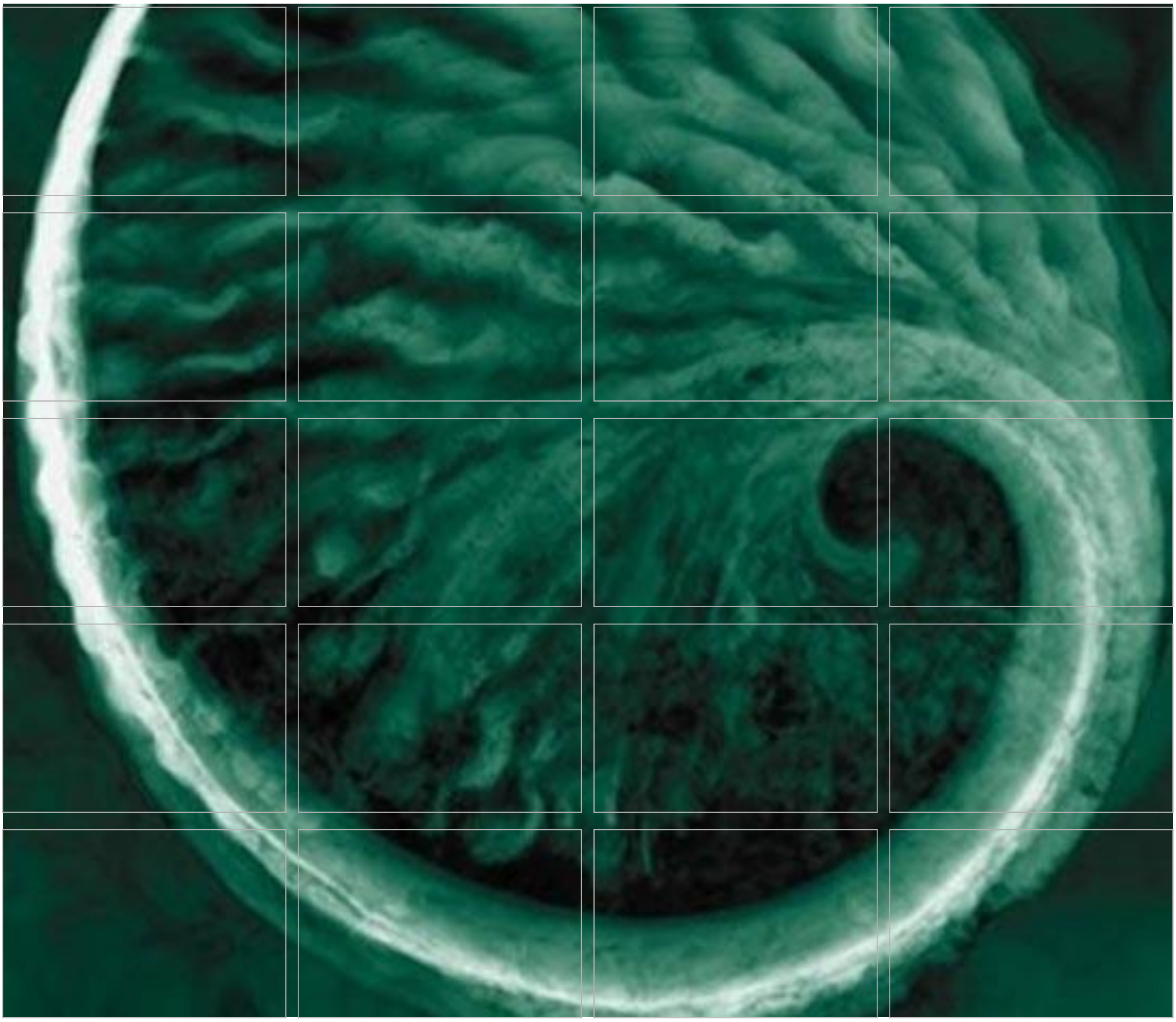

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Greenhouse Gas Impacts of Biowaste Management

Final Report

September 2011

Delivering sustainable solutions in a more competitive world

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Greenhouse Gas Impacts of Biowaste Management

Final Report

September 2011

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For and on behalf of
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2 INTRODUCTION AND BACKGROUND

Early analysis of waste-related climate change impacts focused on landfill, with less attention given to conventional alternative disposal routes. The benefits of mainstream alternatives: recycling commodity materials, such as paper; and energy recovery from thermal treatment processes, through offsetting energy and materials from fossil fuel and virgin sources, are now recognised.

The Landfill Directive requires in Article 5, the progressive diversion of biodegradable municipal waste from landfill over time. In the UK, this waste stream is largely produced by households. As a consequence, the future management of these waste streams will change substantially. There is also an increasing potential that other, non-municipal, biowastes will be diverted from landfill, in order to avert the potential release of methane (a powerful greenhouse gas), to achieve wider environmental benefits, to avoid the rising costs of landfill and the Landfill Tax, and to capture economies of scale from the co-management of waste streams. In due course, increased obligation to divert non-municipal biowastes from landfill can be expected. In some other EU countries, for example, there are bans relating to the landfilling of biodegradable waste.

Biological treatment of biowastes, through composting and anaerobic digestion, is conceptually attractive because of the opportunity of securing 'closed loop' management through the return of a product to soils. These management routes are often perceived, particularly by the public, as offering overwhelmingly positive environmental benefits, and as being delivered through small scale 'local' projects.

However, with respect to their environmental benefits, compost and digestate products differ from commodity materials, where greenhouse gas (GHG) benefit data are readily available. Assessing the benefits of substituting conventional products, such as fertilisers and soil conditioners, is difficult. Functionality, or the service delivered by the products, is also complex and uncertain. For example, the contribution to soil carbon sinks made by applying compost products, and the duration over which carbon is held, or sequestered, is difficult to quantify.

2.1 THE AIMS AND OBJECTIVES OF THIS RESEARCH

ERM and Golder Associates recently carried out a piece of work commissioned under the Defra R&D programme, entitled '*Carbon Balances and Energy Impacts and Benefits of the Management of UK Waste Streams*' (ERM, 2006b). This peer-reviewed project undertook a macro-level investigation of the energy and GHG impacts and benefits associated with alternative management routes for the predominant waste materials arising in the UK (paper & card, metals, wood, textiles, plastics, minerals, soils and various biowaste fractions).

This work pointed to areas in which there was insufficient data or information to be able to draw meaningful conclusions. For example, composting of biowastes performed relatively poorly in carbon and energy terms, but it was determined that a more sophisticated approach to assessing the fertiliser, sequestration and other benefits of compost products was required.

The overall aim of this current research project was to examine in greater detail the GHG costs and benefits of the use of the secondary products of biowaste treatment.

The programme of work was set out in a series of tasks, as follows.

1. Establish systems to be analysed.
2. Develop policy scenarios.
3. Define system characteristics.
4. Develop evidence base for modelling.
5. Modelling of greenhouse gas impacts and benefits.
6. Sensitivity testing.
7. Reporting and results dissemination.

The research was commissioned by the Defra Waste Evidence Branch as part of its wider, three year Waste and Resources Evidence Programme. The programme was developed in response to an identified need for better coordinated waste-related research in the UK.

The aim of the programme is "*to deliver a sound evidence base for better-informed policy development, implementation, monitoring and evaluation for sustainable waste management at both the national and local levels, which incorporates an effective mechanism for access to, and dissemination of, research results*".

2.2 *SOME KEY DEFINITIONS FOR READERS*

Biowaste: in the context of this assessment, 'biowaste' is assumed to comprise those fast-degrading biogenic materials, including kitchen and food wastes, green, garden and crop-derived waste materials, manures and slurries from agriculture and other wastes, such as sewage and other organic process sludges.

Carbon Sequestration: the term carbon sequestration is used in this study to denote a carbon storage sink – be it permanent, or temporary. This is important to note, as the term can mean different things to different people. For example, in the context of soil dynamics, the term sequestration implies net removal of atmospheric CO_2 by plants and its storage as soil organic matter (Lal, 2003). With regard to waste management systems, we are interested in the same principle, but are assessing plant materials that have passed through various systems, and ended up as waste products. We are interested in management systems for this waste that provide the potential to store carbon over indefinite periods, either in soil organic carbon, or in landfill. Storage timescales and permanency are discussed further in the report.

Greenhouse Gas Emissions: throughout the report there is reference to 'Greenhouse Gas Emissions' (GHG). Those GHG accounted are carbon dioxide from fossil and biogenic sources, methane (CH_4) and nitrous oxide (N_2O).

3 THE SCOPE OF RESEARCH CARRIED OUT

Following on from previous research, it was intended that this study would examine different biowaste treatment technologies and the use of different products for different purposes. This section sets out the scoping work carried out in order to inform the direction of the research, and presents the shortlist of biowaste systems and scenarios that were assessed.

3.1 INFORMING THE DEVELOPMENT OF SYSTEMS AND SCENARIOS FOR STUDY

Given the wide range of biowastes arising across industry sectors and from municipal sources, the variety of technologies available to manage them and the breadth of uses to which products can be put, there was a need to focus the research on a constrained set of waste streams, management systems and scenarios.

The objective of initial scoping tasks was to concentrate the direction of research on those wastes, treatment routes and product applications of predominant importance now and in the future. Those that are illustrative of the range of existing and future options for management were also of interest.

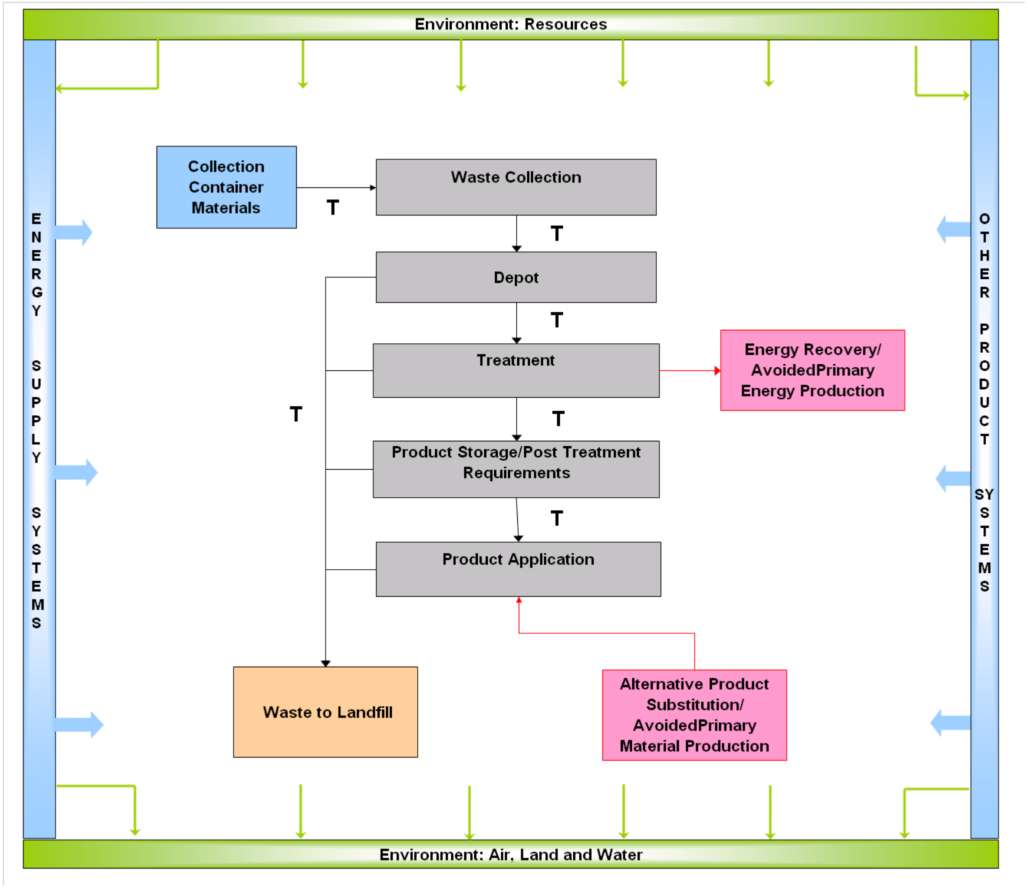
A number of means were used to inform the shortlisting of systems and scenarios for study. These included:

- **consultation with the Project Board**, involving representatives from Defra, the Environment Agency, WRAP and the Composting Association (now known as the Association for Organics Recycling);
- a **seminar for policy-makers** working across the wide range of policy fields that overlap with biowaste management considerations, such as soil protection, energy security, climate change and agriculture;
- a **workshop for stakeholders** involved in all stages of the management of biowastes and the use of secondary products; and
- a **literature review** and contact with wider stakeholders and potential data providers.

3.1.1 The Study Boundary

Figure 3.1 shows the processes and activities that should be included in a holistic, comparative assessment of different options for managing waste materials. These are contained within a boundary that encompasses all of the waste management system aspects that have been included in this study (the study boundary).

Figure 3.1 *Study boundary: activities included in the assessment of different waste management systems*



T = Transport

Note: The assessment has assumed that rejects and residues at each stage in the management chain will be sent to landfill. It is conceivable that, in a fully integrated system, some of these streams may pass on to a subsequent treatment process, such as combustion or biological treatment. However, it has not been in the scope of the assessment to investigate this possibility.

3.1.2 *Shortlisting Alternative Systems to be Analysed*

Given the limited scope of the research, and the number and combination of biowaste streams, treatment routes and products that might potentially be included, there was a need to constrain the focus of the work to enable a more thorough analysis of those systems selected for inclusion.

Waste Streams

As a first step, and in consultation with the Project Board, it was agreed that the study would concentrate on controlled waste streams, thereby discounting agricultural residues. Furthermore, given the breadth of wider work addressing sewage and other organic sludges, and given the interests of the Waste and Resources Evidence Programme, the focus of the current research would be on the biological treatment of the following waste streams:

- source-separated household green waste;

- source-separated household kitchen waste;
- the organic fraction of residual municipal solid waste (MSW); and
- commercial and industrial (C&I) food and green wastes.

Table 3.1 summarises the reasons for their inclusion.

Table 3.1 Shortlist of biowaste sources included in the assessment

Biowaste streams	Comments and considerations
Source separated green waste from municipal sources	Of specific interest in the context of Landfill Directive Article 5 targets to divert biodegradable municipal wastes from landfill. As such, management of this waste stream will change substantially in the future and increased separation is likely.
Source-separated food waste from municipal sources	Of specific interest in the context of Landfill Directive Article 5 targets to divert biodegradable municipal wastes from landfill. As such, management of this waste stream will change substantially in the future and increased separation is likely.
Food and green waste fraction of residual municipal solid waste	Of specific interest in the context of Landfill Directive Article 5 targets to divert biodegradable municipal wastes from landfill. Management of theses waste fractions will change substantially in the future and it is of interest to compare systems handling residual wastes with those managing source-separated streams.
Commercial and industrial food wastes	Increasing potential to divert this major biowaste stream from landfill to capture economies of scale from co-management with compatible municipal or agricultural wastes, and in order to avoid rising landfill costs.
Green waste from commercial and industrial sources	Increasing potential to divert this stream from landfill to capture economies of scale from co-management with similar municipal wastes, and in order to avoid rising landfill costs.

Initially, it was considered that a limited number of scenarios examining the direct application of treated sewage sludge and pulp/paper sludge to land should also be assessed, as these materials represent potential market competitors for compost products derived from municipal and C&I sources. However, treatment systems for these materials are many and varied, with product outputs differing widely in their properties. This has implications for onward management and affects interactions in the soil environment when outputs are applied to land.

With this in mind, there was concern that a simplified assessment of 'treated sludges' spread on land would fail to provide reliable estimates of GHG gas impacts and benefits and adequately enable comparison with other secondary biowaste products, for which more detailed analysis was being carried out. Furthermore, application systems for secondary sludge products are complex and unlikely to compete directly with quality compost products in the primary market applications considered in this assessment (eg food crops) - due to the constrained guidelines for application, as set out in 'The Safe

Sludge Matrix' (ADAS, 2001). As a result, these biowaste streams were not included within the scope of the assessment.

Treatment Technologies

In consultation with the Project Board, it was considered that the biological treatment routes to be assessed should include the breadth of currently available, proven technologies, including: windrow/open composting; in-vessel composting; other aerobic methods (eg aerobic biostabilisation as an element of MBT); and anaerobic digestion. Process variations, such as aerobic static piles as a variant of open composting, would be considered only where results are considered sensitive to assumptions made. The technologies assessed are shown in *Table 3.2*.

Table 3.2 Shortlist of treatment technologies included in the assessment

Treatment technologies	Comments and considerations
Windrow/ open composting	Common and proven method for the composting of separated green wastes and maturation of other bio-treatment process outputs. There are a number of process variants, primarily differing in means of aeration, degree of mechanisation and residence time. A 'typical' process (in terms of material and energy inputs, emissions, residues and products) was characterised. The degree to which this had influence on GHG balances was considered during results interpretation.
In-vessel composting (IVC)	Common and proven method for the composting of separated green, kitchen and food wastes. There are a number of process variants, primarily differing in means of aeration, degree of mechanisation, residence time (including secondary maturation) and management of emissions and leachate. A 'typical' process (in terms of material and energy inputs, emissions, residues and products) was characterised. The degree to which this had influence on GHG balances was considered during results interpretation.
Aerobic composting as a biostabilisation element of MBT systems for residual waste	Mechanical biological treatment (MBT) processes treating residual waste are many and varied, but currently only MBT processes that use enclosed aerobic composting as the biological element have been proven (in Germany, Italy and Austria) sufficiently to stabilise MSW inputs to meet Landfill Directive requirements (Juniper, 2005). It is unlikely that an MBT process based on open composting of MSW would obtain the necessary waste management licence and IPPC certification to operate in the UK (Juniper, 2005) and so a representative in-vessel process for residual wastes was characterised. The degree to which technology assumptions had influence on GHG balances was considered during results interpretation. Note that this system was assumed to produce a stabilised, compost-like output as opposed to a refuse derived fuel (RDF) for combustion. RDF-based systems were assumed to be more relevant for waste fractions with high calorific content (eg plastics, paper) and were not assessed in this study.

Treatment technologies	Comments and considerations
Anaerobic digestion (AD) for source-separated and residual (via MBT) feedstocks	Proven method for the biological treatment of organic wastes and commonly used across the EU for treating food wastes, sewage sludge and agricultural manures and slurries. Processes can also be adapted to treat residual MSW. There are a variety of specific processes in operation. Representative processes for different feedstocks (food waste, mixed food and green waste and residual waste (through MBT)) were characterised. The degree to which technology assumptions had influence on GHG balances was considered during results interpretation. A range of energy recovery potentials were considered in order to address the sensitivity of this parameter.
Combustion	Common and proven method for the thermal treatment of residual wastes. Assumptions regarding the characterisation of this treatment route drew from the recent research on carbon balances of UK waste management (ERM, 2006b).

Products and Uses

The biological treatment technologies selected for assessment (*Table 3.2*) yield a number of different secondary products. These are many and complex, and so a simplified approach to their characterisation was necessarily taken. The products (and terminologies) considered are listed below.

- **green waste compost (GWC)** – product from windrow composting of source-separated green waste;
- **green and food waste compost (GFWC)** – product from in-vessel composting of green and food waste;
- **food waste digestate (FWD)** – product from anaerobic digestion of source separated food waste (this can be either stabilised or unstabilised);
- **green and food waste digestate (GFWD)** – product from anaerobic digestion of source separated green and food waste (this can be either stabilised or unstabilised);
- **AD liquor** – liquid fertiliser product from some anaerobic digestion processes (assumed in this assessment to be a product from systems treating source separated waste with no stabilisation);
- **compost-like-output (CLO)** – product from aerobic MBT stabilisation process; and
- **digestate-like-output (DLO)** – product from anaerobic MBT stabilisation process.

With regard to product use, it was agreed that a range of applications should be assessed, as this is a key focus of the research. The need for product uses and application systems to be well-defined was identified early on. For example, field crop systems to which composts and digestates can be applied are many and varied, but each has specific implications in terms of management regime, soil interactions, substitution of alternative products and the wider benefits potentially achieved. Given this multiplicity of circumstance, a number of simple, but representative, field crop applications were defined, aimed at showing a range of potential GHG impacts and benefits.

The product types and uses shortlisted for inclusion in the study, and the reasoning behind their selection, are set out in *Table 3.3*. Product uses were selected, in part, on the basis of potential market size. This has a direct influence on the quantity of product potentially used, and therefore benefits likely to be achievable.

Whilst it was considered that a high added value, but low tonnage, product use route, such as sports turf production, might also be interesting to assess, market reports (eg Quality Protocol Technical Report, 2006; WRAP, 2005) show the potential size and growth of this market to be very small. In needing to constrain the scope of work, it was considered that resources would be better placed to inform on the potential impacts and benefits of larger volume markets for secondary products.

Table 3.3 Shortlist of product uses to be included in the assessment

Secondary product uses	**Comments and considerations**
Soil improver and fertiliser for use in arable agriculture	Direct use in arable agriculture has been identified as a key market for quality compost from source-separated biowastes (Quality Protocol Technical Report, 2006). The approach taken was to assess arable rotations, and to look to the major alternative soil types/textures in the UK. A primary reason for assessing rotations is that any benefit awarded to the biowaste product, for example with respect to yield, nutrient replacement and water consumption, will differ according to the crops grown in subsequent years following application. Arable soils were grouped into three broad categories: heavy (clayey), light (sandy) and intermediate (clay loam) and a representative crop rotation was selected for each. Assumed compost application regimes were in accordance with the constraints of the Nitrates Directive. The assumed location of application, and thus soil type/climate was East Anglia, taking account of the representation of crop type across the UK.
Top dressing to grassland	Considered of interest to assess as a potential outlet for using recovered biowaste products. Assumed application rates were limited by the application constraints of the Nitrates Directive. The assessment only considered grassland used for grazing by beef and sheep, as manure use in dairy production areas is likely to act as a barrier to the use of biowaste products. South West England and South Wales were selected as representative regions of the UK for beef and sheep grasslands. Medium and light soils were assessed - the prevalent soil types within grassland used for beef and sheep grazing in these areas.

Secondary product uses	Comments and considerations
Topsoil manufacture for land restoration activities	Use in land restoration projects is identified as a key market for quality compost from source-separated biowastes (Quality Protocol Technical Report, 2006). A potential high volume end route for biowaste products is their use in situ to create topsoil at large restoration sites. This involves the creation of a soil medium suitable for landscape establishment and applies to the installation of various types of plant materials, including grasslands and woodlands (WRAP, 2007b). It was considered that the use of biowaste products to support the planting of short rotation coppice (SRC) would serve as a suitable system for this product route. The location of application assessed was the NW of England, a region housing a high proportion of brownfield sites in the UK.
Reduced-peat growing media manufacture	Growing media manufacture is identified as a key market for quality compost from source-separated biowastes (Quality Protocol Technical Report, 2006). Given constraints regarding product specification in the horticulture industry, this product use route is not considered applicable for compost products derived from food wastes (Anne O'Brien, pers. comm.). Approximately two thirds of the growing media manufactured in the UK is supplied to the retail market (WRAP, 2003). Accordingly, this sector was selected for inclusion in the research.
Mulch product in landscaping applications	Supply of materials to operators who supply landscaping products was identified as a key market for quality compost from source-separated biowastes (Quality Protocol Technical Report, 2006). Within the UK landscaping industry, mulching is by far the largest route of application for organic materials. By volume, this application exceeds any other by more than 100% (WRAP, 2005). The use of biowaste products as mulch involves the application of material to the soil surface following planting activities, and is suitable for various types of plant materials, including trees, shrubs, herbaceous plants and bulbs (WRAP, 2007a). Trees and shrubs in particular are commonly treated with mulch and, for example, Remade Essex recently trialled the use of compost for tree planting on highway landscaping schemes as a potential high volume market (Enviros, 2003). The use of mulch derived from secondary biowaste products for tree planting was similarly considered in this research.
Landfill/ landfill cover	Disposal route for raw wastes and products considered unsuitable for use in the market applications described above. It was assumed that these wastes and products will be disposed or applied as daily landfill cover in a mixed waste landfill typical of a current PPC-permitted site.

