

Evaluation of Green Waste Management Impacts on GHG Emissions Alternative Daily Cover Compared with Composting

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ABSTRACT

Green waste is a key component of California's solid waste stream and so is an important target for effective waste diversion. The California Integrated Waste Management Board (CIWMB) reports that about 15 million cubic yards of organics comprised largely of green waste are diverted annually in California. The diverted organics are principally used as compost and mulch in agricultural and urban green areas. In California, one of the most popular alternative waste diversion options is the use of green waste as landfill alternative daily cover (ADC). Green waste ADC reduces the need for importing clean daily cover soil and so helps conserve limited landfill volume. However when landfilled, green waste can generate methane, an important greenhouse gas (GHG), and so may be regarded as environmentally inferior to green waste composting.

This study uses GHG emissions estimated from life-cycle inventory methodology to compare green waste ADC and composting alternatives. A United States Environmental Protection Agency (USEPA) based life-cycle inventory methodology was developed that considers differences in transport, material handling, green waste emissions, capture and management, energy impacts, and carbon sequestration. The ADC analysis addresses the range of conditions at landfills particular to California landfills including the extent of gas recovery, the gas collection efficiency and methane energy recovery.

This study supports the reported benefits of composting but also shows that green waste ADC can actually be more beneficial in reducing GHG emissions when compared to the composting of green waste. This result indicates the importance of site-specific environmental analysis when considering organics management options.

In this study, details of the life-cycle GHG inventory analyses are provided. Results of the comparison between the two green waste management options are presented. The significance and implications of this study are discussed.

INTRODUCTION

Since passage of California Assembly Bill 32, regulators and stakeholders alike have been engaged in an assessment of waste management practices relative to climate control, including waste management approaches for organic waste. Recognizing the statutory context of the waste management "hierarchy" and the ongoing debate on green waste ADC diversion credit, it is important to develop a technical methodology to study and address the issue.

Years earlier, California Assembly Bill 939 required a 50% diversion of solid waste from landfill disposal. Green waste, as one of the key components of the waste stream, poses an attractive target for effective waste diversion. The use of green waste as ADC constitutes diversion under state law. Just over half of all California-generated solid waste is diverted by various means. As shown in Figure 1 (CIWMB, 2006), landfill ADC is a small, but important, contributor to diversion. Green waste (GW) is the major ADC component but other viable ADC materials include auto shredder fluff and wastewater biosolids.

This study focuses only on green waste as its management in California is currently being debated. Published green waste composition data are used in the study.

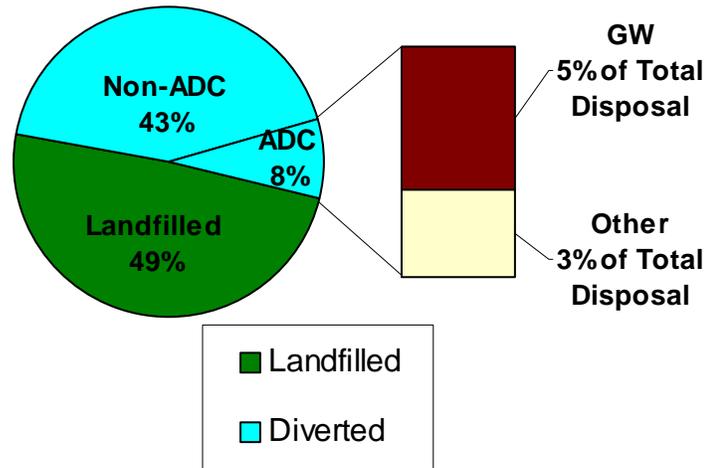


Figure 1. ADC solid waste diversion in California

A significant amount of organics waste is currently diverted in California. ADC represents a relatively small portion of this waste diversion (see Figure 2). In contrast, composting comprises a significant portion of organics diversion in the “farms” category.

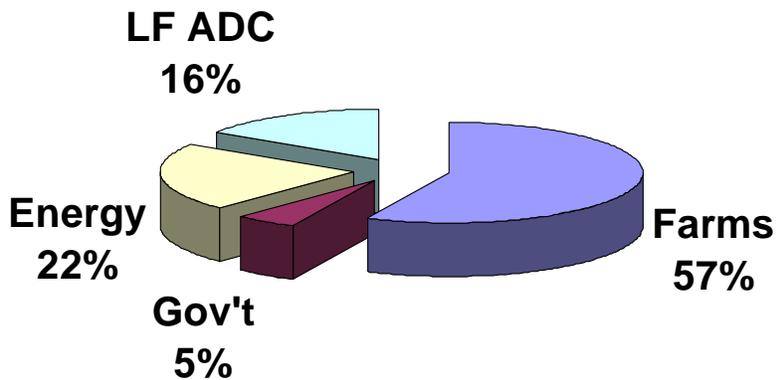


Figure 2. Diversion in California¹

Prior to green waste ADC use, larger amounts of cover soil had to be imported into landfills from offsite sources. As much of the green waste used as ADC had been previously landfilled, there was no change in fossil fuel use for its transport. However use of green waste ADC reduced fossil fuel use for cover soil importation and so reduces GHG emissions. GW ADC can also save valuable landfill volume in two

¹ Year 2000 data (source: <http://www.ciwmb.ca.gov/organics/Measure/Marketplace.htm>; accessed 8/28/2006).

ways. First, it frees the disposal volume that otherwise would be occupied by green waste. Second, GW ADC more efficiently compacts than soil under successive lifts of landfilled solid waste. It is noteworthy that although other ADC's (e.g., film plastic, foam, and tarps) are commercially available and also used by the Los Angeles County Sanitation Districts (LACSD), their uses are often limited due to varying site conditions including wind and precipitation.

Incoming green waste is ground before use as either ADC or feedstock for offsite users, such as composters (Figure 3). When used as ADC, the green waste is spread by a landfill "scraper" across a compacted cell of refuse (Figure 4).



Figure 3. Unprocessed green waste (on left) is ground and stockpiled (on right)



Figure 4. A scraper lays ground green waste ADC over a compacted refuse cell

A full life-cycle analysis of the GHG emissions from ADC and composting was made using a dedicated spreadsheet model developed by LACSD. A second analysis using USEPA's Waste Reduction Model (WARM) was made of GW landfill disposal, similar to the ADC scenario, and GW composting. The results of the two models were compared with a literature study based on the Canadian EPIC model (EPIC, 2002) applied to similar scenarios for yard trimmings landfilling and composting.

This study's life-cycle analysis is based on a GHG budget for the various scenarios, as GHG emissions are a key environmental effect. This GHG analysis accounts for varying conditions at California landfills

using ADC relative to the presence of gas recovery systems, the extent of compliance with stringent New Source Performance Standard (NSPS) emission control rules, and the extent of landfill gas energy recovery.

GREENHOUSE GASES

Life-cycle analysis has four considerations: input of virgin materials and energy; stages of activity such as transportation and processing; emissions from the approach itself; and any reductions in emissions due to carbon sequestration and emission offsets (e.g., displacing fossil fuel use). A greenhouse gas life-cycle analysis is expressed in terms of a budget showing any net increase or decrease in the atmospheric global warming potential (GWP) of an activity.

Because of its importance, it is common practice to express any greenhouse gas emission or reduction in terms of an equivalent amount of carbon dioxide. Emissions of certain compounds other than carbon dioxide, such as methane or nitrous oxide, have greater global warming potentials than carbon dioxide. Such emissions can be expressed in equivalent amounts of carbon dioxide with the same effective GWP. For example, methane, with a GWP of 23, can be expressed as an equivalent amount of carbon dioxide by multiplying the methane weight by 23. And nitrous oxide, with a GWP of 296, can be expressed as an equivalent amount of carbon dioxide by multiplying the nitrous oxide weight by 296.

It is also common practice to express either emissions or reductions in greenhouse gas in terms of the elemental carbon portion of carbon dioxide. That is, the weight of carbon dioxide emissions or reductions is converted to an equivalent weight of carbon. This is done by multiplying the weight of carbon dioxide by the molar ratio of carbon to carbon-dioxide (i.e., 12/44 or 0.2727). Because of its international implications, GHG emissions and reductions are expressed in metric units, commonly, metric tons² carbon equivalents (MTCE). These conventions are used in this report.

