & Research 30(12) 1234–1242, DOI: 10.1177/0734242X12465788.

Scharff, H., Crest, M. *et al*. (2013) Landfill Aftercare – Key Issue paper of Landfill Working Group of ISWA http://www.iswa.org/en/76/publications.html OR more specifically www.iswa.org/index.php?eID=tx_iswaknowledgebase_download&documentUid=3224 . [accessed 13/11/13].

Scheutz, C., Kjeldsen, P. *et al* (2009) Microbial methane oxidation processes and technologies for mitigation of landfill gas emissions. Waste Management & Research 27: 409-455, DOI: 10.1177/0734242X09339325

Spokas, K., Bogner, J. and Chanton, J. (2011). A process-based inventory model for landfill CH_4 emissions inclusive of seasonal soil microclimate and CH_4 oxidation. J. Geophysic. Res., vol. 116, 1–19.

Stegmann, R., Heyer, K-U. and Hupe, K. (2011) Do we have to take care of landfills forever? Paper no 747 in Proceedings of Sardinia 2011, Thirteenth International Waste Management and Landfill Symposium, Cagliari: CISA.

Stern, N., (2007) Stern Review: The Economics of Climate Change, Cambridge, UK: Cambridge University Press ISBN: 9780521700801.

Streese, J. and Stegmann, R. (2005). Potentials and limitations of biofilters for methane oxidation. In Proceedings Sardinia 2005, Tenth International Waste Management and Landfill Symposium, Cagliari: CISA.

Van Soest, P.J. (1994) Nutritional ecology of the ruminant. Cornell University Press. 476pp.

Walker, A.N., Beaven, R.P. and Powrie, W. (1997) Overcoming problems in the development of a high rate flushing bioreactor landfill. pp397-408 in Proceedings of Sardinia 97, Sixth International Waste Management and Landfill Symposium, Cagliari:CISA.

WRAP (2013) Gate fees report 2013 http://www.wrap.org.uk/content/wrap-annual-gate-fees-report (accessed 12 Feb 2014)

Woodman, N.D., Beaven, R.P. and Barker, J.A. (2007) Critique of landfill flushing prediction using exponential models. In proceedings of Eleventh International Waste Management and Landfill Symposium, Cagliari: CISA.