3.1.3 *Combined Unit Systems for Comparison*

One of the key outputs of the research is an estimation of the potential GHG impacts and benefits of different biowaste management routes and product uses on a *unit basis*. To provide a definitive list of these unit comparisons, it was necessary to combine waste streams/sources, with treatment technologies and secondary product uses. It was also necessary to restrict these combinations where technologies or markets are considered unsuitable for a given waste input or product output.

A resulting list of biowaste management systems for comparison is set out below. Note that agricultural systems refer to arable agriculture.

- Source-separated green waste to windrow composting. Compost product used either as a soil conditioner in agriculture, as a landscaping mulch, for topsoil manufacture, in growing media manufacture or applied to grassland.
- Source-separated food and green waste (co-collected) to IVC. Compost product used either as a soil conditioner in agriculture, as a landscaping mulch, for topsoil manufacture or applied to grassland.
- Source-separated food and green waste (separately collected) to IVC. Compost product used either as a soil conditioner in agriculture, as a landscaping mulch, for topsoil manufacture or applied to grassland.
- Source-separated food and green waste (co-collected) to AD with energy recovery. Digestate and liquor products (unstabilised) used either as a soil conditioner in agriculture or applied to grassland.
- Source-separated food waste to AD with energy recovery. Digestate and liquor products (unstabilised) used either as a soil conditioner in agriculture or applied to grassland.
- Food and green waste fractions of residual MSW to MBT (aerobic biostabilisation). Stabilate use as landfill cover or in topsoil manufacture (only possible at brownfield sites currently).
- Food and green waste fractions of residual MSW to MBT (AD with energy recovery). Digestate use as landfill cover or in topsoil manufacture (only possible at brownfield sites currently).
- Food and green waste fractions of residual MSW to combustion with energy recovery. Bottom and fly ash residues to recycling (50%) and landfill (50%).

The relative impacts and benefits of these systems were compared against the unit disposal of raw wastes and secondary products to landfill.

A full description of each of the systems assessed is presented in *Annex A*. *Section 4* and *Annex B* go on to discuss how the potential GHG implications of each system were assessed.

3.2 *SCENARIO DEVELOPMENT*

The next task in initial scoping work was to compile a limited set of scenarios reflecting principal policy directions guiding the future management of the biowastes under study.

Policy may influence biowaste management in a number of ways, for example through the collection systems employed, and hence the quality/purity of input waste materials, or the treatment methods employed and application of products, through market development and/or fiscal instruments and legislation. It is not only policy directed at waste or resource management that influences the ways in which biowastes are managed. The management of biowaste touches on a number of policy fields, including, for example: energy security; soil protection; climate change; and water quality.

In order to identify opportunities for climate change and wider benefits, the implications of different biowaste management routes should be considered in this context. Thus, in order to inform the development of scenarios, a seminar was held to elicit views on the possible policy directions for which it would be valuable to study the carbon balance implications. A number of policy-makers from Defra's Soil, Agriculture, Climate Change and Waste Divisions were invited to attend and to inform the development of scenarios.
With regard to policy considerations for study, the main comments derived from this seminar were as follows.

- Maximising soil protection is a focus of interest.
- It should be noted that there are lots of restrictions that may place constraints on the benefits achievable from biowaste product use (eg phosphate loading/Water Framework Directive restrictions).
- Anaerobic digestion is becoming of increasing interest – with regard to the co-digestion of separated municipal wastes with agricultural manures and slurries and the digestion of food waste only. Considerations include how applicable for use are the outputs (liquid vs solid products) and the potential quantities of food waste that might feasibly be collected from municipal and C&I sources.
- There is interest in residual MSW and the implications of different treatment options.
- The use of biowastes in land restoration activities and the development of brownfield sites is becoming of increasing interest.
- Analyses should take account of the potential different impacts of centralised vs small-scale management systems.

3.2.1 *Scenario Outlines*

Taking account of the policy considerations brought to light, and an aim to 'compile a limited set of scenarios to reflect principal policy directions for the future management of the biowastes under study', *Table 3.4* sets out a number of simple scenarios for assessment. These were developed to:

- investigate the key alternatives for collection and management of green, kitchen and food waste derived from municipal and C&I sources – broadly, residual waste treatment versus source-separation;
- enable further distinction between the potential implications of separately collecting food waste materials and green wastes, versus co-mingled collections - this has an influence on the treatment methods that can be employed, product outputs and markets; and set out the principal alternative treatment routes for both source-separated and residual wastes

– broadly, biological treatment via aerobic or anaerobic methods and thermal treatment (1)

3.2.2 *Structure of Scenarios*

A further aim of this research project was to examine the GHG impacts and benefits of the use of biowaste products within the context of, and building directly upon, recent research carried out for Defra (ERM, 2006b). In order for this to be achieved, the structure of scenarios was developed to mirror those assessed in the previous research. Key considerations are set out as follows.

- Baseline waste arisings and management routes were assumed to be as for the previous research, with the exception that arisings and management data for municipal wastes were updated with 2005/06 statistics. No such update was available for C&I wastes. Baseline waste arisings and management routes assessed are presented in *Table 3.5*.
- Levels of recovery (or collection) considered 'theoretically achievable' were as for the previous research: 90% for residual waste treatment; 90% for source-separation of green waste; and 75% for source-separation of kitchen waste. These maximum limits were set based on best performance demonstrated across Europe – under the proviso that if it has been achieved elsewhere, it is 'theoretically achievable' in the UK.
- Scenarios considered the management of waste arisings over the period 2006 to 2032 (synonymous with the period 2005 to 2031 assessed in previous research).
- For each scenario, it was assumed that 2006 throughput tonnages for the target treatment route (eg windrow, AD, aerobic MBT) would increase linearly over the study period, to meet upper limits in 2032. Similarly, current treatment capacities for alternative management methods were phased out linearly over this period, wherever applicable.
- Due to the time-lag associated with the degradation of biodegradable materials in landfill and on addition to soil, committed GHG emissions (and benefits) over a period of 100 years following application to land, or disposal in landfill, were quantified on a yearly basis.
- As with previous work, with no reliable data or evidence on which to base future growth scenarios, waste arisings were assumed to remain static over the assessment period.

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(1) Considered applicable to residual wastes only.

Table 3.4 Scenario outlines

Scenario	Collection route	Treatment route	Product use
High separation and aerobic treatment (a) – separate collection	Increasing source-separation of food and green waste. Separate collection of food and green fractions.	Increasing in-vessel composting of food waste (plus green waste as required) and windrow composting of additional green waste	% to application route split by predicted market representation
High separation and aerobic treatment (b) – co-mingled collection	Increasing source-separation of food and green waste. Co-collection of food and green fractions.	Increasing in-vessel composting of co-mingled food and green waste	% to application route split by predicted market representation
High separation and anaerobic treatment (a) – separate collection	Increasing source-separation of food and green waste. Separate collection of food and green fractions.	Increasing anaerobic digestion of food waste and windrow composting of green waste	% to application route split by predicted market representation
High separation and anaerobic treatment (b) – co-mingled collection	Increasing source-separation of food and green waste. Co-collection of food and green fractions.	Increasing anaerobic digestion of co-mingled food and green waste	% to application route split by predicted market representation
High residual aerobic treatment	Collection of food and green waste fraction within residual waste. Increasing diversion from landfill for treatment.	Increasing aerobic biostabilisation (in-vessel composting as part of an MBT process)	Secondary products considered to be primarily suitable for use as daily landfill cover
High residual anaerobic treatment	Collection of food and green waste fraction within residual waste. Increasing diversion from landfill for treatment.	Increasing anaerobic digestion	Secondary products considered to be primarily suitable for use as daily landfill cover
High residual thermal treatment	Collection of food and green waste fraction within residual waste. Increasing diversion from landfill for treatment.	Increasing thermal treatment	Recycling (50%) and landfill (50%) of bottom ash. Fly ash residues to hazardous landfill

Table 3.5 Baseline arisings and management (million tonnes)

Waste fraction	Windrow Composting[1]	IVC[2]	AD[3]	MBT	Combustion	Landfill	Landspread/ recovery/ reclamation	Total
Food waste		0.3	0.0025	0.03	1.5	9.6	0.06	11.57
of which municipal food (/kitchen) waste								*5.877*
of which C&I food waste								*5.696*
Green waste	2.0	0.3	0.0025	0.03	0.9	7.2	0.001	10.45
of which municipal green waste								*6.265*
of which C&I green waste								*4.185*
Total	**2.0**	**0.6**	**0.005**	**0.06**	**2.4**	**16.8**	**0.06**	**22.02**

- Updated from ERM (2006b). ERM (2006b) further notes the considerable uncertainty surrounding estimates for C&I wastes.
- Updated sources:
  Defra 2005/06 municipal waste management statistics
  1. Composting Association (2006)
  2, 3. Composting Association (2006). Assumed input to IVC is 50% food waste and 50% green waste
- Totals may not add due to rounding

4 ASSESSMENT APPROACH: QUANTIFYING CARBON FLOWS AND GREENHOUSE GAS EMISSIONS

This assessment has focused on carbon flows and emissions of the following GHGs:

Carbon dioxide (CO_2) – CO_2 releases occur as a result of the degradation of waste during aerobic biological treatment, or combustion. CO_2 is also a component of the biogas output from anaerobic digestion, and of landfill gas. Biogas and landfill gas generally contain roughly equivalent quantities of CO_2 and methane (CH_4). When biogas is captured and combusted, the significant majority of the carbon is ultimately emitted as CO_2. CO_2 is the reference gas against which the relative global warming impacts of other gases are calculated.

Methane (CH_4) – CH_4 releases occur as a result of the degradation of biodegradable materials in an anaerobic environment. In this assessment, the global warming potential (GWP) of CH_4 has been taken to be 23. A further note on GWPs is provided in *Section 4.5.3*.

Nitrous oxide (N_2O) – agriculture accounts for around 80% of global anthropogenic N_2O emissions, predominantly associated with the application of fertilisers and manures. Their mechanism of release is complex, and influenced by a number of factors (discussed in *Annex D*). In this assessment, the GWP of N_2O has been taken to be 296. A further note on GWPs is provided in *Section 4.5.3*.

Other GHG have been shown in previous work to be of lesser concern in the comparative assessment of waste management methods (eg ERM, 2006a).

Flows of carbon and GHG through waste management systems result from:

- the manufacture of collection containers;
- the transportation of waste to and from sites (including collection);
- the use of fuel and energy in processing;
- direct releases from waste materials on processing (biological or thermal degradation);
- direct releases from treatment products (eg compost) on application to land, or for other uses;
- avoidance of GHG emissions or energy use elsewhere in the economy – for example if the need for mineral fertilisers is reduced;
- direct releases from degrading wastes on disposal in landfill; and
- accumulation of un-degraded carbon in landfill and soil.

The following sections set out how these different emissions and savings have been calculated for the different management routes assessed.

4.1 IN BRIEF: THE OVERALL APPROACH

Greenhouse gas emissions were quantified for each unit system using the following steps.

1. The ancillary inputs (kg of diesel, kWh of electricity, kg of polymer for containers, tonne-km of materials transported etc), outputs (eg tonnes of product, kWh energy, litres of wastewater to sewer) and direct GHG emissions associated with the management of wastes were determined for each treatment process and product use, drawing from literature.
2. Avoided products (kg mineral fertiliser avoided, kWh electricity recovered, etc) were calculated on the basis of product characteristics and literature evidence of their performance in use and, substitution of alternatives.
3. GHG emission factors (eg CO_2-equivalents per tonne of diesel produced and combusted, per kWh of electricity generated, per tonne-kilometre of waste transported, per kg of mineral fertiliser produced) were sourced from published life cycle inventory databases and literature.
4. The DAYCENT (1) and GasSim (2) models were used to estimate direct GHG emissions and carbon release and storage during the use of biowaste products on land, and from wastes degrading in landfill.
5. Ancillary impacts, direct process emissions and avoided burdens were multiplied by emission factors and combined to give a total net GHG balance (expressed in CO_2-equivalents).

For scenario comparisons, the net GHG emissions over time for waste collection, treatment and product use/disposal were multiplied by waste tonnages passing via each route in each year. Committed net emissions for a period of 100 years following the final use/disposal of each material were also captured. Total GHG balances for the scenarios assessed combined both emissions over the management period assessed (2006 – 2032) plus committed releases.

4.2 DESCRIBING THE PERFORMANCE OF ALTERNATIVE WASTE COLLECTION AND TREATMENT ROUTES

Of particular importance in quantifying the potential GHG implications of different waste collection and treatment routes was to understand:

- the collection requirements for different waste materials (containers and transport);
- the properties of collected wastes (eg nutrient and organic matter content, nature of organic matter);

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(1) Parton WJ, Hartman M, Ojima DS and Schimel DS (1998). DAYCENT : its land surface sub-model : description and testing. Global Planetary Change, 19, 35-48.

(2) http://www.gassim.co.uk/

- inputs to, and outputs from, treatment processes for different materials (fuel, energy requirements, emissions, products and rejects); and
- the properties of secondary products from treatment (change in nutrient content, change in quantity and nature of organic matter etc).

Annex B sets out the data used and assumptions made in quantifying these aspects for the assessment. It also details the GHG emission factors used to translate collection and treatment inputs and outputs into CO_2-equivalents.

Data describing the properties of raw wastes and treatment products are required in order to understand their likely interactions with the environment on use, or disposal in landfill. These interactions are complex and require detailed modelling in order to understand potential GHG and carbon flows (discussed further in *Section 4.3.1*).

4.3 DESCRIBING THE PERFORMANCE OF ALTERNATIVE PRODUCT USE ROUTES

The difficulty in collating data that are representative of a generic management route has been previously noted (ERM, 2006b). Earlier research has found factors such as direct process emissions from waste management facilities, fuel consumption in waste processing and transport to be of lesser importance in GHG balances (ERM, 2006a; 2006b).

Key influencing factors tend to relate to assumptions regarding the quantity and properties of materials and energy recovered via treatment processes and the uses to which they are put.

The approach taken to quantifying the impacts and benefits of different products and uses is discussed in turn for energy exports and biological treatment products.

4.3.1 Energy Exports

For processes that enable the recovery of energy from feedstock materials, the key influencing factors relate to:

- the properties of waste inputs;
- the efficiency at which carbon or energy content can be converted into usable electrical energy or heat;
- the quantity of electricity or heat available for export; and
- the alternative source of electricity/heat that the exported energy is assumed to displace – 'avoided GHG burdens'.

Annex B sets out assumptions made with respect to energy recovery and avoided burdens for each treatment technology. These are summarised in *Table 4.1*. Given the variety of technologies in operation, a range of potential performance was considered, assessing 'maximum' and 'minimum' avoided burdens through energy recovery.

For all treatment technologies, it was assumed that marginal electricity and heat sources are displaced by energy exported from waste treatment plants. Marginal electricity was assumed to comprise 100% gas (combined cycle gas turbine - CCGT) across the study period. For heat, the marginal source was assumed to be heat production in an industrial furnace.

Table 4.1 Maximum and minimum avoided burdens through energy recovery

Treatment technology	Basis of maximum/minimum avoided burdens
Anaerobic Digestion - source-separated wastes	AD systems vary widely, depending on their function and how they are operated. For example, process temperatures and timescales can be optimised either for maximum biogas yield (and subsequent conversion to energy) or maximum biodegradation of the input materials. The potential GHG implications of different AD systems are likely to differ considerably. The most important difference in this context will be with regard to energy recovery potential – and the GHG 'savings' that are credited to the digestion process. To account for the range of GHG implications, we looked to wider literature and process operators to consider reported maximum and minimum biogas yields and energy recovery. A range of 70-140 m^3 biogas yield per tonne is reported in the literature (Eunomia, 2002). To this was applied maximum and minimum conversion efficiencies, based on those quoted in the Biomass Task Force Report to Government (2005) - a minimum of 30% (electricity only) and a maximum of 80% combined heat and power (40% electricity, 40% heat). Maximum recovery values were sense checked against reported operational performances provided by Greenfinch, DRANCO and Linde for the processes assessed.
Anaerobic Digestion - residual wastes (MBT with production of digestate-like-output)	A range of energy recovery potential was modelled for the anaerobic biological stage of an MBT process, reflecting the variability of plant efficiencies. Data reported a range of 60-90 m^3 biogas yield per tonne throughput (through the digestion stage). To this was applied maximum and minimum conversion efficiencies, based on those quoted in the Biomass Task Force Report to Government (2005) - a minimum of 30% (electricity only) and a maximum of 80% combined heat and power (40% electricity, 40% heat).
Thermal treatment	Maximum and minimum energy conversion efficiencies were based on findings in the literature of approximately 8-27% for conventional incineration with steam cycle electricity generation, 40-45% for gasification with combined cycle gas turbine and up to 50-70% for combined heat and power (CHP). A minimum of 10% (electricity only) and a maximum of 70% combined heat and power (30% electricity, 40% heat) were modelled. These efficiencies were applied to the net calorific value of the food and green waste fractions of residual waste (3.5 MJ/kg and 4.2 MJ.kg respectively).

Note: Maximum avoided burdens, in particular for energy recovery, are purely theoretical, and would be practically achievable only in the framework of significant change, for example for regard to infrastructure for heating systems. Thus it is important that results are interpreted in this context.

4.3.2 *Biological Treatment Products*

The first step in attempting to quantify the potential GHG impacts and benefits of using biowaste treatment products is to define clearly how the product will be used, and what the implications are of its use. Namely:

- what are the product's transport and storage requirement prior to use?
- how much product is applied, and what are the fuel requirements to apply it?
- what happens when the product is applied to soil, or other use - how quickly does the product degrade?
- is degradation aerobic (releasing CO_2) or anaerobic (releasing CH_4) and are other greenhouse gases released (N_2O)?
- in using the product, what alternatives are avoided and what are the GHG burdens of these that can be credited to the use of the biowaste product?

Annex B sets out the data and assumptions we have used in answering these questions and defining the characteristics of each product use route. Information has been drawn from a wide range of literature sources and from personal communication with a number of experts in the field. *Table 4.2* summarises the approach taken.

Table 4.2 Characterising the implications of using biowaste treatment products

Product Use Route	**Transport and storage**	**Application regime**	**Carbon degradation on use**	**Other greenhouse gas emissions on use**	**Avoided alternative products on use**	**Other benefits of product use**
Soil conditioner for use in agriculture	A distance of 10 miles from compost producer to farm assumed. Storage on site assumed to have minimal energy requirements. No emissions from the storage of stabilised waste assumed, but an estimate of CH_4 emissions from unstabilised digestates was quantified. Fuel requirements for application are assumed to be equivalent to those assumed for manure/slurry spreading.	Frequency of application determined on the basis of product nitrogen content and the restrictions set out in the Nitrates Directive.	DAYCENT model used to quantify carbon storage and release on application of different biowaste products to different agricultural systems.	DAYCENT model used to quantify net CO_2, CH_4 and N_2O emissions on application of different biowaste products to different agricultural systems.	***Mineral fertilisers*** Estimates of nutrient replacement benefit made on the basis of the N/P/K of biowaste products and the assumed availability of those nutrients over time. Benefits of avoiding mineral fertilisers encompassed both fertiliser production and N_2O emissions from applying fertilisers. ***Lime*** Reductions in lime consumption on product use estimated from literature. ***Pesticides*** Potential reductions in pesticide use estimated from data presented in Eunomia (2002).	***Increased crop yield*** Used to encompass the wider potential benefits of using biowaste materials: soil condition; synergistic nutrient affects; and disease suppression. Estimates derived from field trials. ***Reduced irrigation*** Reductions in water consumption, and energy use for irrigation calculated on the basis that applying biowaste products would avoid the use of water to irrigate potatoes. ***Reduced tillage*** Applying compost to land improves soil structure, workability and tilth. Fuel savings of approx 20% have been estimated.

Product Use Route	Transport and storage	Application regime	Carbon degradation on use	Other greenhouse gas emissions on use	Avoided alternative products on use	Other benefits of product use
Top dressing to grassland	As above	As above	DAYCENT model used to quantify carbon storage and release on application of different biowaste products to grassland systems.	DAYCENT model used to quantify net CO_2, CH_4 and N_2O emissions on application of different biowaste products to grassland systems.	n/a	Carbon storage in soil was the only benefit of product use quantified for this use route.
Topsoil manufacture in remediation projects (coppice establishment)	A distance of 50 miles from compost producer to final point of use assumed. No on-site storage assumed (and only stabilised products used for this route). Assumed 0.2 hours of machinery use per tonne of compost is required to handle and blend materials.	Initial application of 500 t/ha plus smaller repeat applications every 5 years to coincide with coppice regime (same rates as for agricultural purposes)	DAYCENT model used to quantify carbon storage and release on application of different biowaste products to woodland systems.	DAYCENT model used to quantify net CO_2, CH_4 and N_2O emissions on application of different biowaste products to woodland systems.	Virgin topsoil avoided on a tonne-for-tonne basis. Impacts of extraction and transport avoided (data gap, but assumed to be the same as/negate the impacts of biowaste transport and handling)	None quantified (potential data gap)

Product Use Route	**Transport and storage**	**Application regime**	**Carbon degradation on use**	**Other greenhouse gas emissions on use**	**Avoided alternative products on use**	**Other benefits of product use**
Reduced peat growing media manufacture	A distance of 50 miles from compost producer to final point of use assumed. Storage not considered applicable. Manufacture of growing media assumed not differ with the use of green waste compost in place of peat, so not assessed.	Reduced peat growing media assumed to contain a maximum of 30% (w/w) green waste compost.	Simplified approach taken using an estimate that, over a 100 year time horizon, approximately 92% of carbon applied in compost will be mineralised to CO_2 (first order decay kinetics, turnover time of 40 years)	Data gap - no reliable evidence available to determine releases of CH_4 and N_2O. However, not considered to be of great significance in this system.	***Peat*** Peat is displaced on a volumetric basis. The benefits of peat displacement encompassed both avoided extraction and transport, and the avoidance of the carbon within the peat being released (assumed equivalent to fossil carbon). ***Mineral fertilisers***: Compost will replace some of the fertilisers that are added to peat-based growing media. Calculated on the basis of differences in typical media mixes.	n/a
Landscaping mulch for tree planting activities	A distance of 35 miles from compost producer to final point of use assumed. No on-site storage assumed (and only stabilised products used for this route). Fuel requirements for application are assumed to be equivalent to those assumed for manure/slurry spreading.	Assumed one-off applications of 7.5 m^3 per 100 m^2	As above	As above	Bark mulch assumed to be offset on a volumetric basis. The benefits of displacement include avoided production of bark chips and avoided transport from typical sources.	None quantified (potential data gap)

4.3.3 *Limitations in Quantifying Product Benefits*

It must be noted that, while every attempt has been made to quantify the benefits of using biowaste products for different applications, data are lacking to enable all of their perceived advantages to be included in the assessment. For example:

- The supply of crop residues, organic fertilisers and soil improvers like compost are extremely important for balancing the humus demand of the soil. A balanced humus in the soil is the basic requirement for soil fertility and sustainable agriculture. Different organic materials are different in their effectiveness to reproduce/regenerate humus, and this depends on the stability of the organic fractions of the materials as well as on quantities applied.

  The increase of humus content by compost application is well documented. We have attempted to account for the benefits of increased soil organic matter content by effects such as yield increase and reduced fuel requirements for working and irrigating the soil. However, it is likely that this does not fully capture the net benefit to the environment of maintaining soil health. For example, we have not attempted to quantify the potential of reduced susceptibility to erosion.

- When inorganic fertiliser is applied, there will be a loss of nitrogen as a leachate into groundwater and surface water. The assessment has not taken into account the potential for biowaste application to reduce these emissions when fertilisers are displaced (and the energy costs associated with water treatment to remove them). However, the benefits of product use in this context are likely to be small in comparison with total system impacts and benefits. We do not think this omission has any influence on results.

4.4 MODELLING LANDFILL IMPACTS

The landfill of raw wastes and secondary products has been used as a comparator against which alternative management routes can be assessed.

The GasSim model (1) was used to generate a profile of net CO_2-equivalents releases over a 100-year period following disposal for a unit quantity of each biowaste waste material or product.