An important concept in GHG life-cycle analysis is that emissions may be considered either biogenic or anthropogenic. Biogenic emissions are those that are part of the natural atmospheric cycle. For example, the green waste carbon content was originally derived from ambient air carbon dioxide; any subsequent green waste release of carbon dioxide simply restores the atmosphere to prior levels and is not considered a greenhouse gas emission.

In contrast, anthropogenic emissions are those that occur outside the natural carbon cycle. Notably, fossil fuels produce anthropogenic emissions as their combustion release carbon dioxide in excess of natural levels. In the case of green waste, while the carbon content is derived from ambient air carbon dioxide, processes such as landfilling and composting produce methane and, in the case of composting, nitrous oxide. As generally accepted, both methane and nitrous oxide have GWPs greater than that of carbon dioxide, and so are considered anthropogenic emissions.

Some forms of carbon may persist under various conditions in a stable form and so are removed from the natural carbon cycle. Such carbon is considered “sequestered” or “stored”. Examples of sequestered carbon include soil lignin and peat. Both green waste composting and green waste ADC sequester carbon. Such processes represent reductions in the atmospheric carbon dioxide level at an equivalent rate of one unit of carbon dioxide removed for each unit of sequestered carbon.

Various processes may either offset or increase fossil fuel use. Changes in truck transport have corresponding changes in carbon dioxide releases. Recovery of energy from landfill gas created in part by green waste ADC offsets fossil fuel use.

² A metric ton is 1000 kilograms.

The comparison of GHG reductions for ADC and composting is made using a comprehensive GHG life-cycle analysis.

GHG LIFE-CYCLE ANALYSIS

Two models and a literature report using a third model are presented in this analysis. LACSD developed a dedicated spreadsheet model to analyze GW composting and ADC applications. USEPA's WARM is a general purpose tool useful for analyzing a variety of solid waste management practices including GW composting and landfilling. The WARM GW landfilling scenario is presented as it is very similar to the GW ADC scenario. Finally, a study using the Canadian EPIC model applied to yard trimmings composting and landfilling are also reported here.

The following subsections discuss the GHG life-cycle analyses for the two GW management options (composting and ADC) used in the dedicated LACSD spreadsheet model in a relatively conceptual manner. More systematic and detailed analyses are presented in an appendix.

Scenario Starting Point

In the study, the starting point for both scenarios was at a site where chipping and grinding of green waste took place. Emissions from the transport of green waste from the curb to the chipping and grinding facility (which, in this case, is co-located with a landfill), as well as emissions from the actual chipping and grinding of green waste, were assumed to be the same for both scenarios and, thus, were not included in the analysis.

This approach is consistent with the LACSD's experience where ground green waste could either be used directly on site for ADC or exported to another end user such as a compost facility. It was realized that the local green waste chipping and grinding facility could be at a location other than the landfill using ADC. However experience with the LACSD model indicates that any difference would typically be negligible as compared to other factors.

Composting Scenario

The GW composting life-cycle scenario evaluates composting of shredded green waste with the end product used in agricultural and farming applications. Because in California most of the composting operations are turned windrow processes, hence, the modeled composting facility here in the analysis is based on a centralized, turned windrow system. However, the impacts of aerated static pile (ASP) composting operation on GHG emissions will be analyzed and discussed in a later part of this paper.

There are four stages in the composting GHG life-cycle analysis resulting in either GHG emissions or GHG reductions (Figure 5). An initial shredding stage is omitted, as it is common to either composting or ADC applications, and so entails no net emissions or reductions when comparing the two processes. The first composting stage is transportation in which green waste is transported from a landfill or similarly located chipping and grinding facility to a rural compost facility and then from the compost facility to its ultimate end use location, for example, to a farm or nursery. GW transport consumes fossil fuels and generates GHG carbon dioxide emissions.

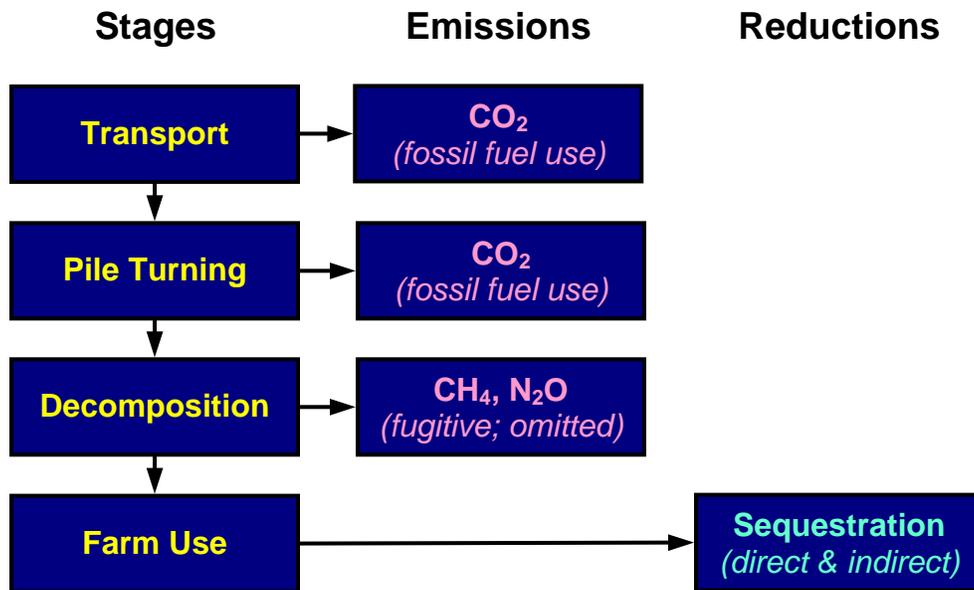


Figure 5. Composting GHG life-cycle analysis flow chart

The second stage addresses emissions from fossil fuel use during compost pile turning. Pile turning maintains aerobic conditions that reduce methane emissions. Alternate compost methods employing aerated static piles may have different fossil fuel requirements but these are uncommon.

The third stage is the GW decomposition in which GW under optimal conditions decomposes aerobically producing biogenic carbon dioxide. However, studies (Stredwick, 2001; Amlinger *et al.*, 2008) show that composting can produce fugitive methane emissions at a rate similar to an adequately operated landfill gas emission control system. Amlinger *et al.* also show that another GHG, nitrous oxide (N₂O), is produced under aerobic conditions. Due to limited data available, these emissions are not included in the analysis discussed here. However, utilizing available data, an analysis that includes the impacts of composting-related fugitive methane and nitrous oxide emissions will be presented and discussed later in this paper.

The fourth stage is the agricultural and farming applications of GW compost. The use of compost in farming produces a small amount of indirect and a larger amount of direct carbon sequestration. Carbon normally accumulates (“sequesters”) in soils due to the presence of non-degradable organics (e.g., “lignins”). Additionally, composting indirectly sequesters carbon by fostering improved growth of farmed products. Other indirect factors such as reduced water and fertilizer use (and so reduced fossil fuel use) were not included as there are as yet no standard USEPA methodologies to calculate these.

ADC Scenario

The ADC life-cycle scenario evaluates placement of shredded green waste as a daily cover and subsequent contribution to landfill gas generation.

There are four stages in the ADC GHG life-cycle analysis resulting in either GHG emissions or reductions (Figure 6). The first stage is ADC placement, which may reduce soil importation for cover and so reduce fossil fuel use. Since not all landfills import dirt for cover, this aspect is omitted from the modeling results presented below. Some landfills may excavate onsite soil for cover. Replacing onsite soil with ADC reduces GHG emissions but the reductions are small and so not considered in this study.

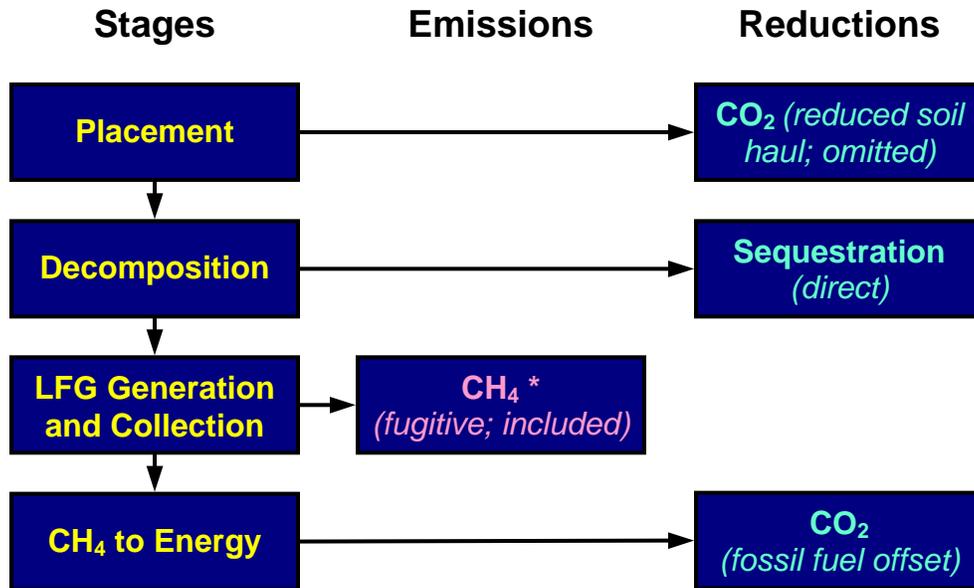


Figure 6. ADC GHG life-cycle analysis flow chart

The second stage is GW decomposition. GW directly sequesters a large amount of carbon during the decomposition process. GW carbon sequestration (in other words, carbon storage) in a landfill is quantitatively larger than for composting because the conditions within a landfill are not favorable for decomposition. Noted “garbologist” Dr. William Rathje has long reported the resistance of landfill organics to decomposition (Rathje, W. and C. Murphy, 2001). However, this study uses conservative assumptions based on the research of Dr. Morton Barlaz of North Carolina State University on behalf of the USEPA (Barlaz 2000, 2005). His work documents the maximum possible extent of landfill decomposition and so minimizes the calculated sequestration. Decomposition also generates landfill gas; this is addressed in the third stage.

The third stage is landfill gas (LFG) generation and collection. Virtually all GW ADC in California is used at landfills that are equipped with LFG collection systems. A commonly expressed concern is that the green waste will rapidly decompose before the landfill gas collection system can be effective. Contrary to this view, organic wastes including green wastes have been verified to require years to decompose under landfill conditions and then only incompletely (Al-Yousfi, 1992, Barlaz *et al.*, 1992). As a practical matter, routine monitoring, for example that required by the South Coast Air Quality Management District Rule 1150.1, shows that emissions measured directly over green waste ADC are no different than from other areas of a landfill. This indicates that any GW emissions are negligible.

An average gas collection efficiency value representative of California landfills was developed for the third stage. This value accounted for the amount of green waste ADC taken to landfills with gas collection systems and the relative number of collection systems operated for emission control purposes versus those operated for other purposes such as energy recovery. Recently published papers (e.g., Huitric and Kong, 2006, Huitric, *et al.*, 2007) show that LFG collection systems operated for emission control (e.g., the federal NSPS Municipal Solid Waste New Source Performance Standards) are highly effective, collecting nearly all gases. However, conservative collection efficiency estimates representative of California landfills were made for this analysis.

The fourth stage considered in this analysis is the amount of methane recovered for energy recovery and so offset fossil fuel use. The methane energy recovery for California is derived from the USEPA LMOP

* Landfill gas collection efficiency must be assumed here.

database (2004, 2006) and the CIWMB SWIS database (2006). Analysis of the data shows about 60% of collected LFG is used for energy recovery purposes at California landfills that use GW ADC.

Although not considered as an assumption in the life-cycle analysis, GW ADC usage can conserve valuable landfill volume. Other ADC's can also conserve landfill volume although these may have significant operational limitations. GW ADC is typically used where other ADC's cannot be used as effectively.

Life-Cycle Analysis – GHG Budget

The results of a GHG life-cycle analysis can be expressed as a simple budget, the difference between reductions and emissions. That is,

$$\text{Net GHG Reduction} = \text{Reductions} - \text{Emissions}$$

SUMMARY OF RESULTS

LACSD developed a dedicated spreadsheet model to evaluate two GW applications, ADC and composting, using GHG life-cycle analysis. The USEPA Waste Reduction Model (“WARM”) was also employed to perform a similar analysis. Finally, the results from a Canadian study using the EPIC model were used to compare with results generated by the two other models (LACSD and USEPA WARM). All results were expressed in terms of metric tons carbon equivalents per english ton of green waste (MTCE/ton GW). This allows the ADC and composting scenarios to be directly compared. Table 1 summarizes the modeling results.

Table 1. Summary of GHG life-cycle analysis results

Model	Location	ADC Net GHG Reductions (<i>MTCE/ton GW</i>)	Composting*
LACSD (<i>green waste</i>)	California	0.165	0.048
EPIC (<i>yard trimmings</i>)	Canada	0.12 (<i>landfilling</i>)	0.00
USEPA WARM (<i>green waste</i>)	U.S.	0.22 (<i>landfilling</i>)	0.05

* turned-windrow composting operation

All three life-cycle models show ADC (or the similar landfilling scenario) to reduce GHG emissions substantially more than GW composting. Figure 7 presents the relative performance of ADC and composting for the LACSD model in terms of the weight of GHG reductions as a percentage of the GW weight³. It indicates a more than three fold reduction in GHG emissions for ADC as compared to composting. The USEPA WARM predicts a more than four fold reduction in GHG emissions for GW landfilling relative to composting (however it uses less current factors as compared to the LACSD model). The Canadian study using the EPIC model estimates GHG reductions similar to the other two models for yard trimmings landfilling relative to composting.

³ Note that this percentage is about 10% below the true value due to the difference between the metric ton used for emissions and reductions and the english ton used for green waste.

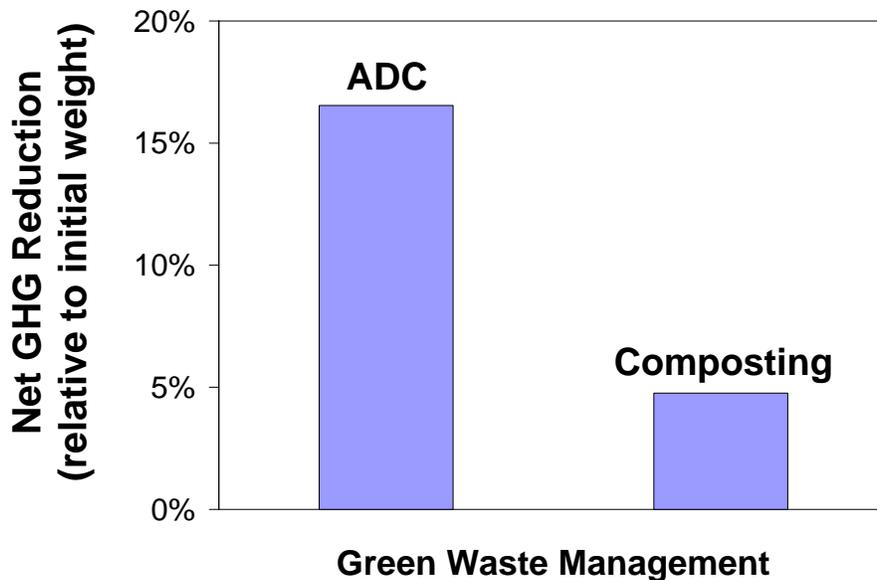


Figure 7. Results of GHG life-cycle analysis (LACSD model)

DISCUSSION

In the GHG life-cycle analyses presented above, important assumptions were made relative to various factors. Important among these are the assumed landfill gas collection efficiency and the extent of carbon sequestration. These issues are discussed below.

Landfill Gas Collection Efficiency

Efficient landfill gas collection reduces the potential for methane emissions. Overall California landfills have the highest collection efficiencies in the nation for a variety of reasons. Landfill gas collection was first pioneered in California in the early 1970's for control and energy recovery purposes. The nation's earliest landfill gas emission control rules were developed by California air districts in the 1980's. The federal landfill emission control rule (Municipal Solid Waste New Source Performance Standards) was adopted in 1996. The large landfills typically operated in California ensure that most of the in-place waste is subject to either or both local air district and federal emission control rules. Because of the mature development of landfill gas collection systems for control and energy recovery purposes and because of the widespread applicability of emission standards, collection efficiency is very high in California.