Previous research (ERM, 2006b) considered a landfill gas capture rate of 75% over the 100-year period assessed, but acknowledged the uncertainty of this estimate, and the sensitivity of results to it. In this assessment, a maximum/minimum gas capture rate has been considered, with 50% as the lower limit and 75% the upper.

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(1) Environment Agency (2006). GasSim2 User Manual. Available at www.gassim.co.uk

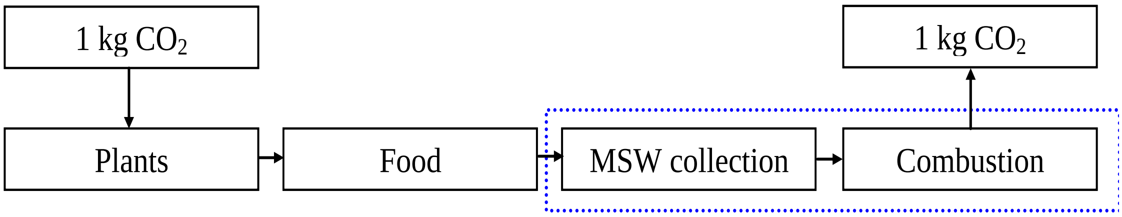
As well as forecasting gas generation, GasSim can determine the amount of degradable cellulose which has not yet undergone degradation in a given year. Of the pool of degradable carbon, not all is released as landfill gas in the year of deposition. Some remains in the landfill, stored for subsequent degradation. This pool of accumulated carbon will eventually become depleted. There is also a pool of accumulated carbon which will not be depleted over short to medium timescales, as it is unavailable for microbial degradation. Both forms have been quantified in the assessment.

4.5 *DIFFERENT APPROACHES TO ACCOUNTING FOR BIOGENIC CARBON FLOWS*

The carbon contained within food and green waste materials is often termed biogenic, or short-cycle carbon. This carbon has, in a relatively recent timescale, been taken up from the atmosphere during plant photosynthesis and growth. Subsequently, when it is degraded in an aerobic environment and released as CO_2, it has been common practice to allocate to this no GHG burden (1). The reasons for doing this, and alternative approaches that might be taken, are set out in the following paragraphs.

Consider a simplified system where plants are processed into food and combusted when entering the waste management system, instantly releasing the carbon within (*Figure 4.1*). The boundary of assessment usually applied for studies looking at waste management activities (including this one) is shown by the dotted blue line. The net GHG balance for this system is 1 kg CO_2. However, should we have chosen the boundary of the system to include food production and plant growth, then the assessment would also have accounted for the 1 kg CO_2 taken up by the plants when growing. The net GHG balance would be zero.

Figure 4.1 ***Simplified system showing waste management boundary***



In studies analysing waste management systems, a zero weight to CO_2 from biogenic sources is commonly applied in order to compensate the system for a process that we know to occur, but that is not included within the study boundary (ie in this the case uptake of CO_2 by plants). Every molecule of CO_2 has the same effect when released to the atmosphere, be it from biogenic or non-biogenic (fossil) sources. The reason for discounting is not that biogenic

(1) For example, the Environmental Agency LCA tool for waste management, WRATE, takes this approach

CO_2 does not cause impact, it stems from the need for studies to constrain their boundaries, and to account for the omissions made when they do so.

Discounting of biogenic carbon is also a form of shorthand to account for the difference in timescale for different carbon sinks. Biogenic sources feed the short-term carbon cycle, in which carbon was taken up recently by the biomass when it grew and is assumed to be in equilibrium with atmospheric releases if biomass growth is sustained. Conversely, fossil sources feed the long-term carbon cycle, which prior to combustion was stored underground in geological timeframes and hence is regarded as a net addition to the atmosphere.

When recovering energy from organic wastes, and using it to displace fossil sources, a system is credited with avoided emissions of fossil carbon. In doing this, the system will often show a net GHG benefit. Similarly, if a compost-producing system reduces the need for mineral fertilisers, we credit the system with avoiding the fossil fuel combustion that has gone in to producing these products.

Carbon accounting becomes more difficult when we look to waste management systems that offer the potential to provide a carbon storage sink. In the earlier example, we were considering a system in which the carbon cycle is complete (from uptake through to release back into the atmosphere). Where the carbon cycle is not completed, and the carbon is stored for a prolonged period within an organic material, then consideration can be given to the award of a 'carbon sequestration' benefit. Studies of timber products and wastes are a common arena for debate and consideration of carbon sequestration benefit (eg discussed in Miner (2006)).

There is much uncertainty and discussion with regard to the sequestration benefit that is attributable. Consideration needs to be given to timeframes and the biodegradability of the material. The net flow of carbon to the atmosphere is the primary parameter of interest, and so permanency of the storage sink must be considered.

To this is added the question of whether there is benefit to the environment, or to society, of storing carbon over a period of time – effectively delaying its release until later years.

Processes which sequester CO_2 in land have been shown to be significant sinks and drivers for climate models. In the UK situation this is currently a relatively small contribution: the UK GHG inventory for 2005 (NAEI, 2007) indicates that land use, land use change and forestry (LULUCF) reduces net UK GHG emissions by 0.3% (2 million tonnes CO_2-eq against a total UK emission of 657 million tonnes CO_2-eq).

The Kyoto Protocol requires that LULUCF projects result in long-term changes in terrestrial carbon storage and CO_2 concentrations in the atmosphere. However, the definition of 'long-term' varies substantially, and there is no consensus regarding a minimum time frame for project duration (1). This lack of definition has caused uncertainty to all parties involved, from regulatory bodies to project developers and investors (IPCC, 2000).

Several approaches have been proposed for accounting for temporary carbon sequestration in land use change and forestry projects (LUCF) that are implemented to offset permanent emissions of CO_2 from the energy sector. The commonly used accounting system is the 'stock change' method that the IPCC agreed to use in the implementation of LUCF projects under the Kyoto Protocol (2). An alternative is the average storage method – created to account for the carbon benefits of dynamic systems. It consists of averaging the amount of carbon stored in a site over the long term.

The accounting approach to the time frame of carbon emissions and project benefits may affect investments and project attractiveness. Projects that bring benefits at an earlier stage may be favoured by some planners, which raises the issue of time preference. Time preference relates to society's preference for benefits that accrue at an earlier rather than a later stage. In the context of climate change, time preference can be used to introduce a sense of urgency in relation to GHG emission mitigation measures.

One problem in using discounting relates to the selection of an appropriate discount rate to reflect financial (interest rates), economic, or social degrees of time preference attached to the carbon mitigation benefits of a project (or waste management system). High rates favour short-term projects, discouraging long-term sustainability and forest maintenance. Rates that are too low discourage efficiency and approaches that promote more rapid results. Discounting also favours activities that prevent the release of carbon, such as conservation or reduced-impact logging, instead of activities that actively remove carbon from the atmosphere over a longer period (eg forest establishment). A number of recent studies have argued that discount rates for climate change related impacts and mitigation should be zero or close to zero (Stern, 2006).

The practice of carbon accounting for temporary storage measures is complex and there is no general agreement on how to compare systems which store and release carbon over different timescales. The difficulty is an appreciation of future CO_2 concentrations, future adaptation, cumulative consequences of climate change and tipping points. Global climate change is now likely to occur over the next 20 years even if global GHG emissions are stabilised, due to the long time-lags involved in atmospheric systems. Therefore, for comparison of temporary carbon sequestration measures, a minimum comparison period of 20 years is suggested by many (and 40 years is typically used for forestry projects). For policy decisions, a longer term time horizon of 100 years is suggested.

(1) Several pilot projects have been conducted for a variety of time frames: from 20 to 99 years.

(2) Stock change method: the method most commonly used for expressing carbon storage, based on calculating the changes in carbon stocks of a project and its baseline during a given period of time, and measurements are usually expressed in tC/ha-1.

4.5.1 *Recent Developments in Carbon Accounting*

Since the original drafting of this report, there has been much discussion on the subject of carbon storage and delayed emissions. A number of standards and guidance documents that address carbon accounting for products and services have been developed. It is not the intention of this study to revisit the debate behind these, but the current context of these carbon accounting methods is of relevance and the approach taken in each is outlined briefly, as follows.

- The ***Publically Available Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services*** (PAS 2050) (1) was published in 2008 by the British Standards Institute, sponsored by Defra. It sets out requirements for the assessment of the life cycle GHG emissions of goods and services (collectively termed 'products'), based on LCA techniques and principles. Requirements with regard to biogenic carbon, delayed emissions and carbon storage are summarised below.
    - Biogenic carbon uptake and subsequent release are given a zero weighting (as earlier described).
    - The timeframe of the assessment is 100 years, with only the CO_2-eq impact of GHG emissions over this period included in footprint calculations. Equations are provided to enable users to take account of the weighted average amount of time that gases are present in the atmosphere over the 100-year assessment period. A benefit is given to the product system where biogenic carbon is stored - both temporarily within the 100 year period, or for longer than 100 years (*Annex F* explains this further).
- The specification is currently undergoing a review process, being informed by comments from experts that have used and tested it over the past two years. The revised PAS 2050 is to be published in summer 2011, and the following changes are anticipated in PAS 2050:2011.
    - Instead of the 'zero weighting' approach, biogenic carbon removals across the product system are to be included (with a global warming potential of -1 to signify CO_2 removal from the atmosphere) and subsequent biogenic CO_2 emissions are also to be included (with a global warming potential of 1, as for fossil CO_2). (2)
    - The timeframe of the assessment remains the same (100 years) and so the net effect of removals/emissions is the same. Biogenic carbon that is taken up, but not subsequently released

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(1) http://www.bsigroup.com/en/Standards-and-Publications/How-we-can-help-you/Professional-Standards-Service/PAS-2050/

(2) NB - food items are to be excluded from this requirement, due to the fast turnover of carbon and limited storage. The requirement to account all biogenic carbon is considered to be overly demanding in this respect.

    - .after 100 years remains as a negative credit to the system (ie a carbon storage benefit).
    - However, a key change is with respect to the treatment of temporary carbon storage within 100 years (eg as described in *Annex F*). This will be an optional, as opposed to mandatory requirement.

- The International Standards Organisation (ISO) has published, in draft form, ***ISO 14067 - Carbon Footprint of Products: Quantification and Communication.*** (1) This provides an internationally applicable standard for product carbon footprinting, based on a life cycle approach. At the time of drafting this report, ISO 14067 was some way from being finalised, but the following requirements with regard to biogenic carbon, delayed emissions and carbon storage were set out in draft:
    - both biogenic emissions and removals are to be included in the assessment (as described for the revised PAS above);
    - carbon storage/sequestration is to be reported separately;
    - no specific time period is specified, only that temporal boundaries should be reported and justified and, if the time period for end-of-life occurs over more than 10 years, emissions and removals should be reported separately.

- WRI/WBCSD has developed the ***GHG Protocol: Product Accounting and Reporting Standard*** (referred to as the Product Standard). (2) Although currently available only in draft, the final standard is expected to be published in the summer of 2011. This will be the first international standard on product carbon footprinting to provide a global methodological approach. With regard to biogenic carbon, delayed emissions and carbon storage, the following requirements are specified:
    - both biogenic emissions and removals are to be included in the assessment;
    - no time boundary is specified, only guidance given;
    - if it is known that embedded carbon within the product is not released to the atmosphere at end-of-life, a company is required to disclose and justify this in the inventory report; and
    - no temporary carbon storage credit is permitted.

- The European Commission Joint Research Centre (JRC) has produced a handbook on best practice in LCA. This, ***International Reference Life Cycle Data System (ILCD) Handbook*** provides governments and businesses with a basis for assuring quality and consistency of life cycle data, methods and assessments. With regard to biogenic carbon, delayed

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(1) http://www.ghgprotocol.org/feature/product-and-scope-3-accounting-standards-available-public-comment

(2) http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=59521

emissions and carbon storage, the following recommendations are specified.

- Both biogenic emissions and removals are to be included in the assessment (it is recommended that they are recorded separately).
- Emissions within the first 100 years are subject to the same life cycle impact assessment (LCIA) as are other inputs/outputs from the system (eg biogenic CO_2 is assigned a GWP of 1).
- Emissions beyond 100 years are not included in the general LCIA results calculation and aggregation, but are to be calculated, presented and discussed as separate LCIA results. Whilst separately recorded/calculated, these future emissions are not given a lower impact weighting.
- Any quasi-permanent storage of CO_2 is accounted for by inventorying no emissions (ie a negative credit to the system) – but only if there is 'guarantee', according to current scientific knowledge, that the substance is not emitted for at least 100,000 years.
- Temporary carbon storage is only to be included if considered necessary with regard the study's goal.

4.5.2 *The Approach Taken for This Assessment*

In this assessment, results have been calculated and presented to show the effect of using different timescales and methodological approaches to compare the GHG gas implications of different management options.

The first, time-independent scenario sets the temporal boundaries of the study to be such that all of the degradable carbon within organic materials is released within the period assessed. No carbon is assumed to be stored indefinitely and so no sequestration is credited to the system.

100 years is often used as a marker year, by which point most of the degradable material that is disposed in landfill, or applied to land, has already degraded, and the carbon remaining is of a more recalcitrant nature. A second carbon accounting approach was assessed, whereby all carbon remaining in landfill or soil after a period of 100 years was given a 'sequestration credit'. This credit equates to 3.6 (44/12) kg CO_2 per kg of carbon remaining.

Further carbon accounting approaches assessed the implications for net GHG balances should carbon sequestration credits also be applied to carbon stored over a shorter timescales: 50; 20; or 10 years. This was used as a crude means of accounting for a preference for delaying emissions. A system whereby emissions are delayed, and some carbon remains stored after 10/20/50 years, benefits from a carbon credit. The shorter the timescale accounted, the greater weight given to systems that delay emissions.

A summary of the accounting approaches taken is presented below.

- **Time-independent/no-credit scenario** - it is assumed that any carbon storage in soils/landfills is temporary and so no sequestration credits are applied.
- **100-year scenario** - a sequestration credit is given to carbon that has not degraded (and remains in soil or landfill) after 100 years.
- **50-year scenario** - a sequestration credit is given to carbon that has not degraded after 50 years.
- **20-year scenario** - a sequestration credit is given to carbon that has not degraded after 20 years.
- **10-year scenario** - a sequestration credit is given to carbon that has not degraded after 10 years.

Addendum:
Since drafting this report in 2007/08, developments in carbon accounting methods led to the publication of the PAS 2050, earlier noted. The PAS 2050 presents a method to calculate the impact of delayed GHG emissions and carbon storage, taking account of the weighted average amount of time that gases are present in the atmosphere, or carbon is stored, over a 100-year assessment period. Due to the direct relevance of this approach, and the prominence of the PAS 2050, it was decided that the PAS 2050 method should be applied retrospectively to investigate implications for the systems assessed in this study. The results of this exercise are presented in *Annex F*.

4.5.3 *Global Warming Potentials (GWPs)*

The global warming potential of a GHG is a measure of its radiative forcing effect (ie warming effect) relative to that of CO_2 (1) over a specified time period. The radiative forcing of a release of each gas will change over time as each gas is removed from the atmosphere by atmospheric processes. GWPs therefore reflect the relative (to CO_2) cumulative radiative forcing over a specified time period. Each GHG has a defined lifetime in the atmosphere which is used to calculate GWPs. GWPs can therefore be calculated for the time periods of interest.

The GWPs of CH_4 and N_2O relative to CO_2 are lower over longer time horizons, due to their shorter atmospheric lifetime and assumptions about their future atmospheric concentration relative to CO_2.

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[1] Global Warming Potential (GWP) is an index, describing the radiative characteristics of well mixed greenhouse gases, that represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. This index approximates the time-integrated warming effect of a unit mass of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide. (IPCC 2001)

Table 4.3 Direct GWPs of major greenhouse gases (IPCC 2001)

Greenhouse gas	**Atmospheric lifetime (years)**	**20 year GWP**	**100 year GWP**	**500 year GWP**
Carbon Dioxide (CO_2)	500*	1	1	1
Methane (CH_4)	12	62	23	7
Nitrous oxide (N_2O)	114	275	296	156

* Assumed value in IPCC well mixed climate models

Note – IPCC global warming potentials have been updated since the time of undertaking this analysis. For example, IPPC 2007 increases the 100-year GWP for methane to 25. The analysis has not been amended in this respect.

The International Panel on Climate Change (IPCC) recommend use of the 100 year GWP values when making policy decisions. This time horizon was chosen to help policy makers consider the longer term impact of different emission scenarios on man-made climate change in the year 2100 (ie approx 100 years from now). Therefore, it is appropriate that, when comparing different waste treatment options, the 100 year GWP is used, irrespective of the time period over which GHG gases are released.

It is important to note that GWPs are theoretical estimates of relative contributions to global warming. As such, there is a level of uncertainty associated with them. For CH_4 and N_2O, the uncertainty (95% confidence limits) is around ± 35%. This uncertainty should be borne in mind when comparing waste treatment options that release different ratios of CO_2, CH_4 and N_2O.

5 RESULTS: UNIT WASTE MANAGEMENT SYSTEMS

This section reports on the greenhouse balances calculated for the unit waste management systems assessed.

Annex D presents the outputs from DAYCENT soil modelling and GasSim landfill modelling that inform these GHG balances.

The graphs and tables following present unit process analyses for the different biowaste management systems modelled - namely **the GHG implications of managing one tonne of waste via each management route.**

Results are reported alternatively for 'food waste' and 'green waste' fractions, regardless of whether they are collected separately, jointly, or within the residual waste stream. This is for ease of comparison with previous research (eg ERM, 2006b).

There is a lack of compositional data and processing data to distinguish between food and green waste materials derived from municipal sources and those derived from commercial sources. We can infer how collection systems for municipal/commercial wastes might differ, but not what the implications for treatment processes and product characteristics might be.

As such, the potential GHG impacts of these waste streams have been calculated, and reported on, together. A representative split of municipal: commercial arisings was determined (*Table 3.5*) and collection burdens were apportioned accordingly. From the point at which waste arrives at the treatment plant (or landfill), food and green waste fractions were assumed to incur the same burdens/benefits regardless of the stream in which it arose.

Similarly, systems handling separately and co-collected food and green waste materials differ only in terms of their assumed collection burdens (containers and transport – see *Annex B* for calculation assumptions).

The GHG implications of each unit system is a balance of the following:

- ancillary GHG emissions (collection container production, transport for collection and disposal or product use, fuel and energy requirements of processing and of wastewater treatment);
- direct GHG releases from the degrading waste – either instantaneously during treatment, or as a prolonged release when applied to soil (/other use) or disposed in landfill; and
- any avoided GHG emissions associated with the displacement of alternative products, energy or fuels.

Carbon degradation profiles over a **100 year period** have been calculated for each waste and product stream and each use route (presented in *Annex D*).

These have been used to assess the potential GHG benefits of storing carbon over short to medium timescales.

A background to the different accounting methods for carbon from plant and animal-derived materials (biogenic carbon) is discussed in *Section 4.5*. In the tables presented, GHG balances have been calculated to show the difference in results under the following assumptions:

- **time-independent**, whereby it is assumed that any carbon storage in soils/landfills is temporary and so no sequestration credits are applied;
- **a 100-year time period**, whereby a sequestration credit is given to carbon that has not degraded (and remains in soil or landfill) after 100 years;
- **a 50-year time period**, whereby a sequestration credit is given to carbon that has not degraded after 50 years;
- **a 20-year time period**, whereby a sequestration credit is given to carbon that has not degraded after 20 years; and
- **a 10-year time period**, whereby a sequestration credit is given to carbon that has not degraded after 10 years.

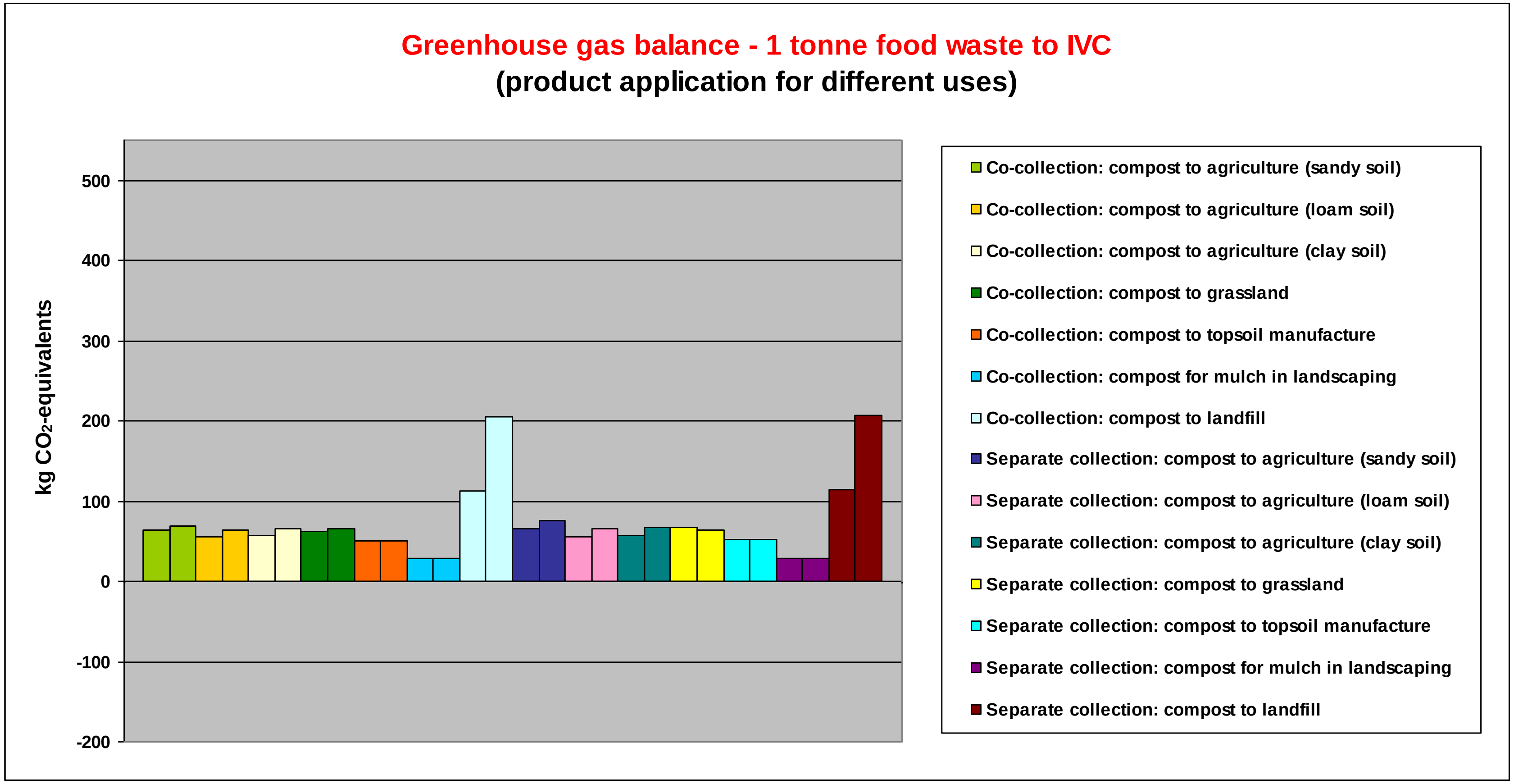
Results are grouped according to processing technology, for ease of presentation.

5.1 WASTE MANAGEMENT OPTIONS FOR FOOD WASTE

5.1.1 Source Separation: In-Vessel Composting

Figure 5.1 presents maximum and minimum GHG balances for the time-independent/no-credit carbon accounting scenario. A summary of all results for food waste composting is presented in *Table 5.1* and *Table 5.2*.

Figure 5.1 *Net greenhouse gas emissions: 1 tonne food waste to IVC: no carbon sequestration accounted*



Note: two bars are presented for each unit system, showing maximum and minimum potential emissions
Co-collection = collection with green waste

Table 5.1 Greenhouse gas balances - 1 tonne food waste to in-vessel composting (MINIMUM net emissions)

	Co-collection: compost to agric (sandy soil)	**Co-collection: compost to agric (loam soil)**	**Co-collection: compost to agric (clay soil)**	**Co-collection: compost to grassland**	**Co-collection: compost to topsoil manufacture**	**Co-collection: compost for mulch in landscaping**	**Co-collection: compost to landfill**	**Separate collection: compost to agric (sandy soil)**	**Separate collection: compost to agric (loam soil)**	**Separate collection: compost to agric (clay soil)**	**Separate collection: compost to grassland**	**Separate collection: compost to topsoil manufacture**	**Separate collection: compost for mulch in landscaping**	**Separate collection: compost to landfill**
Ancillary GHG (kg CO_2-eq)	41	41	41	41	46	44	42	42	42	42	42	47	45	43
GHG from fraction (kg CO_2-eq)	49	38	38	25	23	16	104	49	38	38	25	23	16	104
Avoided GHG (kg CO_2-eq)	-27	-24	-22	-4	-18	-32	-32	-27	-24	-22	-4	-18	-32	-32
Sub-total (kg CO_2-eq) – no storage credit	**64**	**55**	**57**	**63**	**51**	**28**	**114**	**65**	**56**	**58**	**64**	**52**	**29**	**115**
Carbon storage - 100 yrs (kg CO_2-eq)	*-24*	*-19*	*-19*	*-14*	*-39*	*-29*	*-168*	*-24*	*-19*	*-19*	*-14*	*-39*	*-29*	*-168*
Carbon storage - 50 yrs (kg CO_2-eq)	*-33*	*-23*	*-23*	*-58*	*-98*	*-84*	*-171*	*-33*	*-23*	*-23*	*-58*	*-98*	*-84*	*-171*
Carbon storage - 20 yrs (kg CO_2-eq)	*-107*	*-99*	*-100*	*-148*	*-152*	*-172*	*-194*	*-107*	*-99*	*-100*	*-148*	*-152*	*-172*	*-194*
Carbon storage - 10 yrs (kg CO_2-eq)	*-148*	*-149*	*-150*	*-196*	*-169*	*-224*	*-227*	*-148*	*-149*	*-150*	*-196*	*-169*	*-224*	*-227*
Total (kg CO_2-eq) - 100 year	**40**	**36**	**38**	**48**	**12**	**-1**	**-55**	**41**	**37**	**39**	**49**	**13**	**0**	**-54**
Total (kg CO_2-eq) - 50 year	31	32	33	5	-48	-56	-57	32	33	34	6	-47	-55	-56
Total (kg CO_2-eq) - 20 year	-43	-44	-43	-86	-101	-144	-81	-42	-43	-42	-85	-100	-143	-80
Total (kg CO_2-eq) - 10 year	-84	-94	-93	-133	-118	-196	-113	-83	-93	-92	-132	-117	-195	-112

Notes:

- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit

Table 5.2 Greenhouse gas balances - 1 tonne food waste to in-vessel composting (MAXIMUM net emissions)

	Co-collection: compost to agric (sandy soil)	**Co-collection: compost to agric (loam soil)**	**Co-collection: compost to agric (clay soil)**	**Co-collection: compost to grassland**	**Co-collection: compost to topsoil manufacture**	**Co-collection: compost for mulch in landscaping**	**Co-collection: compost to landfill**	**Separate collection: compost to agric (sandy soil)**	**Separate collection: compost to agric (loam soil)**	**Separate collection: compost to agric (clay soil)**	**Separate collection: compost to grassland**	**Separate collection: compost to topsoil manufacture**	**Separate collection: compost for mulch in landscaping**	**Separate collection: compost to landfill**
Ancillary GHG (kg CO_2-eq)	41	41	41	41	46	44	42	42	42	42	42	47	45	43
GHG from fraction (kg CO_2-eq)	49	38	38	25	23	16	187	49	38	38	25	23	16	187
Avoided GHG (kg CO_2-eq)	-21	-18	-17	-4	-18	-32	-23	-21	-18	-17	-4	-18	-32	-23
Sub-total (kg CO_2-eq) – no storage credit	**70**	**61**	**63**	**63**	**51**	**28**	**206**	**71**	**62**	**63**	**64**	**52**	**29**	**207**
Carbon storage - 100 yrs (kg CO_2-eq)	*-24*	*-19*	*-19*	*-14*	*-39*	*-29*	*-168*	*-24*	*-19*	*-19*	*-14*	*-39*	*-29*	*-168*
Carbon storage - 50 yrs (kg CO_2-eq)	*-33*	*-23*	*-23*	*-58*	*-98*	*-84*	*-171*	*-33*	*-23*	*-23*	*-58*	*-98*	*-84*	*-171*
Carbon storage - 20 yrs (kg CO_2-eq)	*-107*	*-99*	*-100*	*-148*	*-152*	*-172*	*-194*	*-107*	*-99*	*-100*	*-148*	*-152*	*-172*	*-194*
Carbon storage - 10 yrs (kg CO_2-eq)	*-148*	*-149*	*-150*	*-196*	*-169*	*-224*	*-227*	*-148*	*-149*	*-150*	*-196*	*-169*	*-224*	*-227*
Total (kg CO_2-eq) - 100 year	**46**	**42**	**43**	**48**	**12**	**-1**	**38**	**47**	**43**	**44**	**49**	**13**	**0**	**39**
Total (kg CO_2-eq) - 50 year	37	38	39	5	-48	-56	35	38	39	40	6	-47	-55	36
Total (kg CO_2-eq) - 20 year	-37	-38	-37	-86	-101	-144	11	-36	-37	-36	-85	-100	-143	12
Total (kg CO_2-eq) - 10 year	-79	-88	-87	-133	-118	-196	-21	-78	-87	-86	-132	-117	-195	-20

Notes:

- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of $N_2$0 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit

When no carbon storage credits are applied, GHG balances for all food waste composting processes assessed show the GHG impacts of transport, processing and waste degradation to be greater than the avoided burdens realised through alternative product displacement. The net positive GHG balance is small where products are used, and much greater where products are assumed to be sent to landfill.

Further interrogation of the GHG models showed the predominant contributors to ancillary emissions to be transport - in particular collection via refuse collection vehicle (approx 40% of ancillary impacts) - and the fuel requirements of processing (approx 40%). Ancillary burdens for green and food waste collected either together, or separately, appear to be very similar. This indicates that GHG balances are not sensitive to the alternative collection assumptions made for these systems.

For non-landfill product use routes, the predominant contributor to GHG emissions direct from the waste fraction (1) is N_2O emissions. *Annex D* discusses the outputs from soil modelling in this respect, as well as the model's limitations. N_2O emissions are shown to be highest when products are applied to agricultural crop systems, and this is apparent in the figures shown. N_2O releases from products when used as mulch are assumed to be minimal, so here, the greenhouse gas release from fraction is associated with the landfill of rejects/residues from the composting process.

Where products from composting are disposed to landfill, CH_4 is released from the degrading material, and so we see a relatively large 'GHG from fraction' emission. Note that the difference seen between maximum and minimum profiles relates to assumptions with regard to landfill gas collection (50% gas collection and 75% gas collection assumed respectively).

In terms of 'avoided' emissions, these are a quantification of the potential benefits of product use (eg as set out in *Table 4.2*). For landfill as an end route, avoided emissions relate to the recovery of energy from landfill gas. Compost product use benefits have been found to be similar for all use routes, with differences only minor. The use of compost as mulch appears to have the highest potential benefit, and this is, in part, because the use of bark mulch from sources across Europe (and associated transport) is assumed to be avoided.

The use of compost in agriculture shows lower benefits than might have been expected, and lower than those reported by some other researchers (eg Brinkman, 2006; ROU, 2007) (2). The predominant reason for this is twofold, as follows.

1. The fertiliser equivalency of this applied compost is often estimated to be high, and results in researchers assuming relatively high quantities of avoided mineral fertilisers (with associated GHG benefits). In this

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(1) 'GHG from fraction'

(2) But are in line with the findings of others (eg Hansen *et al*, 2006; Christensen *et al*, 2006).

assessment, the fertiliser equivalency of applied materials was determined on the basis of their relative C/N ratio, with a detailed consideration of quantity of nitrogen potentially available to crops over time. *Annex B* sets out the approach further, which is based on a formula set out in WRAP (2006b); and

2. In the systems assessed, the amount of compost that can be applied/frequency of application is limited by nitrogen restrictions set out in the Nitrates Directive (as would occur in practice).

Should greater applications of compost be allowed, greater nutrient benefits would be seen. A sensitivity analysis was carried out in order to investigate this potential. The sensitivity test assessed a doubling in the application of green and food waste compost to clay soil. Reduced N_2O emissions on use were seen and, assuming product use benefits are also doubled, the resulting greenhouse gas balance is 26 – 37 kg CO_2-eq per tonne of food waste managed (no carbon storage accounted). This represents an approximate halving of net GHG emissions.

Note that energy recovery from in-vessel composting systems was not assessed as a scenario, as this is not an economically realistic treatment option in the UK. Depending on the scale of energy recovery from such a system, we would expect to see a negative greenhouse gas balance where the benefits of generating useful products in the form of electricity, heat and compost are realised.

Overall GHG balances for the co-collection and separate collection systems are almost identical. Note, however, that in the core analyses, the potential for differences in reject rates for co-collection and separate collection systems were not considered, as data for the different systems are lacking.

A sensitivity analysis was carried out to show the potential difference between separate and co-collection systems should co-collection lead to an increase in rejects/residues of 10% (and thus 10% less product). The sensitivity test investigated an increase in residue rate for the co-collection system with product use in agriculture (clay soil). The outcome is heavily dependent on whether we assume that residues are organic in nature, or inert materials (such as plastic). If we assume the latter, GHG balances are not affected to any extent. However, if we assume the former, the resulting GHG balance could increase by more than 50% (depending on landfill gas capture later).

Looking to alternative perspectives for accounting for carbon storage, the shorter the period over which we assume there is a benefit of storing carbon, the greater the credit given to the systems. This is most pronounced where products are sent to landfill, as materials tend to degrade more slowly in landfill (comparative degradation rates are presented in *Annex D* and modelling assumptions in *Annex B*).

The range of benefits for each composting system in comparison with sending raw food waste to landfill is shown in *Table 5.3* and *Table 5.4*. Maximum benefits show the difference between the maximum emissions for landfill and the minimum emissions for composting. Minimum benefits show the difference between the minimum emissions for landfill and the maximum emissions for composting.

Table 5.3 and *Table 5.4* in particular show the implications of two different carbon accounting methods (no carbon sequestration and 100 year carbon sequestration) – borne through differences in carbon degradation profiles for different product use routes and for disposal of waste in landfill.

This is discussed further in *Section 7.2*.

Table 5.3 *Net greenhouse gas impacts of 1 tonne food waste IVC composting versus 1 tonne food waste landfill (maximum)*

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Co-collection: compost to agriculture (sandy soil)	-445	-349
Co-collection: compost to agriculture (loam soil)	-453	-353
Co-collection: compost to agriculture (clay soil)	-451	-352
Co-collection: compost to grassland	-446	-341
Co-collection: compost to topsoil manufacture	-458	-377
Co-collection: compost for mulch in landscaping	-480	-390
Co-collection: compost to landfill	-395	-444
Separate collection: compost to agriculture (sandy soil)	-444	-349
Separate collection: compost to agriculture (loam soil)	-452	-352
Separate collection: compost to agriculture (clay soil)	-451	-351
Separate collection: compost to grassland	-445	-340
Separate collection: compost to topsoil manufacture	-457	-376
Separate collection: compost for mulch in landscaping	-479	-389
Separate collection: compost to landfill	-394	-443

Note: Maximum = the difference between the maximum emissions for landfill and the minimum emissions for composting. Negative figures reflect potential savings.

Table 5.4 Net greenhouse gas impacts of 1 tonne food waste IVC composting versus 1 tonne food waste landfill (minimum)

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Co-collection: compost to agriculture (sandy soil)	-162	-67
Co-collection: compost to agriculture (loam soil)	-171	-71
Co-collection: compost to agriculture (clay soil)	-169	-70
Co-collection: compost to grassland	-169	-64
Co-collection: compost to topsoil manufacture	-181	-101
Co-collection: compost for mulch in landscaping	-204	-114
Co-collection: compost to landfill	-26	-75
Separate collection: compost to agriculture (sandy soil)	-161	-66
Separate collection: compost to agriculture (loam soil)	-170	-70
Separate collection: compost to agriculture (clay soil)	-168	-69
Separate collection: compost to grassland	-168	-64
Separate collection: compost to topsoil manufacture	-180	-100
Separate collection: compost for mulch in landscaping	-203	-113
Separate collection: compost to landfill	-25	-74

Note: Minimum = the difference between the minimum emissions for landfill and the maximum emissions for composting. Negative figures reflect potential savings.

5.1.2 *Source Separation: Anaerobic Digestion*

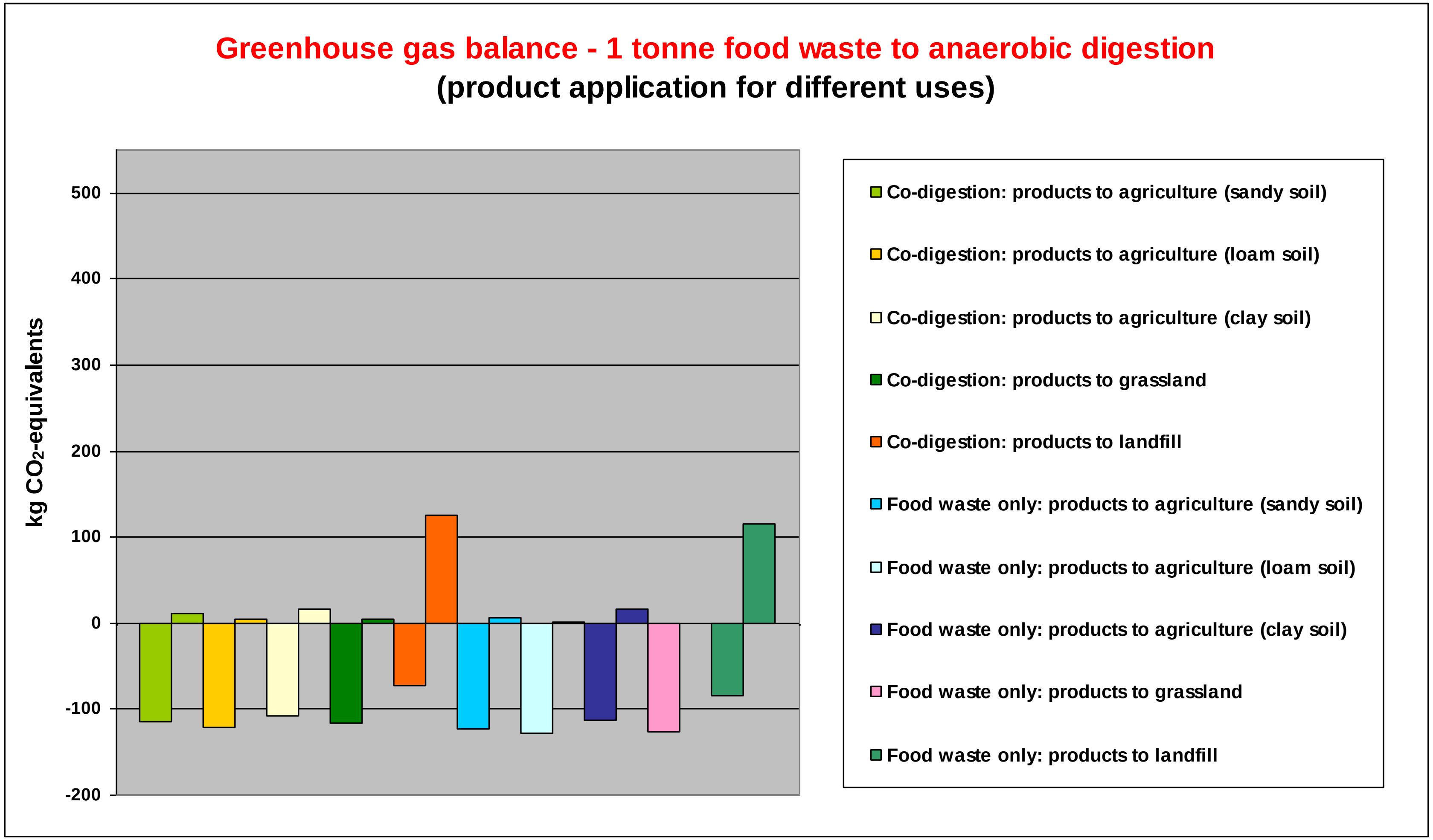
Figure 5.2 presents maximum and minimum GHG balances for the 'no storage credit' accounting scenario. A summary of all results for food waste anaerobic digestion is presented in *Table 5.5* and *Table 5.6*.

Ancillary GHG emissions for food waste AD are shown to be similar to those for IVC, and again these are dominated by contributions from collection transport (approx 40% of ancillary impacts) and the fuel requirements of processing (approx 40%).

The ancillary burdens for green and food waste collected either together, or separately, are again very similar. The analysis did consider some potential for difference in reject/residue for co-collected and separately collected waste (data provided by Greenfinch and shown in *Annex B*). Accordingly the co-digestion scenario shows higher ancillary burdens associated with processing the rejects and higher GHG release from the residue fraction degrading in landfill.

Avoided GHG emissions are dominated by the benefits of energy recovery during the digestion process, and displacement of fossil energy sources. *Table 4.1* presented the range of energy conversion efficiencies that were assumed for anaerobic digestion. These account for the difference between the maximum and minimum GHG balances shown in *Table 5.5* and *Table 5.6*. *Table 5.6* shows that net GHG emissions vary considerably depending on assumed energy recovery. If the lowest range of net recovery is achieved, then the burdens of collection, processing and landfill of residues are approximately equal to the benefits of energy recovery. If greater efficiencies are achieved, then the benefits of digesting food waste are clear.

Figure 5.2 *Net greenhouse gas emissions: 1 tonne food waste to AD: no carbon sequestration accounted*



Note: two bars are presented for each unit system, showing maximum and minimum potential emissions
Co-digestion = digestion with green waste

Table 5.5 Greenhouse gas balances - 1 tonne food waste to anaerobic digestion (MINIMUM net emissions)

	Co-digestion: products to agriculture (sandy soil)	**Co-digestion: products to agriculture (loam soil)**	**Co-digestion: products to agriculture (clay soil)**	**Co-digestion: products to grassland**	**Co-digestion: products to landfill**	**Food waste only: products to agriculture (sandy soil)**	**Food waste only: products to agriculture (loam soil)**	**Food waste only: products to agriculture (clay soil)**	**Food waste only: products to grassland**	**Food waste only: products to landfill**
Ancillary GHG (kg CO_2-eq)	43	43	43	43	45	41	41	41	41	43
GHG from fraction (kg CO_2-eq)	34	25	37	16	82	28	20	36	13	74
Avoided GHG (kg CO_2-eq)	-191	-189	-188	-175	-198	-192	-190	-189	-179	-201
Sub-total (kg CO_2-eq) – no storage credit	**-114**	**-121**	**-108**	**-117**	**-72**	**-123**	**-129**	**-112**	**-126**	**-83**
Carbon storage - 100 yrs (kg CO_2-eq)	*-14*	*-11*	*-11*	*-6*	*-124*	*-11*	*-8*	*-8*	*-3*	*-95*
Carbon storage - 50 yrs (kg CO_2-eq)	*-20*	*-12*	*-12*	*-31*	*-126*	*-15*	*-9*	*-9*	*-21*	*-97*
Carbon storage - 20 yrs (kg CO_2-eq)	*-61*	*-55*	*-56*	*-84*	*-147*	*-44*	*-39*	*-39*	*-60*	*-116*
Carbon storage - 10 yrs (kg CO_2-eq)	*-82*	*-82*	*-83*	*-110*	*-174*	*-58*	*-58*	*-58*	*-79*	*-140*
Total (kg CO_2-eq) - 100 year	**-128**	**-132**	**-119**	**-122**	**-196**	**-134**	**-136**	**-120**	**-129**	**-178**
Total (kg CO_2-eq) - 50 year	-134	-133	-121	-148	-198	-138	-137	-121	-147	-180
Total (kg CO_2-eq) - 20 year	-175	-176	-164	-200	-219	-167	-168	-151	-185	-199
Total (kg CO_2-eq) - 10 year	-196	-203	-191	-226	-246	-181	-187	-170	-205	-223

Notes:

- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit.

Table 5.6 Greenhouse gas balances - 1 tonne food waste to anaerobic digestion (MAXIMUM net emissions)

	Co-digestion: products to agriculture (sandy soil)	**Co-digestion: products to agriculture (loam soil)**	**Co-digestion: products to agriculture (clay soil)**	**Co-digestion: products to grassland**	**Co-digestion: products to landfill**	**Food waste only: products to agriculture (sandy soil)**	**Food waste only: products to agriculture (loam soil)**	**Food waste only: products to agriculture (clay soil)**	**Food waste only: products to grassland**	**Food waste only: products to landfill**
Ancillary GHG (kg CO_2-eq)	43	43	43	43	44	41	41	41	41	43
GHG from fraction (kg CO_2-eq)	34	25	37	16	151	28	20	36	13	139
Avoided GHG (kg CO_2-eq)	-66	-64	-63	-54	-70	-63	-61	-60	-54	-68
Sub-total (kg CO_2-eq) – no storage credit	**11**	**4**	**17**	**4**	**126**	**6**	**1**	**17**	**0**	**115**
Carbon storage - 100 yrs (kg CO_2-eq)	*-14*	*-11*	*-11*	*-6*	*-124*	*-11*	*-8*	*-8*	*-3*	*-95*
Carbon storage - 50 yrs (kg CO_2-eq)	*-20*	*-12*	*-12*	*-31*	*-126*	*-15*	*-9*	*-9*	*-21*	*-97*
Carbon storage - 20 yrs (kg CO_2-eq)	*-61*	*-55*	*-56*	*-84*	*-147*	*-44*	*-39*	*-39*	*-60*	*-116*
Carbon storage - 10 yrs (kg CO_2-eq)	*-82*	*-82*	*-83*	*-110*	*-174*	*-58*	*-58*	*-58*	*-79*	*-140*
Total (kg CO_2-eq) - 100 year	**-3**	**-7**	**6**	**-2**	**2**	**-5**	**-7**	**9**	**-3**	**20**
Total (kg CO_2-eq) - 50 year	-9	-8	4	-27	0	-8	-8	9	-21	18
Total (kg CO_2-eq) - 20 year	-50	-51	-39	-80	-21	-38	-38	-22	-59	-1
Total (kg CO_2-eq) - 10 year	-71	-78	-66	-106	-48	-52	-57	-41	-79	-25

Notes:

- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit.

As well as assessing a range of energy recovery benefits, a sensitivity analysis was carried out to investigate the potential GHG implications of an AD system that produces a stabilised digestate product. AD systems vary widely, depending on their function and how they are operated. For example, the process can be designed as 'wet' and 'dry', according to the physical state of the input material types. In addition, process temperatures and timescales can be optimised either for maximum biogas yield (and subsequent conversion to energy) or maximum biodegradation of the input materials (greatest stabilisation). Processes can result in only 'whole digestate', or use additional separation equipment to derive separated fibre and liquor.

Given the need to limit the scope of research, effort was made to derive 'typical' system parameters for AD processes accepting different waste feedstocks: food waste; and mixed food and green waste (1). Greenfinch and the Renewable Energy Association were contacted in order to do this. Together, these organisations are at the forefront of AD systems research, development and operation in the UK.

Nevertheless, the potential GHG implications of different AD systems are likely to differ considerably. The most important difference in this context will be with regard to energy recovery potential – and so the effect of a range of potentials was examined. In undertaking sensitivity analysis, an alternative AD system was assessed, in order to understand the potential variation in climate change implications that might be seen. This alternative represents a digestion plant accepting food and green waste in equal quantities and producing a single digestate product stream that undergoes a stabilisation process prior to use. It was assumed that the stabilised product would be used in agriculture (clay soil).

Maximum and minimum GHG balances are presented in *Table 5.7* and *Table 5.8*. These show approximately 50% greater ancillary burdens, as a result of greater fuel requirements in processing. Accordingly, net GHG emissions for the system are higher. However, significant potential for GHG savings are still observed.

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(1) In practice, those that are procuring AD facilities will need to carefully consider a system or technology appropriate to the feedstock material collected (eg proportion of food and green waste).