The modeled landfill gas collection efficiency used in this study is an overall value that accounts for the proportions of green waste ADC directed to landfills with and without gas collection and, for landfills with gas collection, the kinds of collection systems. Collection systems at landfills accepting ADC are operated either for emission control that may include energy recovery or exclusively for energy recovery.

Almost all green waste ADC (99.2%) is used at landfills with some form of gas collection. Nearly 85% of the collection systems are operated for emission control purposes. As described in the appendix, such systems are estimated to have collection efficiencies ranging from 95 to 100%. The lower range 95% value estimate was used in this analysis for emission control systems.

The remaining 15% of the collection systems are operated exclusively for energy recovery. Such systems are estimated to have collection efficiencies ranging from 85 to 99%. A much lower value of 75% was used in this analysis. The overall weighted average collection efficiency accounting for the distribution of collection systems and for ADC taken to landfills without any gas collection is 91%.

The effect of this assumed collection efficiency on the results of this analysis is presented in Figure 8. The trend line shows the net GHG reduction as a function of collection efficiency. The point on the trend line where the two dotted lines meet shows the net GHG reduction modeled in this study at the weighted average 91% collection efficiency appropriate for California landfills using green waste ADC.

This figure shows that the conclusion of this analysis holds for a broad range of collection efficiencies, even for USEPA’s very conservative default 75% efficiency that is sometimes used where no better information exists.

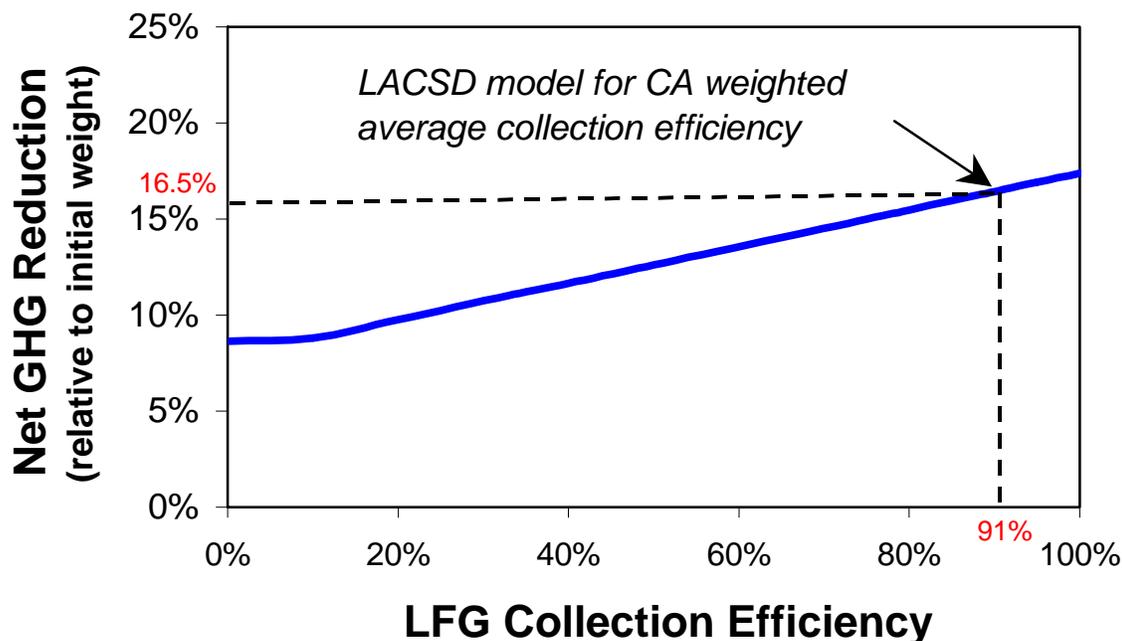


Figure 8. Sensitivity of GHG reduction to LFG collection efficiency

Role of Landfill Carbon Sequestration

It is well known that landfilling and composting provide carbon sequestration (e.g., USEPA, 1998, 2002, 2006, Bogner *et al.*, 2008). In addition, the California Air Resources Board (CARB) recognizes carbon sequestration in its greenhouse gas inventory (CARB generically includes sequestration within its “Sinks” line item). The USEPA (2006) recognizes and incorporates carbon storage (sequestration) in landfills in its GHG inventory life-cycle analysis. This study’s analyses were consistent with EPA’s methodology.

The relative importance of carbon sequestration is illustrated in Figure9. It shows that even if carbon sequestration was just half the value assumed in this study, there are significant GHG reductions. Furthermore, even there is no carbon sequestration incorporated into the analysis, green waste ADC continues to have a significant advantage over composting.

In summary, landfill and compost carbon sequestration are recognized by the USEPA and CARB as significant factors in a GHG life-cycle analysis. This study was based on USEPA methodologies and shows that even large uncertainties in carbon sequestration do not alter the conclusions reported here. Specifically, green waste ADC still provides a significant GHG advantage over composting, even when carbon sequestration is not considered in the analysis (see Figure 9).

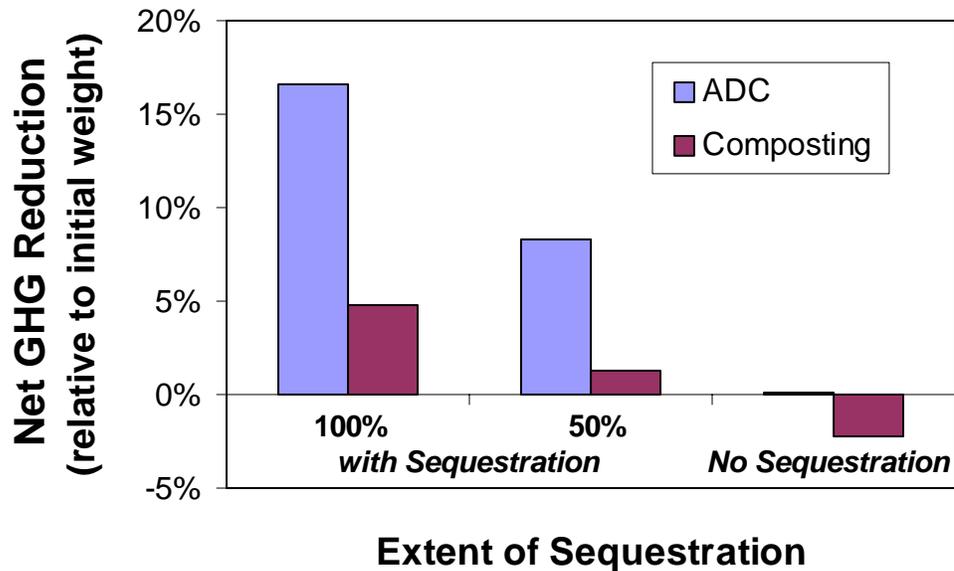


Figure 9. Net GHG reductions at 100%,50%, and 0% of best carbon sequestration estimates

Effect of Transportation Distance

The modeled composting scenario in the analysis above reflects a southern California reality for which the major compost end-market is agricultural farming in central California. At minimum, this entails a 90 mile one-way haul. What’s the impact of transportation distance on net GHG reduction of composting scenario?

Figure 10 shows the effect of transportation distance on net GHG reduction of composting scenario. As indicated by the figure, transportation distance does have an impact on net GHG reduction of composting scenario, however, this impact is very minor. In fact, even for the case of zero transportation distance (end-market for compost products is local), GW-ADC use still poses a significant advantage over composting, in terms of net GHG reduction.

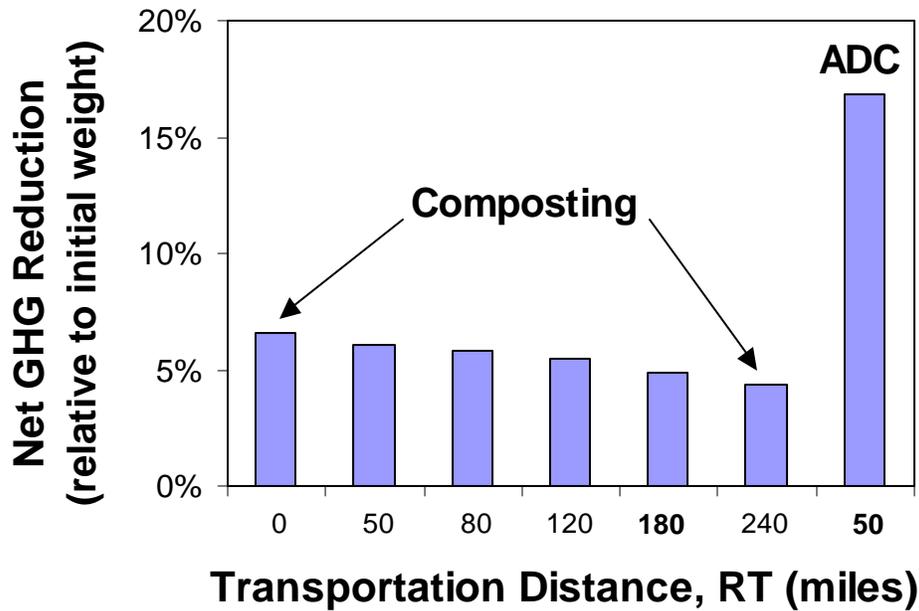


Figure 10. Effect of transportation distance on net GHG reduction

Effect of Aerated Static Pile Composting Operations

In the analysis discussed earlier, the modeled composting facility is a centralized turned windrow composting operation. Although turned windrow process is still the most popular method of composting in California, there are a number of facilities that utilize aerated static pile (ASP) for composting. This section addresses the effect of ASP composting operation on net GHG reduction.

The modeled ASP composting scenario is based on data obtained from a southern California composting facility which operates aerated static piles for biosolids and green waste composting (IERCF, 2008). While other parameters in a GHG life-cycle analysis are assumed to be the same for turned windrow and ASP composting, energy consumptions per ton of green waste processed are different for turned windrow and ASP composting operations. Specifically, the ASP operation consumes more fossil fuel, thus generates more carbon dioxide emissions during the composting processes.

Figure 11 compares turned-windrow and ASP composting operations, in terms of net GHG reductions. Because ASP operation consumes more fossil fuel, generates more energy-related carbon dioxide emissions, thus results in less net GHG reduction as compared to turned-windrow operation. However, the difference is not significant (< 5%) for this case. GW-ADC use still maintains a significant (> 3 times) net GHG reduction advantage over composting, turned-windrow or ASP, as evident by Figure 11.

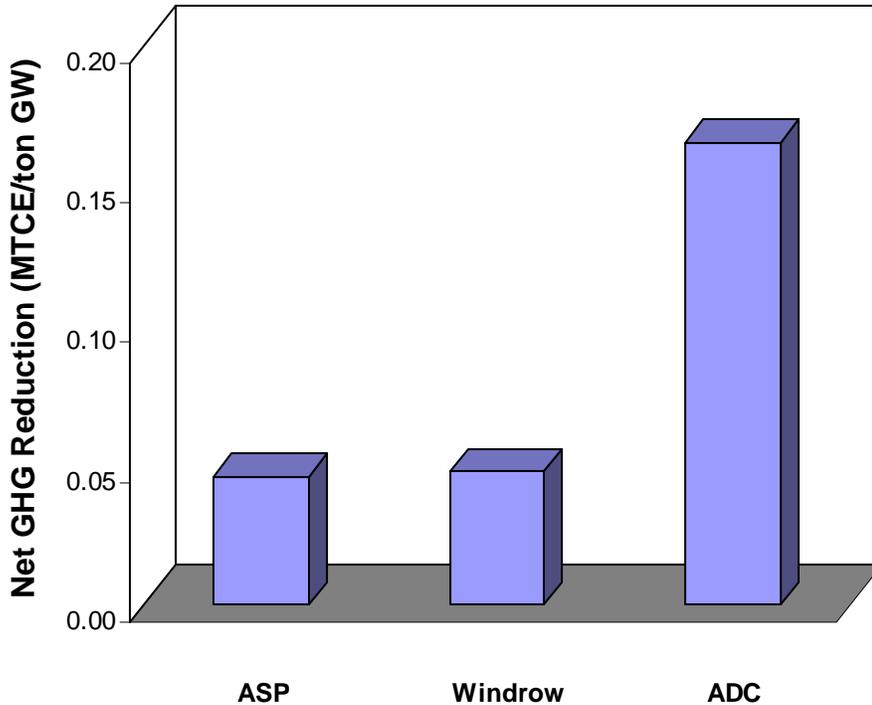


Figure 11. Comparisons of net GHG reductions between windrow and ASP composting operations

Inclusion of Fugitive Methane and Nitrous Oxide Emissions

In the GHG life-cycle analyses presented earlier in this paper, fugitive methane (CH₄) and nitrous oxide (N₂O) emissions of composting operations were omitted due to limited data available. However, it's well known now that composting operation does generate fugitive methane and nitrous oxide emissions, as discussed in the earlier sections of this paper. This section investigates the impacts of incorporating fugitive methane and nitrous oxide emissions from composting operations on net GHG reduction.

Although it's known for long that composting operations generate fugitive CH₄ and N₂O emissions, actual data are very limited and sparse. This analysis utilizes methane emissions data of southern California composting facility from a SCAQMD field study (Stredwick, 2001), and methane and nitrous oxide emissions data from a recent European study (Amlinger, *et al.*, 2008). The results of this GHG life-cycle analysis that considers methane and nitrous oxide emissions are presented in Figure 12, and tabulated in Table 2.

As shown in Figure 12 (and Table 2), the inclusion of fugitive methane and nitrous oxide emissions from composting operations reduces the net GHG reductions to about half, as compared to results of composting scenarios that exclude methane and nitrous oxide emissions. As a result, the gap between GW-ADC and composting, in terms of net GHG reduction, would be greater (e.g., GW-ADC use is 7 or 8 times more beneficial over composting, in terms of net GHG reduction) if fugitive methane and nitrous oxide emissions were included in the GHG life-cycle analyses.

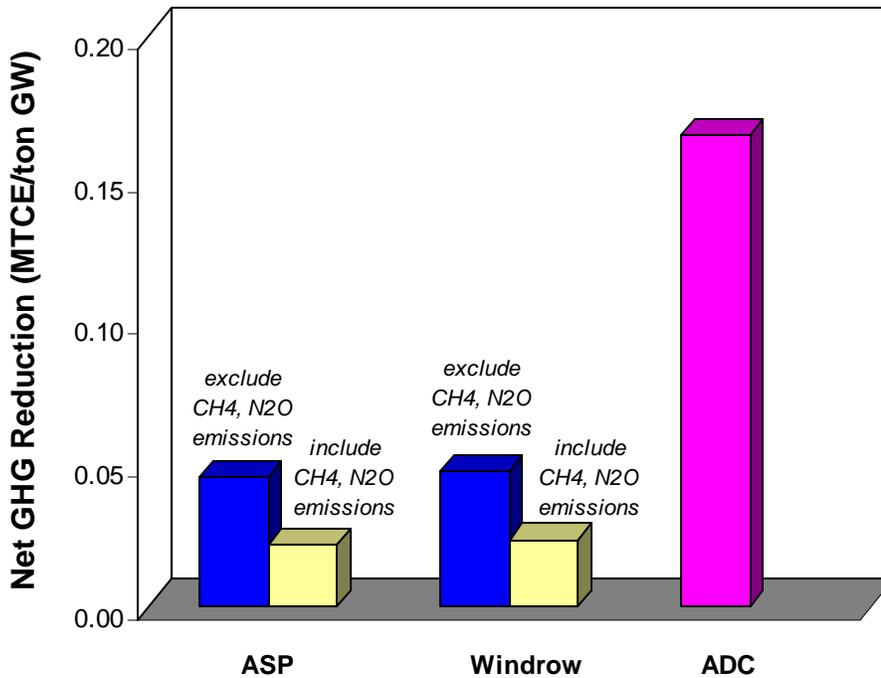


Figure 12. Impacts of inclusion of CH₄ and N₂O emissions on composting GHG reductions

CONCLUDING REMARKS

This study confirms that green waste composting results in a net reduction of GHG emissions, but it also shows that, using conservative assumptions, green waste ADC can generate substantially greater reductions. The LACSD model shows ADC reductions at least three times greater than for composting (see Table 2 below). This finding is consistent with the USEPA WARM projections and a Canadian study based on their EPIC model (USEPA, 1998 and Canadian EPIC, 2002).