Table 5.7 Greenhouse gas balance - 1 tonne food waste to AD (MIN net emissions)

	Stabilised system: products to agriculture (clay soil)	**Baseline system: products to agriculture (clay soil)**
Ancillary GHG (kg CO_2-eq)	63	43
GHG from fraction (kg CO_2-eq)	34	37
Avoided GHG (kg CO_2-eq)	-185	-188
Sub-total (kg CO_2-eq) – no storage credit	**-88**	**-108**
Carbon storage - 100 yrs (kg CO_2-eq)	*-21*	*-11*
Carbon storage - 50 yrs (kg CO_2-eq)	*-25*	*-12*
Carbon storage - 20 yrs (kg CO_2-eq)	*-99*	*-56*
Carbon storage - 10 yrs (kg CO_2-eq)	*-142*	*-83*
Total (kg CO_2-eq) - 100 year	**-109**	**-119**
Total (kg CO_2-eq) - 50 year	-113	-121
Total (kg CO_2-eq) - 20 year	-186	-164
Total (kg CO_2-eq) - 10 year	-230	-191

Table 5.8 Greenhouse gas balance - 1 tonne food waste to AD (MAX net emissions)

	Stabilised system: products to agriculture (clay soil)	**Baseline system: products to agriculture (clay soil)**
Ancillary GHG (kg CO_2-eq)	63	43
GHG from fraction (kg CO_2-eq)	34	37
Avoided GHG (kg CO_2-eq)	-67	-63
Sub-total (kg CO_2-eq) – no storage credit	**30**	**17**
Carbon storage - 100 yrs (kg CO_2-eq)	*-21*	*-11*
Carbon storage - 50 yrs (kg CO_2-eq)	*-25*	*-12*
Carbon storage - 20 yrs (kg CO_2-eq)	*-99*	*-56*
Carbon storage - 10 yrs (kg CO_2-eq)	*-142*	*-83*
Total (kg CO_2-eq) - 100 year	**9**	**6**
Total (kg CO_2-eq) - 50 year	5	4
Total (kg CO_2-eq) - 20 year	-69	-39
Total (kg CO_2-eq) - 10 year	-113	-66

The range of benefits for each anaerobic digestion system in comparison with sending raw food waste to landfill is shown in *Table 5.9* and *Table 5.10*. As previously, maximum benefits show the difference between the maximum emissions for landfill and the minimum emissions for AD. Minimum benefits show the difference between the minimum emissions for landfill and the maximum emissions for AD.

Table 5.9 *Net greenhouse gas impacts of 1 tonne food waste AD versus 1 tonne food waste landfill (maximum)*

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Co-digestion: products to agriculture (sandy soil)	-622	-518
Co-digestion: products to agriculture (loam soil)	-629	-521
Co-digestion: products to agriculture (clay soil)	-617	-508
Co-digestion: products to grassland	-625	-512
Co-digestion: products to landfill	-580	-585
Food waste only: products to agriculture (sandy soil)	-631	-523
Food waste only: products to agriculture (loam soil)	-637	-526
Food waste only: products to agriculture (clay soil)	-620	-509
Food waste only: products to grassland	-634	-518
Food waste only: products to landfill	-592	-567

Note: Maximum = the difference between the maximum emissions for landfill and the minimum emissions for AD. Negative figures reflect potential savings.

Table 5.10 *Net greenhouse gas impacts of 1 tonne food waste AD versus 1 tonne food waste landfill (minimum)*

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Co-digestion: products to agriculture (sandy soil)	-221	-116
Co-digestion: products to agriculture (loam soil)	-228	-119
Co-digestion: products to agriculture (clay soil)	-215	-107
Co-digestion: products to grassland	-228	-114
Co-digestion: products to landfill	-106	-110
Food waste only: products to agriculture (sandy soil)	-226	-117
Food waste only: products to agriculture (loam soil)	-231	-120
Food waste only: products to agriculture (clay soil)	-215	-103
Food waste only: products to grassland	-231	-116
Food waste only: products to landfill	-117	-93

Note: Minimum = the difference between the minimum emissions for landfill and the maximum emissions for AD. Negative figures reflect potential savings.

5.1.3 *Residual Treatment*

Figure 5.3 presents maximum and minimum GHG balances for the 'no carbon credit' accounting scenario. A summary of all results for residual systems is presented in *Table 5.11* and *Table 5.12.*

Table 5.11 and *Table 5.12* show the ancillary burdens of collecting and processing food waste as a residual fraction to be up to as much as 50% higher than for source-separated systems. All residual treatment systems incurred increased collection transport burdens. For MBT systems, additional impacts were also borne in the increased fuel requirements of processing.

A large 'GHG from fraction' emission is shown for the disposal of raw food waste in landfill. This is associated with the CH_4 generated as this material degrades in an anaerobic environment. Note that the large difference between maximum and minimum profiles relates to assumptions with regard to landfill gas collection (50% gas collection and 75% gas collection assumed respectively).

Where products from MBT are disposed in landfill, 'GHG from fraction' emissions are approximately halved, reflecting the more stabilised nature of these products (and the loss of some carbon as CO_2 during treatment). Where MBT products are instead used in land remediation projects, for topsoil manufacture, much lower GHG releases from the degradation of products is seen. In fact, soil modelling showed N_2O emissions from this use route to be relatively low (*Annex D*).

Avoided GHG emissions are highest for the anaerobic MBT and combustion systems. Again, the range of potential benefits seen is reflective of the assumed range of energy conversion efficiencies considered achievable (*Table 4.1*). Landfill of raw wastes shows a relatively high avoided GHG burden. This occurs as a result of the capture of energy from landfill gas, and is dependent on assumptions regarding gas capture (as noted above).

The range of potential benefits for each residual treatment system in comparison with sending raw food waste to landfill are shown in *Table 5.11* and *Table 5.12*. Maximum benefits show the difference between the maximum emissions for landfill and the minimum emissions for treatment. Minimum benefits show the difference between the minimum emissions for landfill and the maximum emissions for treatment.

Table 5.13 and *Table 5.14* show the implications of two different carbon accounting methods – borne through differences in the fate of carbon and its rate of release in landfill, or when applied as topsoil. For example, compare the maximum benefit for anaerobic MBT with digestate-like-output to landfill and topsoil manufacture respectively. Degradation profiles for topsoil application show a much faster rate of carbon release than in landfill (see *Annex D*). Thus, after 50 and 100 years, more carbon remains un-degraded in landfill and, if given a sequestration credit, results in the product-to-landfill system performing favourably.

Minimum net differences (*Table 5.14*) between sending MBT products to landfill and sending raw food waste to landfill are positive– showing a greater impact in comparison with landfill. This occurred where the stabilate from MBT systems was landfilled with minimum landfill gas capture (50%) and raw food waste was landfilled with maximum landfill gas capture (75%). This serves to highlight the importance of this modelling assumption in assessing relative GHG balances, and of maximising gas capture at landfill sites. The efficiency of collection of landfill gas emissions is dependent on many site specific factors, including whether the landfill has no cap, a temporary cap, or a permanent cap; whether the landfill has temporary or permanent gas collection infrastructure; how much degradable waste is in the landfill; the rate of filling of that degradable waste; and how far in time, along the gas production curve the site is.

Important to note from the results is that in all cases where the stabilised product was either used as topsoil or was combusted with energy recovery, a lower impact was shown in comparison to landfill of raw waste.

It should also be noted that there are considerable uncertainties around the estimation of carbon degradation and greenhouse gas emissions from landfill over time – particularly where mixed wastes are landfilled. In this study, modelling of carbon flows and greenhouse gas emissions from landfill was undertaken using the GasSim model. In the model, different waste streams are defined by the different amounts of degradable cellulosic materials they contain, the water content of each fraction, the amount of cellulose and hemicellulose, and the degradability of that cellulose. The alternative properties each have an influence on material degradation and GasSim models this degradation according to modelling rules defined in the user manual (1), (2) .

A key factor influencing the rate of degradation of wastes in landfill are the moisture conditions in the landfill itself. Moisture has an effect on waste degradation because the microbially mediated reactions which take place to degrade cellulose-containing wastes take place on wetted surfaces. The rate-determining step for all the many complex microbially mediated reactions that can take place in the landfill is the rate of hydrolysis of cellulose to glucose (all subsequent microbial degradation processes will occur at faster rates than these). A consequence of this is that a well-wetted (but not saturated) waste, well-shredded with lots of active broken surfaces for hydrolysis to be initiated, is the ideal medium for landfill gas generation.

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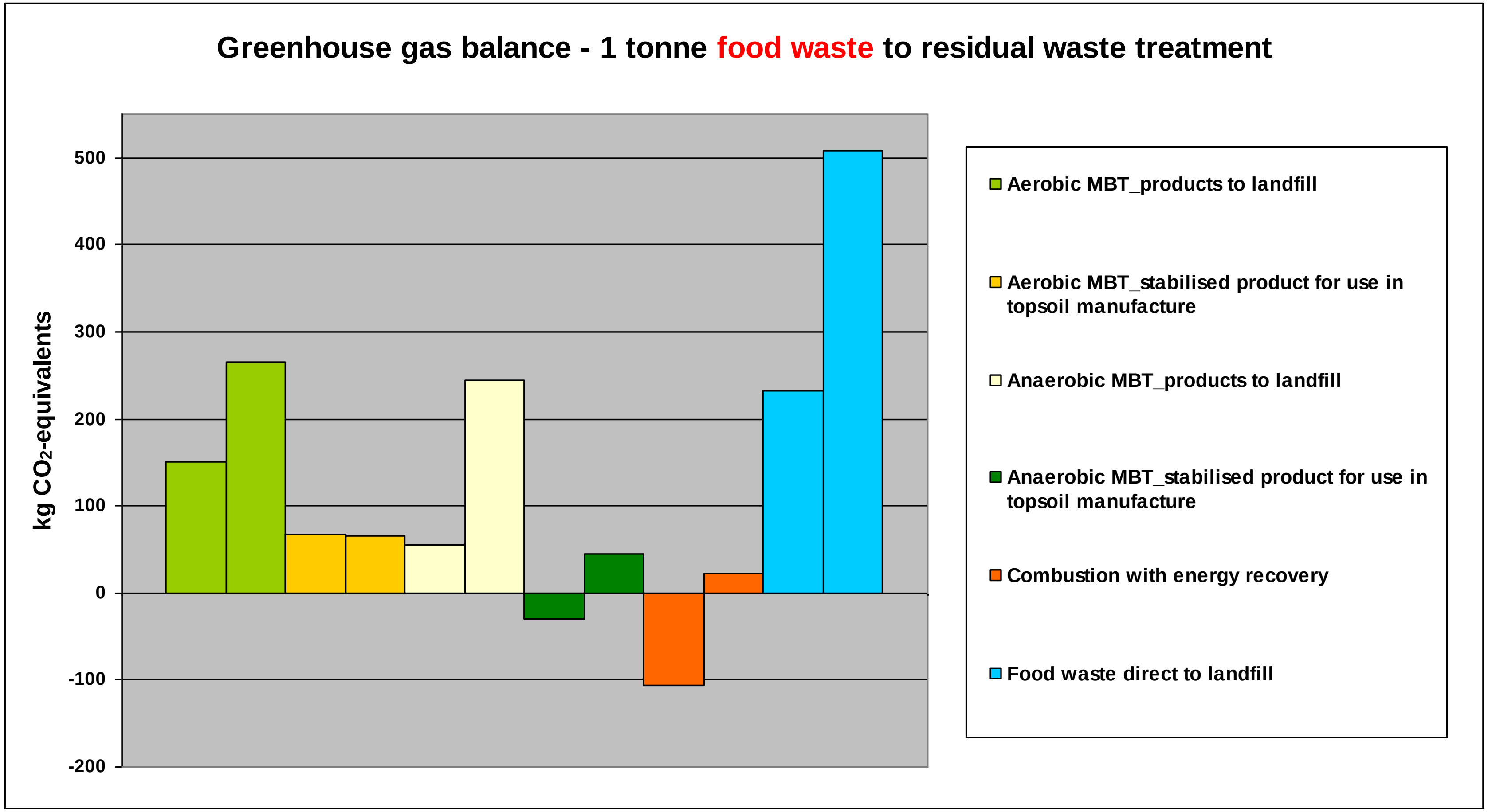
(1) Environment Agency (2006). GasSim2 User Manual. Available at www.gassim.co.uk

(2) Degradation rates can be either default, or user defined. The degradation rates assumed in this assessment are set out in *Annex B*.

In the UK, the majority of landfills can be represented using either average moisture content or wet moisture content degradation rates. For the core analyses in the research, we used average moisture conditions. ERM 2006b undertook sensitivity analysis to show resulting greenhouse gas emissions over time, should a wet degradation rate instead be assumed. The rate of gas release was found to be increased, due to faster degradation. However the total amount of gas generated over a 100-year period was found to be similar.

Figure 5.3 *Net greenhouse gas emissions: 1 tonne food in residual waste: no carbon sequestration accounted*



Note: two bars are presented for each unit system, showing maximum and minimum potential emissions

Table 5.11 Greenhouse gas balances - 1 tonne food in residual waste (MINIMUM net emissions)

	Aerobic MBT: products to landfill	**Aerobic MBT: stabilised product for use in topsoil manufacture**	**Anaerobic MBT: products to landfill**	**Anaerobic MBT: stabilised product for use in topsoil manufacture**	**Combustion with energy recovery**	**Food waste direct to landfill**
Ancillary GHG (kg CO_2-eq)	66	70	77	81	41	53
GHG from fraction (kg CO_2-eq)	125	16	125	16	15	261
Avoided GHG (kg CO_2-eq)	-40	-19	-146	-125	-161	-83
Sub-total (kg CO_2-eq) – no storage credit	**151**	**67**	**56**	**-29**	**-106**	**232**
Carbon storage - 100 yrs (kg CO_2-eq)	*-187*	*-34*	*-192*	*-37*	*-13*	*-119*
Carbon storage - 50 yrs (kg CO_2-eq)	*-190*	*-81*	*-196*	*-90*	*-13*	*-120*
Carbon storage - 20 yrs (kg CO_2-eq)	*-221*	*-151*	*-228*	*-163*	*-13*	*-161*
Carbon storage - 10 yrs (kg CO_2-eq)	*-263*	*-181*	*-270*	*-191*	*-13*	*-252*
Total (kg CO_2-eq) - 100 year	**-35**	**33**	**-137**	**-66**	**-106**	**113**
Total (kg CO_2-eq) - 50 year	-39	-14	-140	-119	-106	111
Total (kg CO_2-eq) - 20 year	-70	-84	-172	-192	-106	71
Total (kg CO_2-eq) - 10 year	-111	-114	-215	-220	-106	-20

Notes:

- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit.

Table 5.12 Greenhouse gas balances - 1 tonne food in residual waste (MAXIMUM net emissions)

	Aerobic MBT: products to landfill	**Aerobic MBT: stabilised product for use in topsoil manufacture**	**Anaerobic MBT: products to landfill**	**Anaerobic MBT: stabilised product for use in topsoil manufacture**	**Combustion with energy recovery**	**Food waste direct to landfill**
Ancillary GHG (kg CO_2-eq)	66	70	76	81	41	53
GHG from fraction (kg CO_2-eq)	228	16	228	16	15	510
Avoided GHG (kg CO_2-eq)	-28	-19	-60	-51	-34	-55
Sub-total (kg CO_2-eq) – no storage credit	**266**	**67**	**244**	**45**	**22**	**508**
Carbon storage - 100 yrs (kg CO_2-eq)	*-187*	*-34*	*-192*	*-37*	*-13*	*-119*
Carbon storage - 50 yrs (kg CO_2-eq)	*-190*	*-81*	*-196*	*-90*	*-13*	*-120*
Carbon storage - 20 yrs (kg CO_2-eq)	*-221*	*-151*	*-228*	*-163*	*-13*	*-161*
Carbon storage - 10 yrs (kg CO_2-eq)	*-263*	*-181*	*-270*	*-191*	*-13*	*-252*
Total (kg CO_2-eq) - 100 year	**79**	**33**	**52**	**9**	**8**	**389**
Total (kg CO_2-eq) - 50 year	76	-14	49	-44	8	388
Total (kg CO_2-eq) - 20 year	45	-84	17	-117	8	348
Total (kg CO_2-eq) - 10 year	3	-114	-26	-145	8	257

Notes:

- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit.

Table 5.13 Net greenhouse gas impacts of 1 tonne food in treated residual waste versus 1 tonne food waste landfill (maximum)

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Aerobic MBT: products to landfill	-357	-425
Aerobic MBT: stabilised product for use in topsoil manufacture	-442	-356
Anaerobic MBT: products to landfill	-453	-526
Anaerobic MBT: stabilised product for use in topsoil manufacture	-538	-455
Combustion with energy recovery	-614	-495

Note: Maximum = the difference between the maximum emissions for landfill and the minimum emissions for treatment. Negative figures reflect potential savings.

Table 5.14 Net greenhouse gas impacts of 1 tonne food in treated residual waste versus 1 tonne food waste landfill (minimum)

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Aerobic MBT: products to landfill	34	-34
Aerobic MBT: stabilised product for use in topsoil manufacture	-165	-80
Anaerobic MBT: products to landfill	13	-61
Anaerobic MBT: stabilised product for use in topsoil manufacture	-186	-104
Combustion with energy recovery	-210	-91

Note: Minimum = the difference between the minimum emissions for landfill and the maximum emissions for composting. Negative figures reflect potential savings. Positive figures reflect a *net impact* over landfill

5.2 WASTE MANAGEMENT OPTIONS FOR GREEN WASTE

5.2.1 *Source Separation: Windrow Composting*

Figure 5.4 presents maximum and minimum GHG balances for the 'no carbon credit' accounting scenario. A summary of all results for green waste windrow composting is presented in *Table 5.15* and *Table 5.16*.

Ancillary GHG emissions for windrow composting are shown to be 20-25% lower than those for in-vessel composting, as a result of lower energy requirements for processing. Transport contributes more than 50% of total ancillary emissions, roughly evenly split between collection via refuse collection vehicle and bulk transport in lorries. Refuse collection vehicles have lower importance than seen for the in-vessel composting system (eg see food waste discussion in *Section 5.1.1*). This is because a greater proportion (approx 40%) of this waste stream was assumed to arise via household waste recycling sites (HWRC), as opposed to being collected from kerbsides.

In this assessment the quantification of GHG emissions began at the point of waste collection, and so transport of waste materials to a HWRC by householders/businesses was not included. A simple analysis was carried out to test the potential implications of this exclusion. Assuming a return journey of 20 km to a HWRC, an average load of 20 kg and using Defra conversion factors for the GHG emissions associated with car transport, this results in approximately 10 kg CO_2-eq to transport 1 tonne of waste (in 50 individual journeys). The implication for the results of the overall assessment would be an additional 4 kg CO_2-eq for all the scenarios shown in *Table 5.15* and *Table 5.16* (at 40% arisings from HWRCs). This number would increase linearly if greater distances and smaller loads were assumed, and decrease if the converse were true.

GHG releases from the waste fraction during use are also slightly lower than, but follow the same profile and trends as, those seen for in-vessel composting. *Annex D* discusses the outputs from, and limitations of, soil modelling in this respect. N_2O emissions are shown to be highest when products are applied to agricultural crop systems, and this is apparent in the figures shown. N_2O releases from products when used as mulch are assumed to be minimal. For this product use route, contributions to the 'GHG from fraction' value in the tables are from the landfill of rejects/residues from the composting process.

Avoided GHG emissions are a quantification of the potential benefits of product use (as set out in *Table 4.2*). *Section 5.1.1* discussed the reasons why benefits for compost application to agriculture appear low. A sensitivity analysis showing the increased benefits seen with increased application rates is presented. We would anticipate these findings to also be applicable to the use of green waste compost.

The use of compost as a peat replacement in growing medium shows by far the highest potential GHG benefit. This is due to the avoidance of both the extraction and transport of peat, as well as the avoided release of the carbon within that peat (assumed equivalent to a fossil carbon source). Note that the peat system modelled was based on the amateur retail market. There are barriers to the use of peat by professional horticulture due to issues of performance (eg water holding capacity, packing density etc). These are not yet overcome, but results suggest that there would be benefit in further research in this area.

When no carbon storage credits are applied, GHG balances for the majority of the green waste composting processes assessed show the GHG impacts of transport, processing and waste degradation to be greater than the avoided burdens realised through alternative product displacement. The net positive GHG balance is small where products are used, and much greater where products are sent to landfill.

Looking to alternative perspectives for the accounting of carbon storage, the shorter the period over which we assume there is a benefit of storing carbon, the greater the credit given to the systems. This is most pronounced where products are sent to landfill, as materials tend to degrade more slowly in landfill (comparative degradation rates are presented in *Annex D* and modelling assumptions in *Annex B*).

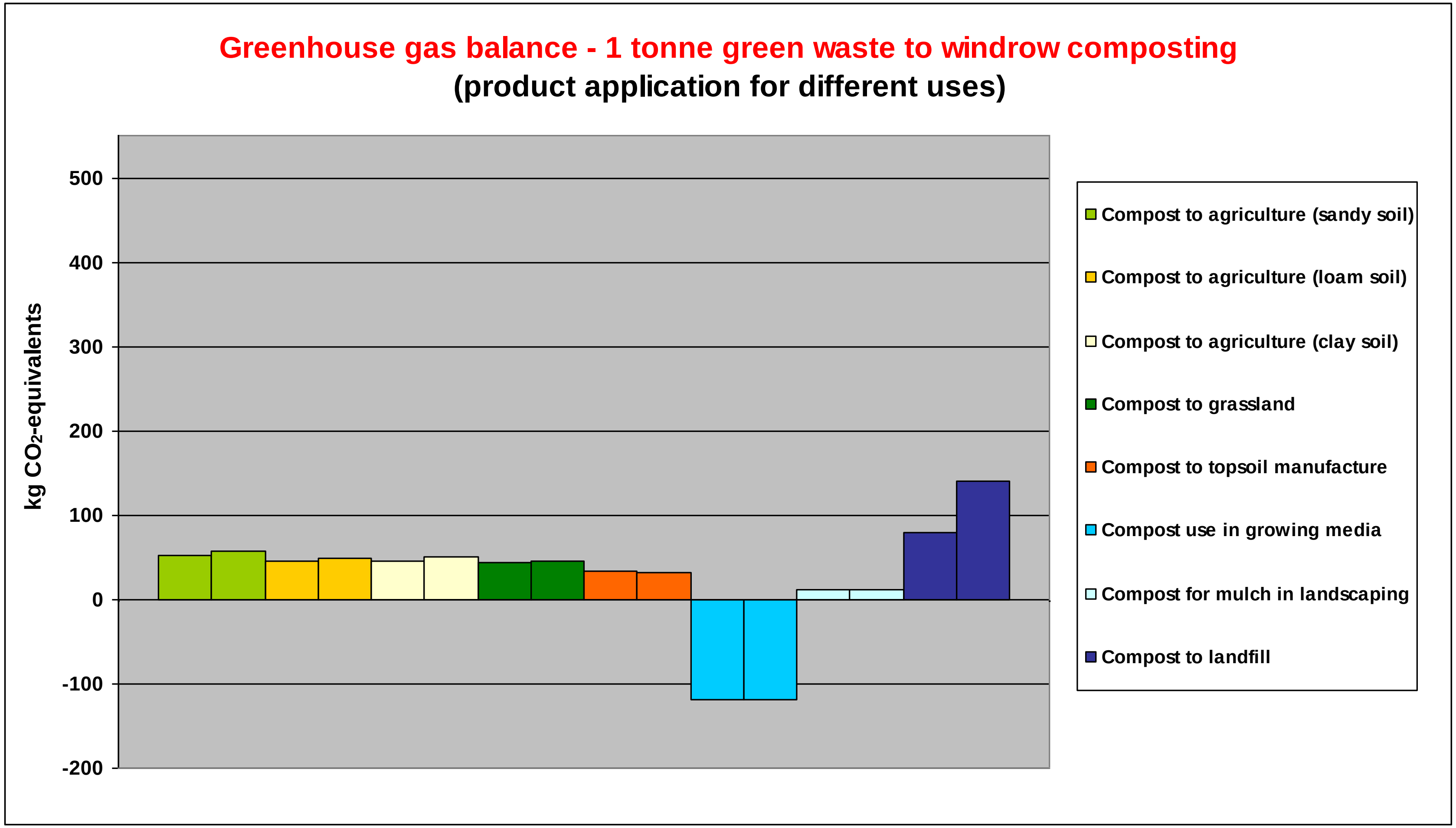
The range of potential benefits for each composting system in comparison with sending raw green waste to landfill are shown in *Table 5.17* and *Table 5.18*. Maximum benefits show the difference between the maximum emissions for landfill and the minimum emissions for composting. Minimum benefits show the difference between the minimum emissions for landfill and the maximum emissions for composting.