Table 2. Summary of results of GW-ADC and composting comparisons

Net GHG Reduction (MTCE/ton GW)			
Composting			ADC
<u>GHG Emissions</u>	<u>ASP</u>	<u>Windrow</u>	
<i>exclude CH₄, N₂O</i>	0.0457	0.0476	0.1654
<i>include CH₄, N₂O</i>	0.0217	0.0236	

Realistic but conservative assumptions for GW ADC technical factors are used in this analysis. Lower range landfill gas collection efficiencies are used that underestimate the ADC GHG reductions. An analysis of ADC GHG reductions relative to collection efficiencies shows that the reductions are insensitive to a broad range of efficiencies, even down to the very conservative USEPA default value of

75%. Indeed, GW-ADC continues to be advantageous over composting, in terms of net GHG benefits, even when there is no collection system in place.

This study's results indicate that landfilling provides much better carbon sequestration than composting. However, even if carbon sequestration is not included in the analysis, ADC still provides a greater GHG reduction than composting.

It is well-known now that composting operations generate fugitive CH₄ and N₂O emissions. However, due to limited data available, fugitive methane and nitrous oxide emissions are excluded from the core life-cycle analysis. Our study shows that when these fugitive methane and nitrous oxide emissions from composting operations are included in the life-cycle analysis, net GHG reduction of green waste composting reduces to about half of that of composting scenario that excludes fugitive methane and nitrous oxide emissions. Furthermore, as a result, the gap between GW-ADC and composting, in terms of net GHG reduction, would be greater (e.g., GW-ADC use is 7 or 8 times more beneficial over composting, in terms of net GHG reduction) if fugitive methane and nitrous oxide emissions were included in the GHG life-cycle analyses.

Although green waste ADC provides substantially better GHG emission reductions than composting, composting is an important waste diversion strategy that complements, rather than replaces, ADC use. This study highlights the importance of case-specific life-cycle analyses when assessing relative GHG emissions of organics management techniques.

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APPENDIX

Details of the GHG life-cycle analyses for the ADC and composting alternative scenarios are presented in this appendix. Following are some issues common to either process.

Carbon dioxide, methane and nitrous oxide are emitted from fossil fuel powered vehicles; all are greenhouse gases (GHG). Nitrous oxide and methane emissions tend to comprise a relatively small portion of overall vehicle GHG emissions (perhaps, 1-2% combined; for example see USEPA, 2004). Consequently only carbon dioxide vehicle emissions are considered here.

It is assumed for either alternative that transport occurs to a local chipping and grinding point. For example, green waste brought to a LACSD landfill for grinding may either be used on site as ADC or may be transported offsite to a composting facility. In this situation, the LACSD landfill serves as the local accumulation point for either option so that local transport is exactly identical. As analyses for long distance transport described for the composting scenario show that these emissions are minor, it was assumed that any differences in emissions due to transport to the local accumulation points were negligible.

1. ADC Scenario

Green waste used as ADC may result in (1) CH₄ emissions from anaerobic decomposition; (2) CO₂ offset due to energy recovery; and (3) long-term carbon sequestration. There may also be GHG emission reduction due to truck-trip reduction for importing clean soil (but this is not counted here).

(a). GHG emissions

Green waste ADC methane emissions depend upon the potential for methane generation per unit weight of waste disposal and the efficiency with which generated methane is collected. A literature-based green waste methane generation potential of 678 cubic feet of methane generated per ton of green waste is used (Barlaz, 2000). A 91.2% weighted average landfill gas collection efficiency is calculated for this analysis based on the ADC usage and gas collection patterns in California as described later.

Actual emissions are calculated from the overall collection efficiency and unit methane generation rate per ton of green waste. Finally, the methane emissions are converted into an equivalent amount of carbon dioxide. Methane has a widely accepted global warming potential (GWP) of 21 (carbon dioxide's GWP is 1) (NSWMA, 2006). However climate experts are considering a slightly higher GWP of 23 for future use. The more conservative value of 23 is used here. Similarly, nitrous oxide has a GWP of 296 (e.g., IPCC, 2001a). Results of methane and nitrous oxide emissions are converted to Metric Tons Carbon Equivalent (MTCE).

The overall landfill gas collection efficiency calculation is described here. Green waste ADC usage was evaluated as a function of gas collection based on 2004 California green waste and LFG management data (ARB, CIWMB, 2006). Nearly all green waste ADC (99.2%) is accepted at landfills with gas collection systems (see Figure 13).

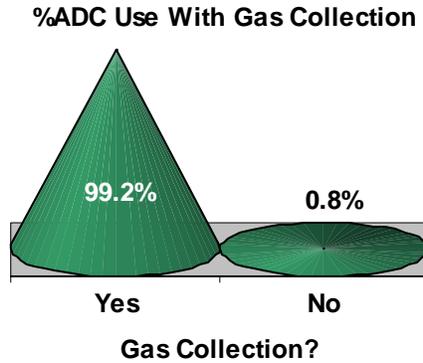


Figure 13. Almost all (99.2%) green waste ADC is used at landfills with gas collection systems

Many landfill gas recovery systems in California were developed through the 1980's for energy recovery purposes. Starting in the late 1980's, local air district and, by 1996, the federal NSPS emission control rules went into effect.

While the energy recovery systems had high collection efficiency due to the value of the methane (actual measurements range from 85 to 99%), recent measurements show that emission control rules push efficiency towards 100%, as described further below. Because there appears to be some variation in collection efficiency between emission control and other collection systems, state databases were analyzed to establish their relative numbers.

It was found that most green waste ADC (84.7%) is accepted at landfills with stringent emission control requirements. The remaining landfills typically collect gas for energy recovery purposes. Figure 14 illustrates the relative amount of green waste ADC managed at landfills operated for emission control or other purposes (i.e., energy)

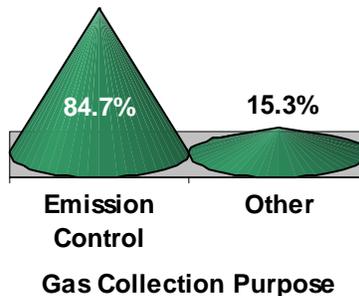


Figure 14. Most green waste ADC (84.7%) at LFs with gas collection is subject to stringent emission rules

Emission control landfills have high collection efficiencies and range from 95% to 100% (see SCS Engineers, 2007). A conservative value of 95% was assumed for such sites. The landfill collection systems that are operated exclusively for energy recovery have actual collection efficiencies ranging from 85% to 99% (SCS Engineers, 2007). A conservative value of 75% was assumed for these sites (see Figure 15).

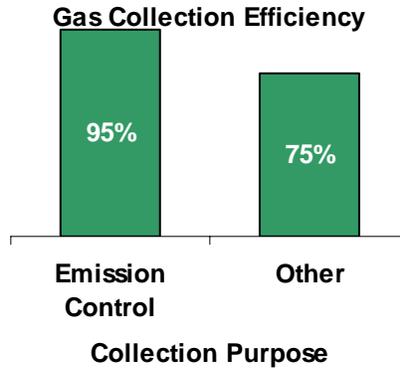


Figure 15. Assumed gas collection efficiencies; actual efficiencies are higher

Overall gas collection efficiency can be calculated from the distributions of ADC use at landfills with and without gas collection, the types of collection systems (emission control or other), and from conservatively assumed collection efficiencies for each system type. The collection efficiency for gas at landfills using green waste ADC is calculated from values in Figure 14 and Figure 15 as:

$$84.7\% \times 95\% + 15.3\% \times 75\% = 91.94\%$$

The overall effective collection efficiency for all sites including those without gas collection is calculated from this result and the proportion of green waste ADC used at sites with gas collection from Figure 13 as:

$$91.94\% \times 99.2\% = 91.2\%$$

The calculated green waste methane emission is calculated from this value and from the unit methane generation rate of 678 cubic feet of methane generated per ton of green waste cited earlier. This value was converted to an equivalent carbon dioxide emission rate using a methane global warming potential of 23. As described in the discussion section, the results of this study are insensitive to the assumed collection efficiencies since very different collection efficiencies do not alter the basic conclusions reported here.

Table 3. Factors for calculating GHG emissions from landfill gases

ID	Category	Factor
(a)	Collection efficiency	91.2%
(b)	Green waste methane generation (ft ³ /ton)	678
(c)	Methane density at 20 °C (kg/ft ³)	0.0203
(d)	Methane GWP	23
(e)	Conversion factor (Carbon dioxide to carbon equivalents)	.0038

The GHG emitted per ton of green waste ADC is calculated from factors in Table 3 as:

$$[100\% - (a)] \times (b) \times (c) \times (d) \times (e) = 0.0076 \text{ MTCE}$$

(b). Carbon dioxide reduction due to ADC cover placement

Green waste ADC use can potentially have two effects on GHG emissions relative to landfill cover placement. There may be a change in emissions involved in the placement of ADC in lieu of other covers. As will be shown, the change in GHG emissions due to the physical placement is negligible, less than the precision of the analysis (i.e., <0.1% of the net GHG budget).

The second effect involves the cessation of offsite soil importation for cover with the use of green waste ADC. The calculations presented here are reasonable for the LACSD green waste ADC program and indicate a small reduction in GHG emissions. However as noted below, this effect was not included in the analysis.

Any emission reductions related to ADC cover placement are presented for completeness but are omitted from the GHG budget as these are small and may be specific to the LACSD facilities. The calculations of the reductions follow.

ADC placement can involve different levels of GHG emissions relative to that of traditional cover soil. Differences arise from the varying material handling requirements. Besides green waste ADC, LACSD employs, for example, foam and film. These materials have technical limitations at times so that other covers such as conventional soil or green waste ADC must be used. The LACSD experience is that green waste ADC is generally used as a substitute for soil where other ADC's cannot be used. Consequently, the emissions effect of green waste ADC handling can be gauged relative to that of conventional cover soil.

Fuel use records were obtained for green waste ADC handling beyond that necessary for cover soil. Using a 2.78 kilogram carbon per gallon diesel conversion factor, an increase in net GHG emissions of less than 0.1% was calculated. This is less than the precision of the analysis and so is not included.

A reduction in carbon dioxide emissions from the cessation of cover soil imports was calculated as follows. A carbon dioxide emission factor of 2179 grams per mile per ton⁴ was applied assuming a 50 mile round-trip distance. This amounts to an emission reduction of 0.030 MTCE per trip. Assuming 22 tons of soil per trip, there is a reduction of 0.001 MTCE per ton of soil. Since green waste is less dense than soil, the reduction may be somewhat larger on a per ton green waste basis. However, as this number is small and may be specific to LACSD landfills, it is not further refined here or included in the summary below.

(c). Carbon dioxide offset due to energy recovery

The majority of collected landfill methane (60%) in California is used for energy recovery, typically by internal combustion engine electrical generator sets (derived from the USEPA LMOP database, 2006). This renewable energy recovery offsets carbon dioxide emissions (otherwise fossil fuel would be used to generate an equivalent amount of energy, emitting carbon dioxide).

The heating value for methane is 1000 British Thermal Unit (BTU) per cubic foot of methane. Applying an emission factor of 0.0835 MTCE per million BTU (USEPA, 1998), the carbon dioxide offset in terms of MTCE can be estimated. summarizes values of parameters used in the analysis.

⁴ California Air Resources Board EMFAC2000 Technical Support Documentation, Section 10.0, Table 10.3-1, http://www.arb.ca.gov/msei/onroad/doctable_test.htm (accessed 4/18/08).

Table 4. Factors for calculating CO2 offset due to energy recovery

ID	Category	Factor
(a)	Portion of collected CH ₄ used for energy recovery ⁵	60%
(b)	Methane heating value (BTU per cubic foot) ⁶	1000
(c)	kWh electricity generated/BTU ⁷	0.00008
(d)	kWh electricity delivered/kWh electricity generated ⁸	0.95
(e)	Conversion factor (BTU equivalents per kWh delivered)	3412
(f)	Emission factor (MTCE/million BTU) ⁹	0.0835

The carbon dioxide offset is calculated as the collected methane flow per ton green waste, q_{gw} , times the Table 4 factors as follows:

$$q_{gw} \times (a) \times (b) \times (c) \times (d) \times (e) \times (f) = 0.008 \text{ MTCE}$$

(d). Landfill green waste carbon sequestration

Carbon sequestration or storage factors for green waste components, grass, leaves, and branches, are based on Dr. Morton Barlaz's previous investigations (USEPA, 1998). Barlaz (2005) subsequently revised the carbon storage factor for leaves downward in his latest investigation for the USEPA (Freed, 2005). The most current USEPA carbon storage factors are summarized in Table 5.

Table 5. Green waste carbon storage factors

Category	Carbon Storage Factor (MTCE/ton)
Grass	0.12
Leaves	0.21
Branches	0.21

As can be seen from Table 5, leaves and branches have identical carbon sequestration factors but grass has a significantly lower value. This makes the assumed grass fraction important. The most recent CIWMB sponsored statewide composition study (Cascadia, 2004) reports two green waste fractions, grass and leaves as one (65% of green waste) and branches or trimmings as another (35% of green

⁵ Derived from USEPA LMOP database (2006) and CIWMB SWIS database; analysis shows about 60% of collected LFG is used for energy recovery purposes at California landfills that use green waste as ADCs.

⁶ "Opportunity for LF Gas Energy Recovery in Kentucky", USEPA/OAR September 1997, p. 2-12.

⁷ USEPA (1998), and also, "Opportunity for LF Gas Energy Recovery in Kentucky", USEPA/OAR September 1997, p. 2-11. Assumes use of internal combustion engines.

⁸ USEPA (1998), and also, USDOE, EIA, "Annual Energy Review 1993" (Washington, DC: DOE/EIA), July 1994, p. 252.

⁹ USEPA (1998), Exhibit 6-3, p.87.

waste).¹⁰ To ensure that the carbon sequestration was not overestimated, it was assumed that a large portion (~75%) of the grass and leaves fraction reported by Cascadia was grass, that is, grass comprised 50% of the total green waste.¹¹ The resulting green waste composition is shown in Table 6.

Table 6. Modeled green waste composition

Categories	Composition
Grass	50%
Leaves + Branches	50%

The overall carbon storage factor (MTCE per ton of green waste ADC) calculated from Table 5 and Table 6 is:

$$50\% \times 0.12 + 50\% \times 0.21 = 0.165$$

Summary of ADC results

The following table (Table 7) totals the emissions and reductions for ADC. As the reduction due to cessation of cover soil import is small and may be specific to LACSD operation, the value determined in “(b) Carbon dioxide reduction due to ADC cover placement” is omitted.

Table 7. Summary of results for ADC scenario

ID	Category	GHG Reductions (MTCE/ton) *
(a)	GHG emissions	-0.008
(c)	CO ₂ offset due to energy recovery	+0.008
(d)	Carbon sequestration	+0.165
	Net GHG reductions	0.165

* “-” indicates an emission; “+” indicates a reduction

2. Composting Scenario

Southern California is a major center for green waste ADC use. Proposals to discourage this practice and instead direct green waste to composting facilities would have a major impact in this region. Consequently the composting scenario described here, in particular the transportation aspects, is focused on southern California conditions. However we believe these may reasonably capture statewide conditions as well.

Composting can produce changes in GHG emissions resulting from (1) methane and nitrous oxide emissions during decomposition; (2) non-biogenic carbon dioxide emissions from green waste transport and mechanical turning of the compost piles at a centralized composting facility; and (3) long-term carbon sequestration. The latter two factors are included in the modeling as described in subsections (a)

¹⁰ “Report to the Board - Statewide Waste Characterization Study”, Table 7, Cascadia Consulting Group, Inc., December 2004.

¹¹ This is conservative relative to national green waste composition data as well. For example, the typical nationwide yard trimmings composition was reported as: 40% grass, 30% leaves, and 30% branches, by weight (see Barlaz, M. BioCycle-July 2000).

through (c). However compost decomposition emissions are *omitted* from this analysis for reasons detailed here.

There is generally limited data on compost decomposition emissions. USEPA (1998) suggested that composting, when managed properly, does not generate methane emissions. However a newly published study (Amlinger *et al.*, 2008) indicates that green house gas emissions, nitrous oxides from aerobic and methane from anaerobic windrow zones, are released during composting. Comparison of the Amlinger *et al.* (2008) results with the performance of landfill gas collection systems (e.g., SCS Engineers, 2007) with respect to green waste ADC indicates that composting emissions are similar to that of an adequately operated landfill gas collection system. As described in the ADC scenario, the landfill emissions are *included*. Omitting composting emissions as done here is a conservative approach for purposes of comparing the ADC and composting alternatives.