Table 5.17 and *Table 5.18* are particularly important in showing the potential implications of different carbon accounting methods. Green waste and green waste treatment products degrade relatively slowly in landfill (see *Annex D* for profiles). The carbon in these materials will eventually degrade and be released to the atmosphere. But if we assume that delaying its release for a period of 100 years or shorter has a benefit, then landfill essentially acts as a carbon sink and shows a favourable net GHG balance.

This phenomenon is discussed further in *Section 7.2,* and it is important to note that there is uncertainty both around the permanence of this carbon sink, and the specific environmental benefits of delayed emissions. Some argue that future CO_2 emissions should receive no lesser weight, but acknowledge that they should be recorded separately because of inherent unknowns around their release and subsequent impacts.

Added to this is the consideration that, by disposing of carbon in landfill, as opposed to applying it to the soil, all of the added value related to soil organic carbon increase, humus reproduction, fertility, and yield increases are lost. It is likely that this assessment does not fully capture the net benefit to the environment of maintaining soil health in this respect.

Figure 5.4 *Net greenhouse gas emissions: 1 tonne green waste to windrow composting: no carbon sequestration accounted*



Note: two bars are presented for each unit system, showing maximum and minimum potential emissions

Table 5.15 Greenhouse gas balances - 1 tonne green waste to windrow composting (MINIMUM net emissions)

	Compost to agriculture (sandy soil)	**Compost to agriculture (loam soil)**	**Compost to agriculture (clay soil)**	**Compost to grassland**	**Compost to topsoil manufacture**	**Compost use in growing media**	**Compost for mulch in landscaping**	**Compost to landfill**
Ancillary GHG (kg CO_2-eq)	30	30	30	30	34	32	32	30
GHG from fraction (kg CO_2-eq)	35	27	27	16	14	12	12	69
Avoided GHG (kg CO_2-eq)	-13	-12	-11	-2	-16	-163	-32	-20
Sub-total (kg CO_2-eq) – no storage credit	**52**	**45**	**46**	**44**	**33**	**-118**	**12**	**79**
Carbon storage - 100 yrs (kg CO_2-eq)	-24	-21	-21	-18	-39	-33	-33	-181
Carbon storage - 50 yrs (kg CO_2-eq)	-32	-25	-25	-54	-91	-85	-85	-183
Carbon storage - 20 yrs (kg CO_2-eq)	-92	-87	-87	-125	-130	-169	-169	-202
Carbon storage - 10 yrs (kg CO_2-eq)	-126	-127	-127	-161	-141	-217	-217	-228
Total (kg CO_2-eq) - 100 year	**27**	**24**	**25**	**26**	**-6**	**-151**	**-21**	**-101**
Total (kg CO_2-eq) - 50 year	20	20	21	-10	-57	-203	-73	-103
Total (kg CO_2-eq) - 20 year	-40	-42	-41	-81	-97	-287	-156	-122
Total (kg CO_2-eq) - 10 year	-75	-82	-81	-117	-108	-335	-205	-148

Notes:

- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit.

Table 5.16 Greenhouse gas balances - 1 tonne green waste to windrow composting (MAXIMUM net emissions)

	Compost to agriculture (sandy soil)	**Compost to agriculture (loam soil)**	**Compost to agriculture (clay soil)**	**Compost to grassland**	**Compost to topsoil manufacture**	**Compost use in growing media**	**Compost for mulch in landscaping**	**Compost to landfill**
Ancillary GHG (kg CO_2-eq)	30	30	30	30	34	32	32	30
GHG from fraction (kg CO_2-eq)	35	27	27	16	14	12	12	124
Avoided GHG (kg CO_2-eq)	-11	-10	-9	-2	-16	-163	-32	-14
Sub-total (kg CO_2-eq) – no storage credit	**54**	**47**	**48**	**44**	**33**	**-118**	**12**	**140**
Carbon storage - 100 yrs (kg CO_2-eq)	-24	-21	-21	-18	-39	-33	-33	-181
Carbon storage - 50 yrs (kg CO_2-eq)	-32	-25	-25	-54	-91	-85	-85	-183
Carbon storage - 20 yrs (kg CO_2-eq)	-92	-87	-87	-125	-130	-169	-169	-202
Carbon storage - 10 yrs (kg CO_2-eq)	-126	-127	-127	-161	-141	-217	-217	-228
Total (kg CO_2-eq) - 100 year	**29**	**26**	**27**	**26**	**-6**	**-151**	**-21**	**-41**
Total (kg CO_2-eq) - 50 year	22	22	23	-10	-57	-203	-73	-43
Total (kg CO_2-eq) - 20 year	-38	-40	-39	-81	-97	-287	-156	-62
Total (kg CO_2-eq) - 10 year	-73	-80	-79	-117	-108	-335	-205	-88

Notes:

- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit.

Table 5.17 *Net greenhouse gas impacts of 1 tonne green waste windrow composting versus 1 tonne green waste landfill (maximum)*

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Compost to agriculture (sandy soil)	-230	-13
Compost to agriculture (loam soil)	-237	-17
Compost to agriculture (clay soil)	-236	-16
Compost to grassland	-238	-15
Compost to topsoil manufacture	-249	-47
Compost use in growing media	-400	-192
Compost for mulch in landscaping	-270	-61
Compost to landfill	-202	-142

Note: Maximum = the difference between the maximum emissions for landfill and the minimum emissions for composting. Negative figures reflect potential savings.

Table 5.18 *Net greenhouse gas impacts of 1 tonne green waste windrow composting versus 1 tonne green waste landfill (minimum)*

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Compost to agriculture (sandy soil)	-89	127
Compost to agriculture (loam soil)	-96	124
Compost to agriculture (clay soil)	-95	125
Compost to grassland	-99	124
Compost to topsoil manufacture	-110	92
Compost use in growing media	-261	-53
Compost for mulch in landscaping	-131	77
Compost to landfill	-3	57

Note: Minimum = the difference between the minimum emissions for landfill and the maximum emissions for composting. Negative figures reflect potential savings. Positive figures reflect a *net impact* over landfill.

5.2.2 *Source Separation: In-Vessel Composting*

Figure 5.5 presents maximum and minimum GHG balances for the 'no storage credit' accounting scenario. A summary of all results for green waste in-vessel composting is presented in *Table 5.19* and *Table 5.20*.

GHG balances for green waste in-vessel composting are very similar to those for food waste in-vessel composting (discussed in *Section 5.1.1*). This is as expected, as the processing requirements and products from the process (green and food waste compost) are the same (1).

The range of potential benefits for each system in comparison with sending raw green waste to landfill are shown in *Table 5.21* and *Table 5.22*. We again see the phenomenon that landfill shows favourable net GHG balances when carbon sequestration benefits are accounted.

This is subject to the same uncertainties around the permanence of carbon storage, benefits of delay and loss of soil organic carbon, as discussed in *Section 5.2.1* and later in *Section 7*.

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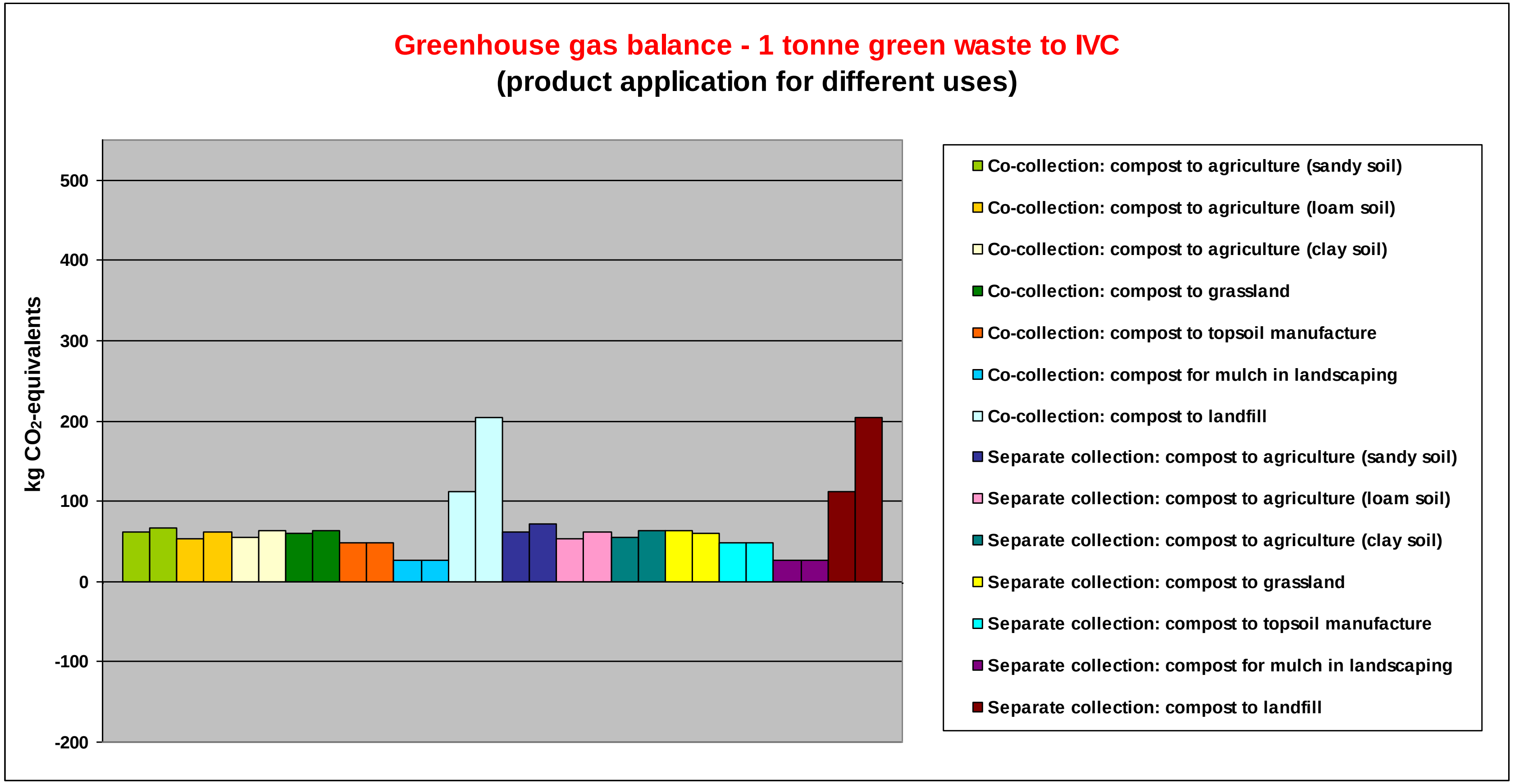
(1) The only difference is that green waste assumed to be rejected from the process has a different impact in landfill than food waste rejected from the process.

Figure 5.5 *Net greenhouse gas emissions: 1 tonne green waste to IVC: no carbon sequestration accounted*



Note: two bars are presented for each unit system, showing maximum and minimum potential emissions
Co-collection = collection with food waste

Table 5.19 Greenhouse gas balances - 1 tonne green waste to in-vessel composting (MINIMUM net emissions)

	Co-collection: compost to agric (sandy soil)	**Co-collection: compost to agric (loam soil)**	**Co-collection: compost to agric (clay soil)**	**Co-collection: compost to grassland**	**Co-collection: compost to topsoil manufacture**	**Co-collection: compost for mulch in landscaping**	**Co-collection: compost to landfill**
Ancillary GHG (kg CO_2-eq)	44	44	44	44	48	46	44
GHG from fraction (kg CO_2-eq)	43	31	31	19	16	10	97
Avoided GHG (kg CO_2-eq)	-25	-22	-20	-2	-16	-30	-30
Sub-total (kg CO_2-eq) – no storage credit	**62**	**53**	**55**	**60**	**49**	**26**	**111**
Carbon storage - 100 yrs (kg CO_2-eq)	-28	-23	-23	-18	-43	-33	-172
Carbon storage - 50 yrs (kg CO_2-eq)	-37	-27	-27	-62	-102	-88	-175
Carbon storage - 20 yrs (kg CO_2-eq)	-110	-103	-103	-152	-156	-176	-198
Carbon storage - 10 yrs (kg CO_2-eq)	-151	-152	-153	-198	-172	-227	-229
Total (kg CO_2-eq) - 100 year	**34**	**30**	**31**	**42**	**6**	**-7**	**-61**
Total (kg CO_2-eq) - 50 year	25	26	27	-2	-54	-62	-63
Total (kg CO_2-eq) - 20 year	-49	-50	-49	-91	-107	-150	-87
Total (kg CO_2-eq) - 10 year	-89	-99	-98	-138	-123	-201	-118

Notes:

- Results for separate and co-collection were found to be very similar. Only results for co-collection are presented, to avoid duplication.
- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit

Table 5.20 Greenhouse gas balances - 1 tonne green waste to in-vessel composting (MAXIMUM net emissions)

	Co-collection: compost to agric (sandy soil)	**Co-collection: compost to agric (loam soil)**	**Co-collection: compost to agric (clay soil)**	**Co-collection: compost to grassland**	**Co-collection: compost to topsoil manufacture**	**Co-collection: compost for mulch in landscaping**	**Co-collection: compost to landfill**
Ancillary GHG (kg CO_2-eq)	44	44	44	44	48	46	44
GHG from fraction (kg CO_2-eq)	43	31	31	19	16	10	180
Avoided GHG (kg CO_2-eq)	-19	-16	-15	-2	-16	-30	-21
Sub-total (kg CO_2-eq) – no storage credit	**67**	**59**	**60**	**60**	**49**	**26**	**204**
Carbon storage - 100 yrs (kg CO_2-eq)	-28	-23	-23	-18	-43	-33	-172
Carbon storage - 50 yrs (kg CO_2-eq)	-37	-27	-27	-62	-102	-88	-175
Carbon storage - 20 yrs (kg CO_2-eq)	-110	-103	-103	-152	-156	-176	-198
Carbon storage - 10 yrs (kg CO_2-eq)	-151	-152	-153	-198	-172	-227	-229
Total (kg CO_2-eq) - 100 year	**39**	**36**	**37**	**42**	**6**	**-7**	**31**
Total (kg CO_2-eq) - 50 year	30	32	33	-2	-54	-62	29
Total (kg CO_2-eq) - 20 year	-43	-44	-43	-91	-107	-150	6
Total (kg CO_2-eq) - 10 year	-84	-93	-92	-138	-123	-201	-26

Notes:

- Results for separate and co-collection were found to be very similar. Only results for co-collection are presented, to avoid duplication.
- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit

Table 5.21 Net greenhouse gas impacts of 1 tonne green waste IVC composting versus 1 tonne green waste landfill (maximum)

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Co-collection: compost to agriculture (sandy soil)	-220	-7
Co-collection: compost to agriculture (loam soil)	-229	-11
Co-collection: compost to agriculture (clay soil)	-227	-9
Co-collection: compost to grassland	-221	1
Co-collection: compost to topsoil manufacture	-233	-35
Co-collection: compost for mulch in landscaping	-256	-48
Co-collection: compost to landfill	-171	-102
Separate collection: compost to agriculture (sandy soil)	-220	-7
Separate collection: compost to agriculture (loam soil)	-229	-11
Separate collection: compost to agriculture (clay soil)	-227	-9
Separate collection: compost to grassland	-221	1
Separate collection: compost to topsoil manufacture	-233	-35
Separate collection: compost for mulch in landscaping	-256	-48
Separate collection: compost to landfill	-171	-102

Note: Maximum = the difference between the maximum emissions for landfill and the minimum emissions for composting. Negative figures reflect potential savings. Positive figures reflect a *net impact* over landfill.

Table 5.22 Net greenhouse gas impacts of 1 tonne green waste IVC composting versus 1 tonne green waste landfill (minimum)

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Co-collection: compost to agriculture (sandy soil)	-76	138
Co-collection: compost to agriculture (loam soil)	-84	134
Co-collection: compost to agriculture (clay soil)	-83	135
Co-collection: compost to grassland	-83	140
Co-collection: compost to topsoil manufacture	-94	104
Co-collection: compost for mulch in landscaping	-117	91
Co-collection: compost to landfill	61	130
Separate collection: compost to agriculture (sandy soil)	-76	138
Separate collection: compost to agriculture (loam soil)	-84	134
Separate collection: compost to agriculture (clay soil)	-83	135
Separate collection: compost to grassland	-83	140
Separate collection: compost to topsoil manufacture	-94	104
Separate collection: compost for mulch in landscaping	-117	91
Separate collection: compost to landfill	61	130

Note: Minimum = the difference between the minimum emissions for landfill and the maximum emissions for composting. Negative figures reflect potential savings. Positive figures reflect a *net impact* over landfill.

5.2.3 *Source Separation: Anaerobic Digestion*

Figure 5.6 presents maximum and minimum GHG balances for the 'no storage credit' accounting scenario. A summary of all results for green waste anaerobic digestion is presented in *Table 5.23* and *Table 5.24*.

GHG balances for green waste co-digestion with food waste are, as expected, very similar to those for food waste co-digestion (discussed in *Section 5.2.3*). Processing requirements and products from the process (green and food waste digestate and liquor) are the same (1).

The range of potential benefits for each system in comparison with sending raw green waste to landfill are shown in *Table 5.25* and *Table 5.26*. Again, we see the phenomenon that landfill shows favourable net GHG balances when carbon sequestration benefits are accounted.

This is subject to the same uncertainties around the permanence of carbon storage, benefits of delay and loss of soil organic carbon, as discussed in *Section 5.2.1* and later in *Section 7*.

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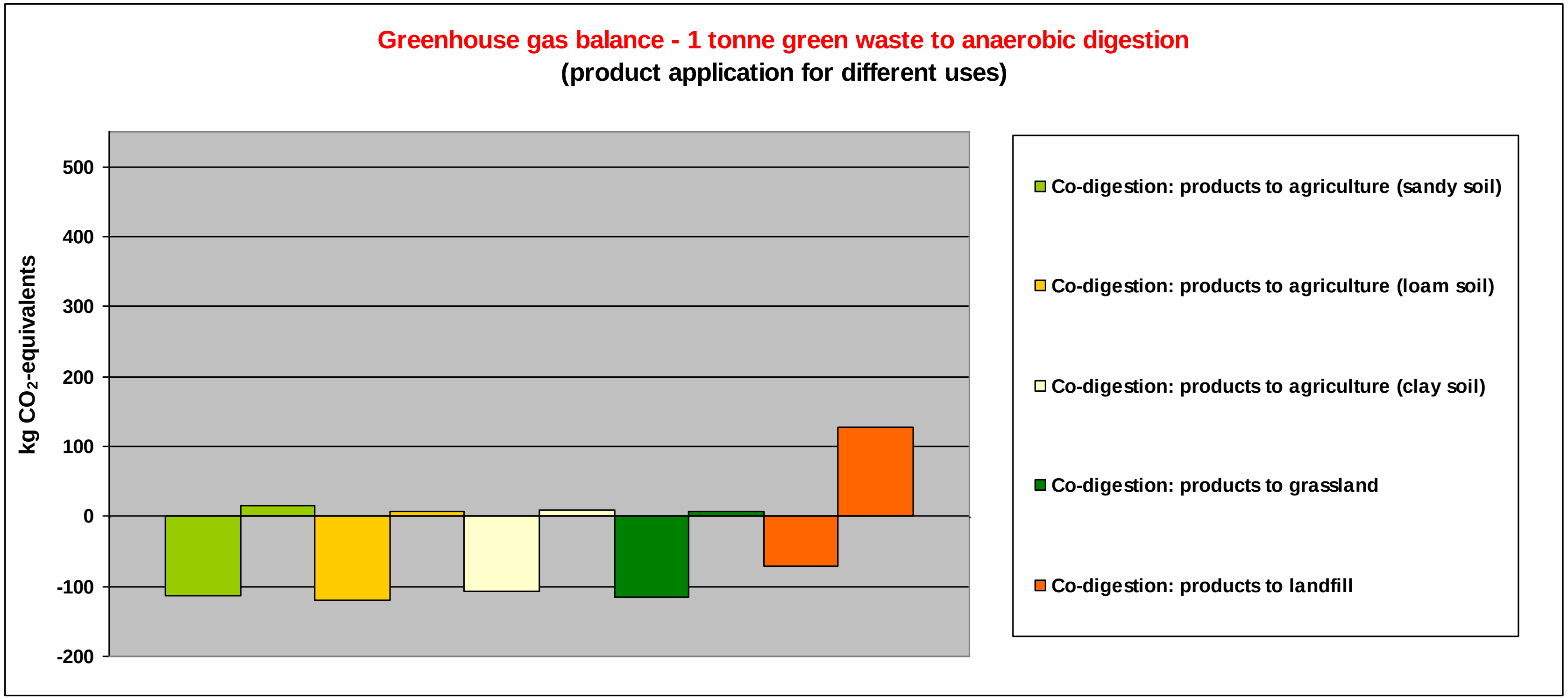
(1) The only difference is that green waste assumed to be rejected from the process has a different impact in landfill than food waste rejected from the process.

Figure 5.6 *Net greenhouse gas emissions: 1 tonne green waste to AD: no carbon sequestration accounted*



Note: two bars are presented for each unit system, showing maximum and minimum potential emissions
Co-digestion = digestion with food waste

Table 5.23 Greenhouse gas balances - 1 tonne green waste to anaerobic digestion (MINIMUM net emissions)

	Co-digestion: products to agriculture (sandy soil)	**Co-digestion: products to agriculture (loam soil)**	**Co-digestion: products to agriculture (clay soil)**	**Co-digestion: products to grassland**	**Co-digestion: products to landfill**
Ancillary GHG (kg CO_2-eq)	45	45	45	45	47
GHG from fraction (kg CO_2-eq)	33	24	36	15	81
Avoided GHG (kg CO_2-eq)	-190	-189	-187	-175	-198
Sub-total (kg CO_2-eq) – no storage credit	**-113**	**-120**	**-107**	**-115**	**-71**
Carbon storage - 100 yrs (kg CO_2-eq)	-15	-12	-12	-7	-124
Carbon storage - 50 yrs (kg CO_2-eq)	-21	-13	-13	-32	-127
Carbon storage - 20 yrs (kg CO_2-eq)	-62	-56	-56	-84	-148
Carbon storage - 10 yrs (kg CO_2-eq)	-82	-83	-83	-110	-174
Total (kg CO_2-eq) - 100 year	**-128**	**-131**	**-119**	**-122**	**-195**
Total (kg CO_2-eq) - 50 year	-133	-133	-120	-147	-197
Total (kg CO_2-eq) - 20 year	-175	-176	-163	-200	-218
Total (kg CO_2-eq) - 10 year	-195	-202	-190	-226	-245

Notes:

- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit.

Table 5.24 Greenhouse gas balances - 1 tonne green waste to anaerobic digestion (MAXIMUM net emissions)

	Co-digestion: products to agriculture (sandy soil)	**Co-digestion: products to agriculture (loam soil)**	**Co-digestion: products to agriculture (clay soil)**	**Co-digestion: products to grassland**	**Co-digestion: products to landfill**
Ancillary GHG (kg CO_2-eq)	45	45	45	45	47
GHG from fraction (kg CO_2-eq)	33	24	36	15	150
Avoided GHG (kg CO_2-eq)	-65	-64	-63	-54	-69
Sub-total (kg CO_2-eq) – no storage credit	**12**	**5**	**18**	**5**	**127**
Carbon storage - 100 yrs (kg CO_2-eq)	-15	-12	-12	-7	-124
Carbon storage - 50 yrs (kg CO_2-eq)	-21	-13	-13	-32	-127
Carbon storage - 20 yrs (kg CO_2-eq)	-62	-56	-56	-84	-148
Carbon storage - 10 yrs (kg CO_2-eq)	-82	-83	-83	-110	-174
Total (kg CO_2-eq) - 100 year	**-3**	**-6**	**6**	**-1**	**3**
Total (kg CO_2-eq) - 50 year	-8	-8	5	-27	1
Total (kg CO_2-eq) - 20 year	-50	-51	-38	-79	-20
Total (kg CO_2-eq) - 10 year	-70	-77	-65	-105	-47

Notes:

- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit.

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Table 5.25 Net greenhouse gas impacts of 1 tonne green waste AD versus 1 tonne green waste landfill (maximum)

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Co-digestion: products to agriculture (sandy soil)	-395	-169
Co-digestion: products to agriculture (loam soil)	-401	-172
Co-digestion: products to agriculture (clay soil)	-389	-159
Co-digestion: products to grassland	-397	-163
Co-digestion: products to landfill	-353	-236

Note: Maximum = the difference between the maximum emissions for landfill and the minimum emissions for AD. Negative figures reflect potential savings.

Table 5.26 Net greenhouse gas impacts of 1 tonne green waste AD versus 1 tonne green waste landfill (minimum)

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Co-digestion: products to agriculture (sandy soil)	-131	95
Co-digestion: products to agriculture (loam soil)	-138	92
Co-digestion: products to agriculture (clay soil)	-125	104
Co-digestion: products to grassland	-138	97
Co-digestion: products to landfill	-16	101

Note: Minimum = the difference between the minimum emissions for landfill and the maximum emissions for AD. Negative figures reflect potential savings. Positive figures reflect a *net impact* over landfill.

5.2.4 *Residual Treatment*

Figure 5.7 presents maximum and minimum GHG balances for the 'no storage credit' accounting scenario. A summary of all results for residual green waste systems is presented in *Table 5.27* and *Table 5.28.*

Table 5.27 and *Table 5.28* show the ancillary burdens of collecting and processing green waste as a residual fraction to be up to as much as 50% higher than for source-separated systems. All residual treatment systems incurred increased collection transport burdens. For MBT systems, additional impacts were also borne in the increased fuel requirements of processing.

A large 'GHG from fraction' emission is shown for the disposal of raw green waste in landfill. This is associated with the CH_4 generated as this material degrades in an anaerobic environment. Note that the large difference between maximum and minimum profiles relates to assumptions with regard to landfill gas collection (50% gas collection and 75% gas collection assumed respectively).

Where products from MBT are disposed in landfill, 'GHG from fraction' emissions are lower – but not to the extent observed when comparing raw food wastes to landfill with stabilised products. This is because raw green wastes are inherently less degradable than food wastes, and so less of a reduction can be achieved. As a result, the MBT of green waste performs poorly in comparison with landfill when lower landfill gas capture rates are achieved.

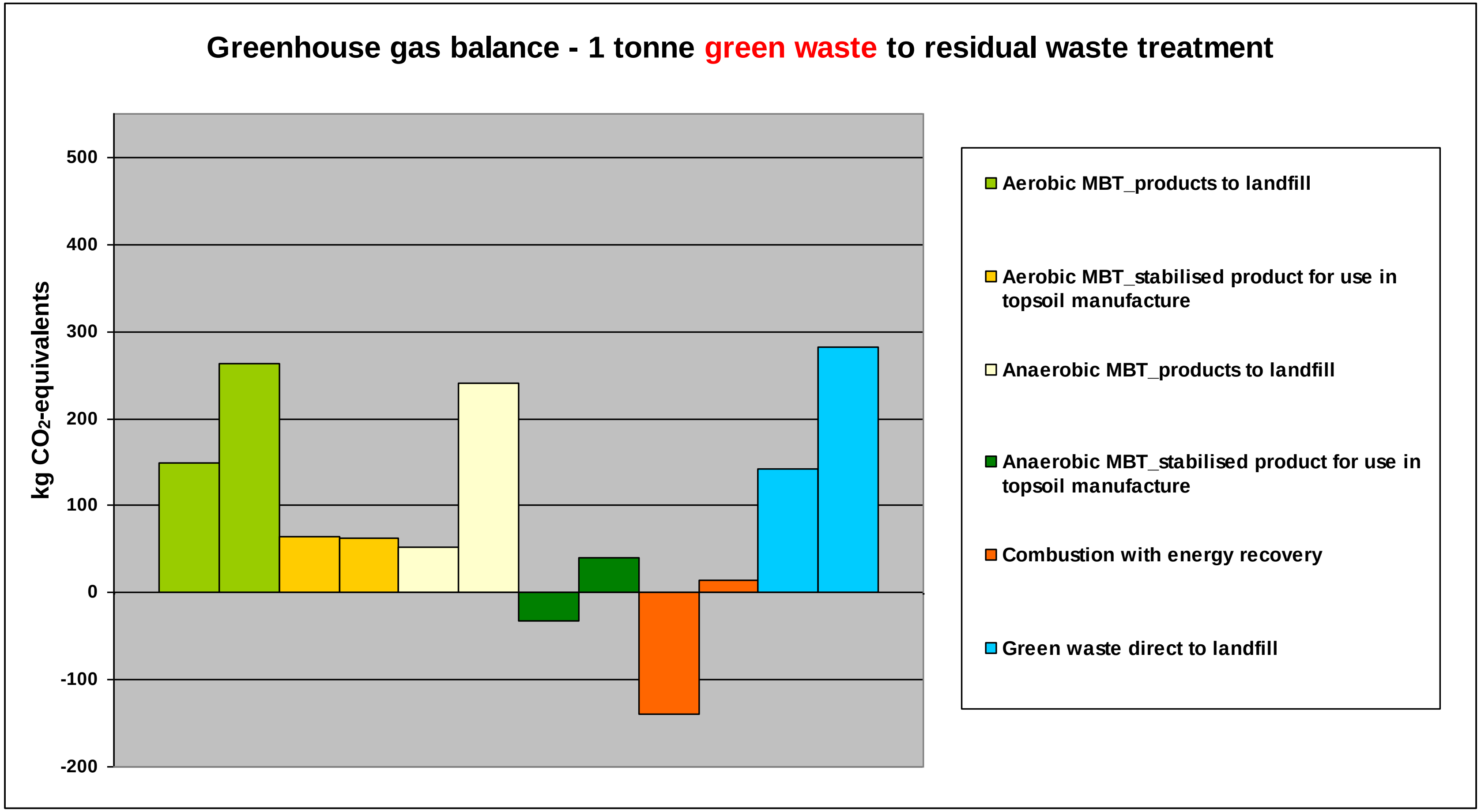
Where MBT products are used for topsoil manufacture, much lower GHG releases from the degradation of products is seen. In fact, soil modelling showed N_2O emissions from this use route to be relatively low (*Annex D*). This leads the MBT system with energy recovery through AD to perform comparatively well.

Avoided GHG emissions are highest for the anaerobic MBT and combustion systems. As for other systems, the range of potential benefits seen is reflective of the assumed range of energy conversion efficiencies achievable (*Table 4.1*).

The range of potential benefits for each residual treatment system in comparison with sending raw green waste to landfill is shown in *Table 5.29* and *Table 5.30*. Maximum benefits show the difference between the maximum emissions for landfill and the minimum emissions for treatment. Minimum benefits show the difference between the minimum emissions for landfill and the maximum emissions for treatment.

The implications of different carbon accounting methods for net GHG balances are discussed further in *Section 7.2* and are subject to the same uncertainties around the permanence of carbon storage, benefits of delay and loss of soil organic carbon discussed in *Section 5.2.1*.

Figure 5.7 Net greenhouse gas emissions: 1 tonne green in residual waste: no carbon sequestration accounted



Note: two bars are presented for each unit system, showing maximum and minimum potential emissions

Table 5.27 Greenhouse gas balances - 1 tonne green in residual waste (MINIMUM net emissions)

	Aerobic MBT: products to landfill	**Aerobic MBT: stabilised product for use in topsoil manufacture**	**Anaerobic MBT: products to landfill**	**Anaerobic MBT: stabilised product for use in topsoil manufacture**	**Combustion with energy recovery**	**Green waste direct to landfill**
Ancillary GHG (kg CO_2-eq)	69	72	79	83	43	53
GHG from fraction (kg CO_2-eq)	117	7	117	7	8	131
Avoided GHG (kg CO_2-eq)	-37	-16	-143	-123	-191	-42
Sub-total (kg CO_2-eq) – no storage credit	**148**	**64**	**53**	**-32**	**-139**	**143**
Carbon storage - 100 yrs (kg CO_2-eq)	-195	-42	-200	-45	-13	-241
Carbon storage - 50 yrs (kg CO_2-eq)	-198	-89	-204	-98	-13	-243
Carbon storage - 20 yrs (kg CO_2-eq)	-229	-159	-236	-171	-13	-286
Carbon storage - 10 yrs (kg CO_2-eq)	-271	-189	-279	-199	-13	-381
Total (kg CO_2-eq) - 100 year	**-46**	**22**	**-148**	**-77**	**-152**	**-98**
Total (kg CO_2-eq) - 50 year	-50	-25	-151	-130	-152	-100
Total (kg CO_2-eq) - 20 year	-81	-95	-183	-203	-152	-143
Total (kg CO_2-eq) - 10 year	-123	-126	-226	-231	-152	-238

Notes:

- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit.

Table 5.28 Greenhouse gas balances - 1 tonne green in residual waste (MAXIMUM net emissions)

	Aerobic MBT: products to landfill	**Aerobic MBT: stabilised product for use in topsoil manufacture**	**Anaerobic MBT: products to landfill**	**Anaerobic MBT: stabilised product for use in topsoil manufacture**	**Combustion with energy recovery**	**Green waste direct to landfill**
Ancillary GHG (kg CO_2-eq)	68	72	79	83	43	53
GHG from fraction (kg CO_2-eq)	220	7	220	7	8	256
Avoided GHG (kg CO_2-eq)	-26	-16	-57	-48	-38	-28
Sub-total (kg CO_2-eq) – no storage credit	**262**	**64**	**241**	**42**	**14**	**282**
Carbon storage - 100 yrs (kg CO_2-eq)	-195	-42	-200	-45	-13	-241
Carbon storage - 50 yrs (kg CO_2-eq)	-198	-89	-204	-98	-13	-243
Carbon storage - 20 yrs (kg CO_2-eq)	-229	-159	-236	-171	-13	-286
Carbon storage - 10 yrs (kg CO_2-eq)	-271	-189	-279	-199	-13	-381
Total (kg CO_2-eq) - 100 year	**68**	**22**	**41**	**-2**	**1**	**41**
Total (kg CO_2-eq) - 50 year	65	-25	38	-55	1	39
Total (kg CO_2-eq) - 20 year	34	-95	6	-128	1	-4
Total (kg CO_2-eq) - 10 year	-8	-126	-38	-157	1	-99

Notes:

- Negative greenhouse gas figures reflect potential savings.
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit.

Table 5.29 *Net greenhouse gas impacts of 1 tonne green in treated residual waste versus 1 tonne green waste landfill (maximum)*

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Aerobic MBT: products to landfill	-134	-87
Aerobic MBT: stabilised product for use in topsoil manufacture	-218	-19
Anaerobic MBT: products to landfill	-229	-189
Anaerobic MBT: stabilised product for use in topsoil manufacture	-314	-117
Combustion with energy recovery	-421	-192

Note: Maximum = the difference between the maximum emissions for landfill and the minimum emissions for treatment. Negative figures reflect potential savings.

Table 5.30 *Net greenhouse gas impacts of 1 tonne green in treated residual waste versus 1 tonne green waste landfill (minimum)*

	Net impact over landfill of raw waste – no C seq (kg CO_2-eq)	**Net impact over landfill of raw waste - 100 year C seq (kg CO_2-eq)**
Aerobic MBT: products to landfill	120	166
Aerobic MBT: stabilised product for use in topsoil manufacture	-79	120
Anaerobic MBT: products to landfill	98	139
Anaerobic MBT: stabilised product for use in topsoil manufacture	-101	96
Combustion with energy recovery	-129	99

Note: Minimum = the difference between the minimum emissions for landfill and the maximum emissions for treatment. Negative figures reflect potential savings. Positive figures reflect a *net impact* over landfill.

6 *RESULTS: SCENARIOS*

6.1 *COMPILING GREENHOUSE GAS BALANCES FOR SCENARIOS*

GHG balances were quantified for the management of municipal and commercial food wastes and municipal green wastes arising in each year from 2006 to 2032.

Net GHG emissions over time for waste collection, treatment and product use/disposal were multiplied by waste tonnages passing via each route in each year. Committed net emissions for a period of 100 years following the final use/disposal of each material were also captured (1). Total GHG balances for the scenarios assessed combined both emissions over the management period assessed, plus committed releases.

An outline of scenarios is presented in *Table 3.4*. Baseline arisings and management are presented in *Table 3.5*. In considering results, also note the following.

- Recovery (collection) levels were as follows: 90% for residual waste treatment; 90% for source-separation of green waste; and 75% for source-separation of food waste. The remaining fraction was assumed to be landfilled (ie 100% diversion assumed not to be achievable).
- For each scenario, it was assumed that 2006 throughput tonnages for the target treatment route (eg windrow, AD, aerobic MBT) would increase linearly over the management period, to meet upper limits in 2032. Similarly, current treatment capacities for alternative management methods were phased out linearly over this period wherever applicable.
- Waste arisings were assumed to remain static over the management period (total arisings over period: 312 Mt food waste; 282 Mt green waste).

Resulting maximum and minimum GHG balances are shown diagrammatically for the 'no storage credit' accounting scenario (*Figure 6.1*). A summary of all calculated results is presented in *Table 6.1* and *Table 6.2*.

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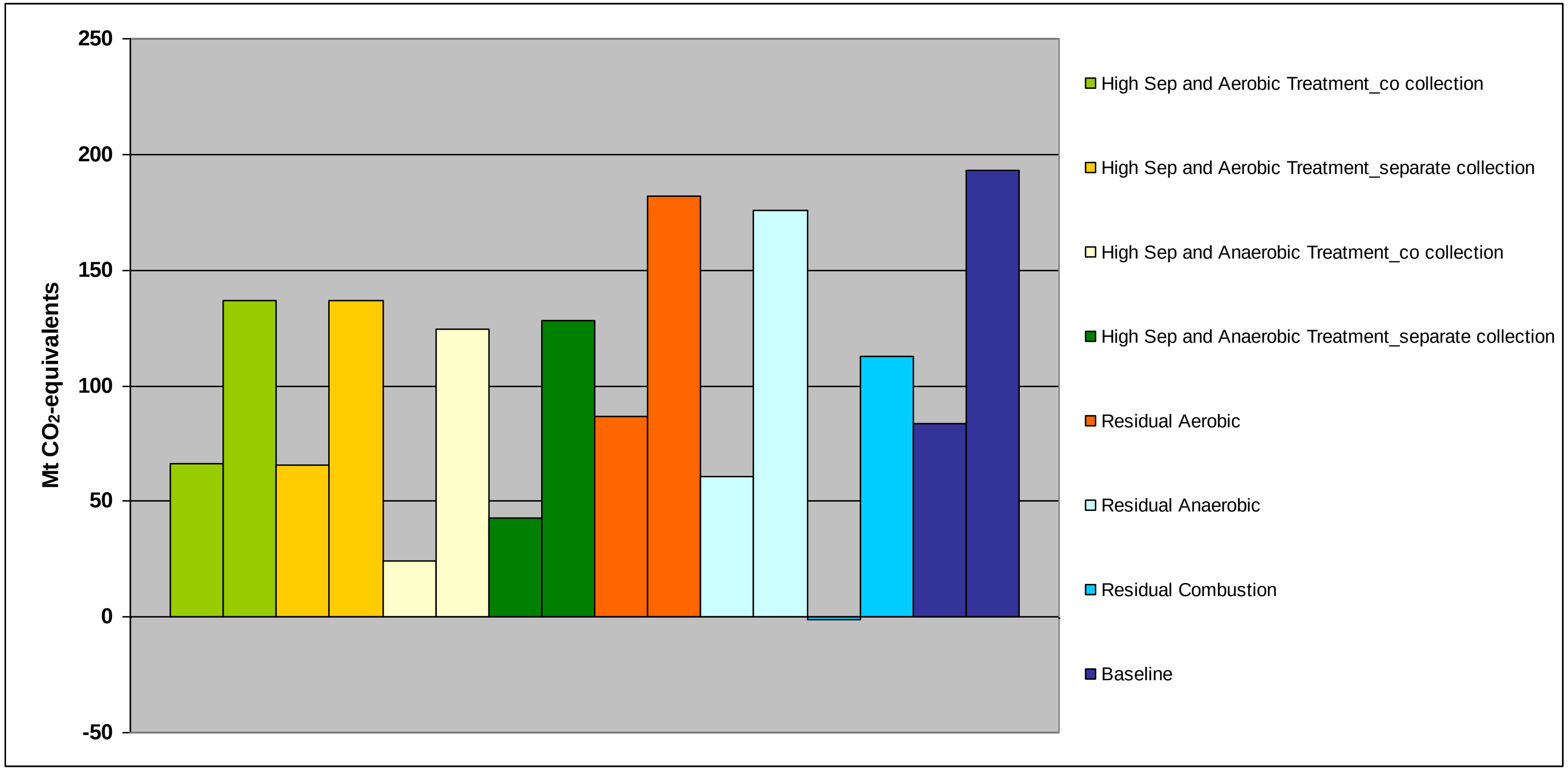
(1) This is the period over which the vast majority of degradable carbon in waste materials will have mineralised

Figure 6.1 Net greenhouse gas emissions: alternatives scenarios for food and green waste management



Note: Two bars are presented for each unit system, showing maximum and minimum potential emissions
Net GHG balances reflect the management of food and green wastes over the period 2006-2032

Table 6.1 *Greenhouse gas balances – scenario MINIMUM net emissions*

	High source-separation and aerobic treatment (co-collection)	**High source-separation and aerobic treatment (separate collection)**	**High source-separation and anaerobic treatment (co-collection)**	**High source-separation and anaerobic treatment (separate collection)**	**High residual aerobic treatment (aerobic MBT)**	**High residual anaerobic treatment (anaerobic MBT)**	**High residual thermal treatment**	**Baseline – current management**
Ancillary GHG (Mt CO_2-eq)	28.1	27.4	28.0	26.3	34.5	37.1	27.6	29.6
GHG from fraction (Mt CO_2-eq)	68.7	68.8	66.8	66.2	56.9	56.9	57.3	96.5
Avoided GHG (Mt CO_2-eq)	-30.2	-30.2	-70.8	-49.6	-27.8	-56.4	-86.2	-42.4
Sub-total (kg CO_2-eq) – no carbon credit	**66.6**	**66.0**	**24.0**	**42.9**	**63.6**	**37.6**	**-1.3**	**83.7**
Carbon storage - 100 yrs (Mt CO_2-eq)	-54.3	-55.1	-50.6	-52.3	-58.3	-59.4	-49.0	-80.6
Carbon storage - 50 yrs (Mt CO_2-eq)	-69.6	-69.8	-59.6	-62.8	-81.1	-84.3	-51.5	-87.3
Carbon storage - 20 yrs (Mt CO_2-eq)	-105.1	-104.9	-93.9	-95.9	-102.7	-103.3	-76.6	-119.8
Carbon storage - 10 yrs (Mt CO_2-eq)	-70.5	-70.9	-67.5	-68.0	-68.8	-68.8	-62.3	-74.6
Total (Mt CO_2-eq) - 100 year	**12.3**	**10.9**	**-26.6**	**-9.3**	**5.4**	**-21.8**	**-50.3**	**3.1**

Notes:

- Negative greenhouse gas figures reflect potential savings.
- Greenhouse gas balances reflect the management of food and green wastes over the period 2006-2032
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit.

Table 6.2 *Greenhouse gas balances – scenario MAXIMUM net emissions*

	High source-separation and aerobic treatment (co-collection)	**High source-separation and aerobic treatment (separate collection)**	**High source-separation and anaerobic treatment (co-collection)**	**High source-separation and anaerobic treatment (separate collection)**	**High residual aerobic treatment (aerobic MBT)**	**High residual anaerobic treatment (anaerobic MBT)**	**High residual thermal treatment**	**Baseline – current management**
Ancillary GHG (Mt CO_2-eq)	28.1	27.3	28.0	26.2	34.5	37.0	27.5	29.6
GHG from fraction (Mt CO_2-eq)	126.9	127.5	126.2	125.0	111.2	111.2	110.7	186.7
Avoided GHG (Mt CO_2-eq)	-18.0	-18.1	-29.4	-23.3	-17.2	-25.8	-25.4	-23.3
Sub-total (kg CO_2-eq) – no storage credit	**136.9**	**136.6**	**124.7**	**127.9**	**128.5**	**122.4**	**112.9**	**193.0**
Carbon storage - 100 yrs (Mt CO_2-eq)	-54.3	-55.1	-50.6	-52.3	-58.3	-59.4	-49.0	-80.6
Carbon storage - 50 yrs (Mt CO_2-eq)	-69.6	-69.8	-59.6	-62.8	-81.1	-84.3	-51.5	-87.3
Carbon storage - 20 yrs (Mt CO_2-eq)	-105.1	-104.9	-93.9	-95.9	-102.7	-103.3	-76.6	-119.8
Carbon storage - 10 yrs (Mt CO_2-eq)	-70.5	-70.9	-67.5	-68.0	-68.8	-68.8	-62.3	-74.6
Total (Mt CO_2-eq) - 100 year	**82.6**	**81.6**	**74.1**	**75.6**	**70.2**	**63.0**	**63.9**	**112.4**

Notes:

- Negative greenhouse gas figures reflect potential savings.
- Greenhouse gas balances reflect the management of food and green wastes over the period 2006-2032
- 'Ancillary GHG' relates to the GHG emissions associated with container production, transportation steps and fuel, energy and material inputs to processing and product use.
- 'GHG from fraction' relates to direct GHG emissions from waste treatment processes and accumulated GHG emissions over a period of 100 years from when products are used or disposed. For agricultural systems these are predominantly a result of N_20 releases. For landfilled products, these are predominantly a result of CH_4 emissions.
- 'Avoided GHG' are the potential savings in GHG emissions as a result of energy recovery (avoiding generation by fossil means) or substitution of materials, eg mineral fertilisers.
- 'Carbon storage' relates to the credit given to carbon that has not degraded (and remains in soil or landfill) after different time periods.
- Totals show indicative emissions estimates under different carbon accounting scenarios. A sum of ancillary GHG + GHG from fraction + avoided GHG + carbon storage credit.

Figure 6.1 shows a large range between the maximum and minimum GHG emissions calculated for each scenario. This is primarily a result of upper- and lower-limit assumptions for landfill gas capture (75% and 50% respectively). As a management method, landfill contributes to all scenarios, as it was considered that there will inevitably be some landfill of residual materials (particularly in the context of C&I arisings).

Landfill gas capture is an area of uncertainty which reflects less on the current operational aspects of the landfill (1), and more on our understanding of longer term fugitive emissions when emissions tail off. As such, it is reasonable to consider that if landfill gas capture is low for one scenario, it will be similarly so for another (and vice versa). So it is useful to compare the minimum net emissions between scenarios and maximum net emissions between scenarios.

On this basis, the balances presented clearly show all scenarios to demonstrate significantly reduced GHG emissions in comparison with the baseline. This is true when no carbon storage credits are applied, and where gas capture is low. If it assumed that all carbon remaining after 100 years is effectively sequestered, and landfill gas capture is high, then only those scenarios that include some form of energy recovery perform favourably. This is due to the significant sequestration credit allocated to slowly degrading materials in landfill – particularly green waste (discussed further in *Section 7.1*).

Shorter term carbon storage periods have not been assessed for these scenarios, due to the complexities of the need to apply different cut-off points for carbon arising in every year. However, given that calculations are based on the same degradation rates as those presented in unit analyses, we would expect the trends similarly seen to apply. If a credit is given to carbon stored over shorter periods, the net emissions for all scenarios will decrease, favouring those scenarios that landfill more slowly degrading materials (green waste and green waste treatment products).

The results broadly show those scenarios encompassing high rates of energy recovery to perform favourably: separation and anaerobic treatment, residual anaerobic MBT and thermal treatment. Residual thermal treatment performs comparatively well as a result of the assumption that 90% of residual wastes could be diverted to treatment. In comparison, it was assumed that a maximum of 75% of food waste could be separately collected. In the light of demonstrated performance of separation systems in Europe, it is not unreasonable to consider that achievable recovery rates will be lower for these materials over the time period assessed.

Note that it was assumed that the predominant outlet for products derived from MBT would be as daily landfill cover. If a sustained market for their use in land remediation activities is achieved, unit system analyses have shown that the net GHG emissions of these scenarios would be significantly lowered.

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(1) With an expectation to capture at least 85% of gas emissions.

The burdens of ancillary activities, such as transportation and processing, are shown to be not insignificant, but relatively similar between scenarios (with the exception of MBT). Home composting was not included in the scenario assessment, and a lack of data exists to characterise the performance of systems and the use and fate of products. If it had, we would expect to see the burdens of ancillary activities to be considerably lowered (and all but disappear for the home composting element itself). The unknown, however, is with respect to quantifying the benefits that can be secured when using the products, and the emissions they incur during use (and processing).

With regard to differences between the co- and separate collection scenarios, to all extents and purposes, the high aerobic treatment scenarios perform the same. A sensitivity test carried out during unit system analyses showed that the potential impacts of the co-collection system could be significantly increased if co-collection were to result in increased organic residues.

The high anaerobic co-collection system shows reduced GHG emissions in comparison with separate collection. This is due to the relative make-up of the scenarios. The separate collection scenario is assessing the maximum separation of food waste for digestion, and green waste for composting. The co-collection scenario assesses the maximum separation of both materials for anaerobic digestion – hence more material is available for energy recovery.

The following limitations of scenario analyses must be noted:

- the scenarios presented are simplistic and assessed at a strategic, not operational, level. It is in no way suggested that these are the only configurations possible. More, they assess the potential for the range of broad alternative methods for management of these waste streams.
- the scenarios presented do not attempt to assess the influence that a technology or collection route might have on waste arisings or the composition of residual wastes; and
- the treatment of biowaste materials in residual waste will not be in isolation, as other materials will be treated at the same time and their management will have knock-on implications from both an operational and greenhouse gas perspective. For example, the presence of plastic bags, may negatively affect some treatment process efficiencies, or increase net greenhouse gas emissions when thermally treated. Hence the greenhouse gas implications of increased residual waste collection cannot be considered for biowaste materials in isolation. It was not within the scope of the research to assess the wider implications of treating residual waste. However, earlier research (ERM, 2006a; 2006b) has explored this further.

7 DISCUSSION AND CONCLUSIONS

7.1 RESULTS SENSITIVITY

A piece of research of this complexity requires a large amount of data from dispersed sources. There are often also gaps in available data and so a number of assumptions must be made. It is important therefore to identify where the results are most significantly influenced by these assumptions, and we have attempted to do so throughout this report.

The following sets out the main ways in which uncertainty has been introduced into the research, and how these have been tackled by sensitivity analysis, or other means. More specific limitations of the results presented are discussed in *Section 7.4*.

- ***Uncertainty in direct emissions, inputs and outputs.*** Where input parameters were known to be sensitive (eg from previous research), ranges were assessed. Energy recovery and landfill gas recovery were the key parameters assessed in this way. Another way of assessing variability was to consider a number of variations within unit systems – for example collecting wastes either separately, or together. In this example, it was shown that results for co-collection and separate collection systems were very similar, and so we can infer that the results are not sensitive to collection assumptions (1).
- ***Uncertainty in emission factors for inputs, outputs and material and energy savings.*** The best available data were used to translate process inputs and outputs into greenhouse gas emissions (CO_2-equivalents). However, these emissions factors are sourced from secondary databases and so do not directly reflect actual emissions. In analysing results, this potential sensitivity was considered, but for the majority of parameters was either found not to have significant influence, or not to have an appropriate alternative.

  This is with the exception of the emission factor used to describe the potential savings associated with energy recovery. It is conceivable that over time the efficiency of the fossil energy generation technologies that are offset by recovering energy from wastes will increase.

  In the core analyses, it was assumed that electricity generation by CCGT operating at the current UK average of 46.7% would be offset. A sensitivity test considered greenhouse gas implications should the average efficiency of these plants be increased to 53.2% (representative of UK F Class CCGT plant). It was found that the relative performance of energy recovery technologies was decreased, as might be expected. However, this

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(1) Note, however, that assessment did not consider the implications of differences in contamination, or in the total quantity of materials recovered, as a result of collection infrastructure. These elements are explored in more detail in recent work undertaken by Eunomia for WRAP (Eunomia, 2007a; 2007b)

decrease did not have any effect on the main findings from the study (*Section 0*).

- ***Methodological uncertainty.*** Commonly in life cycle studies, the temporal boundaries of the study are such that all of the biogenic carbon within organic materials is assumed to degrade within the period assessed. In this study, sensitivity analysis was used to infer what the implications for results might be should we allocate a sequestration benefit to biogenic carbon that does not degrade, but is stored in landfill, or another soil sink.

A statistical margin of error is near impossible to generate for this type of assessment, as we do not have clarity on the full distribution of data points to enable a statistical analysis. Instead, ranges have been presented throughout – reflecting the maximum and minimum greenhouse gas emissions likely to occur as a result of the waste management systems assessed. In some cases, these ranges are large and show that, within the current boundaries of uncertainty, it cannot be equivocally determined that one system confers lower emissions than another.

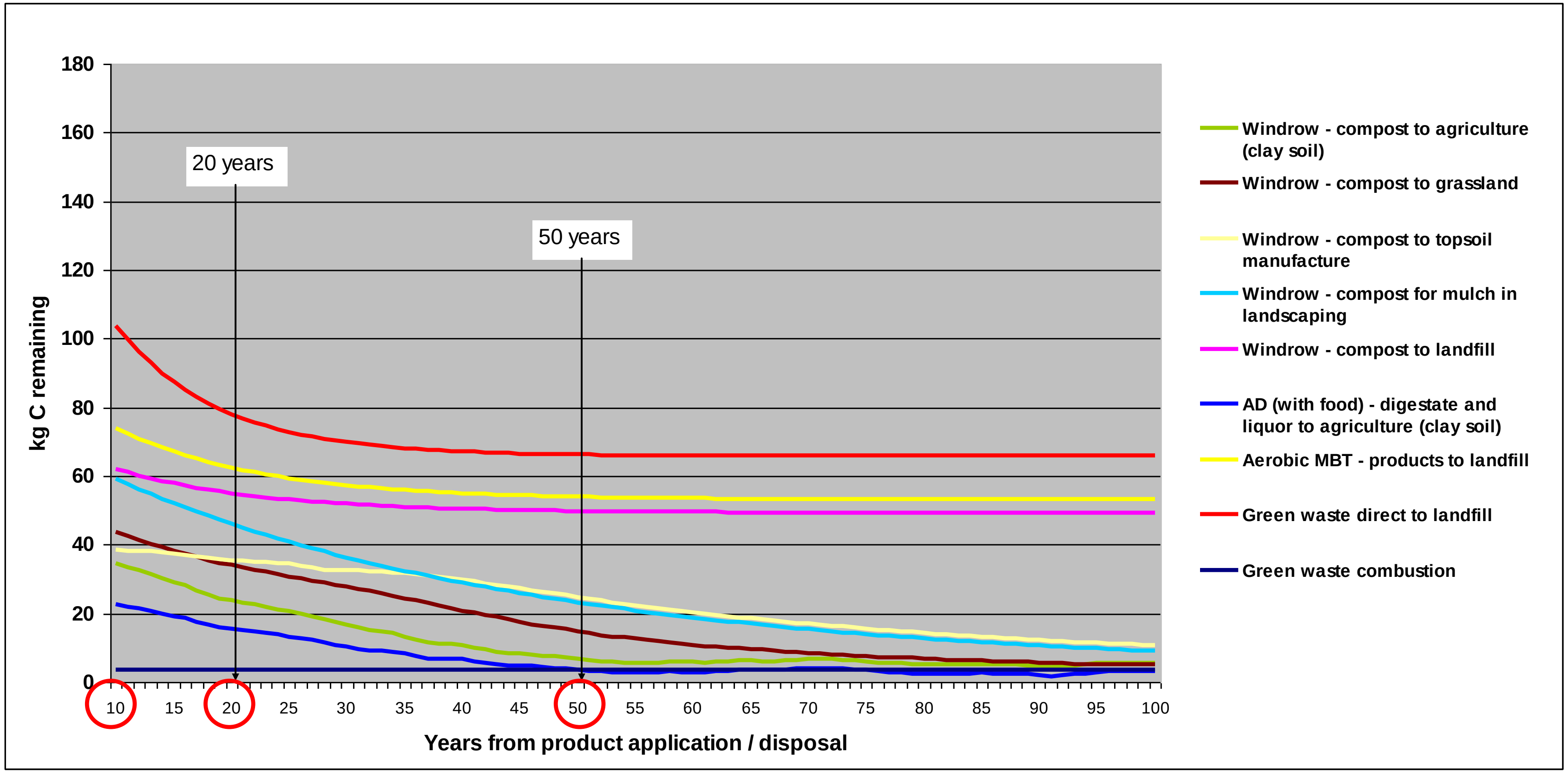
In analysing results it is important to remember that greenhouse gas emissions and savings have been calculated based on models, and are not measured. Models are only simulations of reality. In reality, it is not possible to condense into a single number the intricacies of waste and soil management processes and their potential effect on climate change. At most, we can present a transparent analysis on the basis of the best available data and show the likely implications of making different choices, under the assumptions made. Most important is that we understand what the key drivers for reducing greenhouse gas emissions are. This is discussed further in *Section 0*.

7.2 THE DIFFERENT APPROACHES TO CARBON ACCOUNTING TAKEN

The results presented for unit analyses show that net GHG balances can differ significantly according to the approach taken to carbon accounting. As expected, the greater the credit for carbon storage awarded, the lower the net GHG emission calculated for a given system.

The relative difference between how alternative management systems perform within each accounting method is interesting to observe. The divergences seen are borne through differences in carbon degradation profiles for different product use routes and for disposal of products in landfill. This is most pronounced for the management of green wastes. For example, *Figure 7.1* shows the amount of carbon remaining over time when one tonne of green waste is managed by a variety of systems. In each case, this is a function both of the assumed mass and characteristics of the products from treatment (see *Annex B* for assumptions) and the carbon degradation rate when a product is used/disposed (see *Annex D*).

Figure 7.1 *Amount of carbon remaining in soil or landfill over time: one tonne of green waste to different management routes*



Notes:

- values start at year 10 for presentational purposes, as all lines converge to the same point in year zero. We also note the uncertainty associated with degradation rates for different materials and uses in years 0-10.
- a small amount of residual carbon remains in the landfilled ash residue from thermal treatment

One tonne of green waste contains approximately 175 kg of carbon (at typical moisture content of the waste) (National Assembly for Wales, 2003). On disposal to landfill, the more easily degraded fraction of the waste will mineralise rapidly, over the first 10-20 years. Subsequent to that, decay is slow, leaving approximately 38% of the original carbon remaining after 100 years. If we assume that this is effectively 'locked up' (leaving the short carbon cycle) and receives a sequestration benefit of 3.67 kg CO_2/kg C, this gives a total potential sequestration credit of 241 kg CO_2 for green waste to landfill.

When green waste is treated, rather than being sent directly to landfill, carbon is released from the material over a relatively short timescale (instantaneously during combustion and over a matter of weeks during biological processing). The different degradation profiles for treatment products applied to different uses then affect the amount of credit that is allocated over time. Products sent to landfill show a very slow rate of decay, with 68% and 57% of carbon remaining after 100 years for green waste compost and compost-like-output from MBT respectively.

Carbon degradation rates for materials applied to land (eg agriculture) have been shown to be comparatively fast (see *Annex D*), leaving less than 10% of the original carbon remaining after 100 years. Thus, even over relatively short periods, little credit for sequestration, or delay, is allocated. Others have found similarly that long term storage of carbon in composts applied to soil is small (eg USEPA, 2002). The figures presented in *Annex D* show that continuous applications of biowaste products to land has an extremely positive impact on the soil organic carbon content. However, this is as a result of continuous top-up – the majority of carbon in each tonne applied will be cycled back to the atmosphere over a relatively short timescale.

The implication of the different carbon storage profiles shown in *Figure 7.1* is that, if we assume that there is environmental benefit in delaying carbon releases, landfill systems for green waste appear to perform favourably.

There are very few arguments to suggest that there is a quantifiable environmental benefit of delaying carbon emissions in the short term, and landfill is not considered as a carbon sink in Kyoto reporting. It was also earlier noted that several researchers argue that emissions should not be discounted (eg Stern, 2006), or that longer time periods should be assessed.

There is, in general, greater acceptance of the concept that carbon sequestration over long timescales has the potential to reduce GHG emissions. The 100-year carbon accounting approach is one that is often discussed (eg Miner, 2006). However, if we are considering sequestration, rather than delayed release, then the question of permanence is paramount. What is important is a net reduction in GHG emissions to the atmosphere. This can only be achieved where carbon is stored indefinitely.

It is more than likely that biowaste materials and products will continue to degrade in landfill for periods longer than 100 years following application, albeit very slowly. However, as far as we are aware, there is little insight as to what longer term degradation rates might look like. So the question remains as to where to set a cut-off, if one should be set at all. It was not the place of this research to answer this question – merely to set out the implications of taking one perspective over another.

Many of the product life cycle accounting methods recently developed propose that longer term emissions are separately accounted, due to their inherent uncertainty. This would appear to be a sensible approach – informing on the potential significance of future emissions, or carbon storage, but acknowledging that both are unknown. As well as data uncertainties, the ILCD, for example, highlights other unknowns, postulating that, as landfills are environmentally relevant long-term emitters, mankind will potentially have intervened within 100 years to excavate to sanitise them and/or recover metals or other secondary resources.

7.3 GREENHOUSE GAS BALANCES FOR UNIT SYSTEMS AND SCENARIOS

GHG balances for the unit systems and scenarios assessed in this study were presented in *Sections 4, 5* and *6*.

These show the range of potential GHG emissions associated with different management options. Presenting this range, and understanding why it occurs, is useful in order to recognise where some modelling assumptions are very sensitive, and where others are less so. It also allows us to identify where efforts to potentially reduce emissions, or improve understanding, might be best targeted.

Assumptions regarding the percentage of landfill gas that can be captured and combusted are key. Earlier research (ERM, 2006b) also pointed to the need for further work in this area. Also important is the energy conversion efficiency assumed for thermal treatment and anaerobic digestion plants. In these cases, the lowest efficiencies assumed used historically reported data and show that these systems could result in net GHG emissions if poorly designed or managed. Although this is unlikely to be the case in future-commissioned plants, it is important that this is borne in mind.

We have not attempted to rank the results presented for different systems. This is partly as a result of the ranges found, but predominantly because results for different systems and product uses are in many cases very similar. Given the uncertainty associated with all modelling attempts, it would be misleading to suggest that, for example, one compost product use route is better than another, unless this is clearly the case. Instead some notable findings from the analyses have been drawn out and are summarised below.

Importantly, the main limitations of the study are also set out in *Section 7.4*.

In the following, the terms carbon storage, or sequestration, relate to different methodological approaches taken to carbon accounting. Commonly in life cycle studies, the temporal boundaries of the study are such that all of the biogenic carbon within organic materials is assumed to degrade within the period assessed. This forms the basis of our 'no storage credit' approach. Sensitivity analysis was used to infer what the implications for results might be should we allocate a sequestration benefit to biogenic carbon that does not degrade, but is stored in landfill, or another soil sink. Quantities of biogenic carbon remaining stored in landfill, or soil, after 10/20/50/100 years were calculated. An additional benefit of 3.6 (44/12) tonnes of CO_2 per tonne of carbon was given to this stored biogenic carbon.

Green Waste Management Systems

- Systems enabling the recovery of energy, either through thermal treatment, or anaerobic digestion (with food waste), performed well, regardless of the time period accounted.
- The performance of these systems varied significantly, depending on the net energy recovery rates assumed in the analysis. The greater the energy conversion efficiency of the process, the lower the net GHG emissions.
- When systems are credited for carbon storage over shorter timescales, anaerobic digestion performs more favourably than thermal treatment.
- The use of green waste compost in place of peat in growing media was shown potentially to result in significant net GHG benefits. This is as a result of the avoided mineralisation of fossil carbon from peat.
- The use of biowaste products for agricultural applications performed marginally less well than other use routes, as soil modelling predicted positive net N_2O emissions associated with the use of these products. This is an observation made also by a few other researchers (eg Christensen and Hansen, 2006; Laegrid and Aastveit, 2002), but not one that is commonly considered in assessments of composting systems. It is also subject to the uncertainties associated with the soil modelling approach.
- A further reason for the comparatively poor performance of agricultural systems is that product applications are limited by the constraints of the Nitrates Directive. Sensitivity analysis showed that, if product applications were doubled, net GHG emissions for these systems might be halved.
- It must also be noted that the application of biowaste products to land was shown to lead to increased soil organic carbon content, even at application rates constrained by the Nitrates Directive. This declined rapidly when applications stopped, demonstrating the importance of repeated applications. The importance of maintaining soil organic carbon content is a priority area in Defra's Draft Soil Strategy. The 2008 consultation

document sets out the pressures currently faced by soils in the UK (Defra, 2008).

- The use of products as topsoil and mulch performed relatively favourably. However, data to describe emissions in use and carbon degradation for mulch applications are lacking.
- If no sequestration credits are applied, composting and useful application of green waste materials perform favourably in comparison with landfill.
- If green waste management systems (including landfill) are credited with carbon sequestration benefits, direct landfill and the landfill of treatment products begins to perform favourably. This is particularly the case when gas collection efficiencies at landfills are assumed to be high. However, it is important to highlight that by disposing of carbon in landfill, as opposed to applying it to the soil, all of the added value related to soil organic carbon increase, humus reproduction, fertility, and yield increases are lost.

Food Waste

- Systems enabling the recovery of energy, either through thermal treatment, or anaerobic digestion (with green waste), performed well, regardless of the time period accounted.
- The performance of these systems varied significantly, depending on the net energy recovery rates assumed in the analysis. The greater the energy conversion efficiency of the process, the lower the net GHG emissions.
- AD systems performed better than thermal treatment for the majority of systems and accounting methods. Putting products to useful application was favoured when sequestration benefits were not given, and vice versa.
- The application of biowaste products to land was shown to lead to significantly increased soil organic carbon content. This declined rapidly when applications stopped, demonstrating the importance of repeated applications.
- Landfill was shown to perform worst against all carbon accounting scenarios.
- A large range in the potential net impacts of landfill was shown. This results from the uncertainty surrounding landfill gas collection efficiencies (ie how much is captured and combusted over time).
- Comparisons between product uses (biowaste products for agricultural applications, peat, topsoil and mulch) followed the same trend as discussed above for green waste (as in the majority of cases products and co-treated products are the same).

Scenarios

- The scenarios assessed are simplistic, as there will always be a need for a range of technologies. There is no one-size-fits-all solution. However, they are useful in putting the scale of potential benefits achievable in context.

- All scenarios demonstrated significantly reduced GHG emissions in comparison with the baseline. This is with the exception that, if it is assumed that all carbon remaining after 100 years is effectively sequestered, and that landfill gas capture is high, only those scenarios that include some form of energy recovery perform favourably.
- Those scenarios encompassing high rates of energy recovery perform favourably: both separation and anaerobic treatment; and residual anaerobic MBT/thermal treatment.
- Residual thermal treatment performs comparatively well as a result of the assumption that 90% of residual wastes could be diverted to treatment. In comparison, it was assumed that a maximum of 75% of food waste could be separately collected.
- It must be noted, however, that the treatment of biowaste materials in residual waste will not be in isolation, as other materials will be treated as the same time and their management will have knock-on greenhouse gas implications. For example, some residual materials, such as plastics, may result in net greenhouse gas emissions when thermally treated. Earlier research (ERM, 2006a; 2006b) has explored this further.
- MBT systems performed relatively poorly, as it was assumed that the products would be used as landfill cover. Alternatively, if used in land remediation activities, net GHG emissions would be significantly lowered.

7.4 *STUDY LIMITATIONS: KEY UNCERTAINTIES*

Throughout this report, every attempt has been made to note where data to quantify potential GHG impacts or benefits are lacking or uncertain. The analysis of results also showed where this had greatest influence on the net balances calculated.

In summary, listed below are a number of the uncertainties that we consider to be material to the research and its outcomes.

- Data relating to the key characteristics of the biowaste streams and products assessed are limited (carbon content, lignin content, nutrient contents etc). This is an important limitation of the research – and affects all aspects of assessing product use implications. At the time of completing this research, the best available data from literature were used. However, information regarding the composition of products from AD and MBT were, in particular, lacking. This is a recommended area of further research.
- Modelling the potential fate of carbon and emissions of wider GHG when different biowaste products are applied to land is complex. The results of

modelling in DAYCENT showed low modelling efficiencies (see *Annex D*) for agricultural systems and the following key limitations were noted:

- outputs for the topsoil/SRC scenario are based upon grassland soil data (rather than woodland), due to a lack of available data. The modelling results for woodland were not satisfactory as the distribution of errors (residuals) associated with N_2O, CH_4, CO_2 and SOC were not acceptable in terms of deviation from predicted values;
- an over-prediction of carbon remaining in soil in early years of application;
- nitrogen mineralisation rates behind the model are not fully clarified and understood;
- the soil moisture regime modelled with DAYCENT is simplified and has an influence on N_2O emissions, in particular for the ADL. The model is thought to significantly underestimate N_2O emission potential associated with the application of ADL; and
- in the absence of any data, carbon pools assigned to digestates and liquor have been assumed to be the same as for composts (50 % of carbon in the active pool, 50 % in the slow pool and 0 % in the passive pool). However, in view of the fact that these carbon pools significantly affect the results of the model, it is important to highlight that further research is needed to consider the different decomposition rates of different types of biowaste treatment products when applied to the soil.

- As a consequence of data gaps and scope constraints, a less detailed analysis of the degradation of carbon in landfill, or in mulch or growing media applications was carried out. Degradation profiles for materials in landfill are fundamental when attempting to assess different carbon storage timescales. The Environment Agency GasSim model, plus additional calculations, was used in this respect. As such, we would consider that the findings are in line with current thinking. However, further research in this area – particularly in understanding longer term degradation (or sequestration) rates – would be beneficial. Some of the wider uncertainties in modelling landfill emissions are also discussed further in ERM 2006b.
- Organic matter is known to be a key indicator of soil health. A balanced soil organic carbon (SOC) content is the basic requirement for soil fertility and sustainable agriculture, particularly the humic fraction. The results of soil modelling clearly showed that the application of biowaste products over a sustained period led to an increase in soil organic matter. The benefits of this were accounted for by effects such as yield increase and reduced fuel requirements for working and irrigating the soil. However, it is likely that this does not fully capture the net benefit to the environment of maintaining soil health. It is entirely possible that this is not quantifiable in only carbon/GHG terms, and is recommended wider area of research.

- The scenarios presented are simplistic, and assessed at a strategic, not operational, level. They assess only the potential for a range of broad alternative methods for management of food and green wastes (not all). They do not attempt to assess the influence that a technology or collection route might have on waste arisings or the composition of residual wastes. Note also, that estimates surrounding waste arisings for the streams assessed are uncertain.
- It is important to note that there is a level of uncertainty associated with GWPs for different GHGs. For CH_4 and N_2O, the uncertainty (95% confidence limits) is around ± 35%. This uncertainty should be borne in mind when comparing waste treatment options that release different ratios of CO_2, CH_4 and N_2O.
- Finally, please note that this study considers only greenhouse gas emissions. Other emissions could be generated by waste treatment alternatives, leading to wider environmental impacts, such as groundwater pollution or terrestrial toxicity. The assessment of a broader range of environmental impacts was beyond the scope of this study.