With respect to transportation, it was assumed that the green waste would first need to be locally consolidated before transport to a remote compost facility. Since green waste consolidation already occurs at LACSD landfills for either onsite ADC use or export to offsite users including composting facilities, it was assumed that there was no net difference between the two scenarios. As a result, local transport was omitted from either scenario. Helpful in evaluating this approach are the results for the long distance transport necessary for delivery to composting facilities and later to agricultural applications as indicated further below. The long haul transport results in a measurable but minor part of the overall GHG budget for compost. Consequently, any variations between ADC and compost applications with respect to the much shorter local haul would have no significant affect on the GHG budget for either scenario.

A second activity common to the ADC and composting applications is the shredding of the material. As these activities are comparable and, in the case of green waste exported from LACSD landfills, are identical, shredding has been omitted from either scenario.

(a). Carbon dioxide emission during transport

For the composting scenario, green waste is transported in two stages. Initially it is transported from a local accumulation point to a remote centralized composting facility and then again to its final use in agricultural applications. As illustrated in this section, transport over large distances has a minor but measurable affect on the GHG budget.

Due to the sparsity of centralized composting facilities, especially in southern California, it was decided that 180 miles round-trip is a reasonable yet conservative number. This was based on a combined one-way trip of 90 miles from the local accumulation point to a composting facility in northern Ventura County and then to farming applications in Kern County. According to the California Air Resource Board (ARB)'s EMFAC, the emission factor for trucks is 2179 grams carbon dioxide per mile traveled.¹² It is assumed for this analysis that each truck carries about 22 tons of green waste. Table 8 summarizes the factors used in this analysis.

¹² California Air Resources Board EMFAC2000 Technical Support Documentation, Section 10.0, Table 10.3-1, http://www.arb.ca.gov/msei/onroad/doctable_test.htm (accessed 4/18/08).

Table 8. Factors for calculating compost transportation CO₂ emissions

ID	Category	Factor
(a)	Truck-trip distance, round trip (miles)	180
(b)	Truck emission factor (grams CO ₂ per mile)	2179
(c)	Carbon dioxide to carbon conversion factor	0.2727
(d)	Grams to metric tons conversion factor	1 x 10 ⁻⁶
(e)	Truck capacity (tons green waste)	22

The carbon dioxide emissions per ton of green waste are calculated as:

$$(a) \times (b) \times (c) \times (d) / (e) \\ = \mathbf{0.018 \text{ MTCE}}$$

(b). Fossil fuel consumption in turning the compost piles

1. Turned-windrow composting operation

In this analysis, the modeled composting facility is a windrow type that uses a turner. The windrow pile turner is necessary to maintain aerobic conditions but consumes fossil fuel and so emits GHG carbon dioxide. According to USEPA (1998), the windrow pile turner consumes diesel fuel at a rate of about 0.221 million BTU per ton green waste and the emission factor is 0.021 MTCE per million BTUs of diesel fuel used. Therefore, the GHG emission rate for compost pile turning is:

$$\mathbf{0.221 \text{ million BTU per ton} \times 0.021 \text{ MTCE per million BTU}} \\ = \mathbf{0.0046 \text{ MTCE}}$$

2. Aerated static pile (ASP) composting operation

For the case of an ASP composting operation, while other parameters in a GHG life-cycle analysis are assumed to be the same for turned windrow and ASP composting, energy consumptions per ton of green waste processed are different for turned windrow and ASP composting operations. Specifically, the ASP operation consumes more fossil fuel, thus generates more carbon dioxide emissions during the composting processes. According to IERCF (2008), to process one ton of green waste, the energy consumption is 50.85 kWh. For IERCF, this required power is supplied by the Southern California Edison (SCE). According to Price (2002), the emissions factors for SCE are 0.122 kgC/kWh (for May) and 0.132 kgC/kWh (for October). Taking an annual average, hence, the average electricity-related GHG emission factor for SCE is 0.127 kgC/kWh. Therefore, the GHG emission rate for ASP composting is:

$$\mathbf{50.85 \text{ kWh} \times 0.127 \text{ kgC/kWh} \times (1 \text{ MT}/1000 \text{ kg})} \\ = \mathbf{0.0065 \text{ MTCE}}$$

(c). Carbon sequestration

Compost carbon sequestration can be divided into two storage processes – direct (humus formation) and indirect (soil carbon restoration).

According to USEPA (2002), the increased humus formation (direct carbon sequestration) is 0.05 MTCE per ton of compost. Because more than one ton of green waste is needed to form one ton of compost, the

actual green waste direct carbon sequestration rate will be lower on a per ton basis. However a conservative value of 0.05 MTCE was used for the green waste; this will tend to overestimate the benefits of carbon storage for green waste composting in this analysis.

According to USEPA (2002), the soil carbon restoration (indirect carbon sequestration) is 0.02 MTCE per ton compost. Again, as was done for the direct sequestration, this value was conservatively applied to the green waste tonnage and so will tend to overestimate the benefits of carbon soil restoration on a per ton green waste basis.

The total carbon sequestered is then 0.05 MTCE direct and 0.02 MTCE indirect per ton of greenwaste.

Summary of compost results

The following table (Table 9) totals the emissions and reductions for green waste composting. As noted above, the carbon sequestration factor is expressed relative to the compost tonnage, which is less than the actual green waste tonnage. Consequently, the indicated carbon sequestration is somewhat higher than actually occurs for green waste on a per ton basis.

Table 9. Summary of results for green waste compost scenario

ID	Category	GHG Reductions (MTCE/ton) *	
		Windrow	ASP
(a)	CO ₂ emission during transportation	-0.018	-0.018
(b)	Fossil fuel consumption in operating the composting processes	-0.005	-0.007
(c)	Carbon sequestration (direct and indirect)	+0.070	+0.070
(d)	Net GHG reductions	0.048	0.046

* “-” indicates an emission; “+” indicates a reduction

Inclusion of fugitive methane and nitrous oxide emissions

(a). Methane emission from composting piles

One South Coast Air Quality Management District (SCAQMD) study (Stredwick, 2001) found that 0.83 pounds of CH₄ had been emitted per ton of green waste from a green waste composting facility in southern California. Another most recent study (Amlinger *et al.*, 2008) shown that methane emissions of a green waste composting operation is 1517 g/Mg green waste¹³. Taking an average of the two data sets, the GHG (CH₄ with a GWP of 23) emission rate is:

$$\begin{aligned}
 &0.5 \times ((0.83/2.2)+(1517 \times (0.001) \times (2000/2200))) = 0.878 \text{ kg/ton of green waste} \\
 &= 0.000878 \text{ MT/ton of green waste} \\
 &= 0.000878 \times 23 = 0.0202 \text{ MTCO}_2\text{E} = 0.0202 \times (12/44) \text{ MTCE} \\
 &= 0.0055 \text{ MTCE}
 \end{aligned}$$

¹³ Data were obtained from green waste and biowaste windrow composting. Examining raw data in details found that the total CH₄ and N₂O emissions over the entire test period are comparable for green waste and biowaste composting (with green waste composting having higher overall emissions). Taking a conservative approach, it is assumed that the values used here are averages of green waste and biowaste composting.

(b). Nitrous oxide emission from composting piles

Also according to Amlinger *et al.* (2008), nitrous oxide emission of a green waste composting operation is 252 g/Mg green waste¹³. Thus, the GHG (N₂O with a GWP of 296) emission rate is:

$$252 \times (0.000001) \times (2000/2200) \times (296) \times (12/44) \\ = 0.0185 \text{ MTCE}$$

Summary of compost results (with CH₄, N₂O emissions included)

Table 10 below summarizes the emissions and reductions for green waste composting with fugitive methane and nitrous oxide emissions included in the analyses. Due to the lack of specific data, it is assumed that fugitive methane and nitrous oxide emissions are the same for both turned-windrow and ASP composting operations. Further research is needed to better quantify GHG emissions from composting operations.

Table 10. Summary of results for green waste composting (CH₄, N₂O emissions included)

ID	Category	GHG Reductions (MTCE/ton) *	
		<i>Windrow</i>	<i>ASP</i>
<u>(a)</u>	CH ₄ emission during composting processes	-0.0055	-0.0055
<u>(b)</u>	N ₂ O emission during composting processes	-0.0185	-0.0185
	Net GHG reductions (CH ₄ , N ₂ O emissions excluded) (table 9 (d))	0.048	0.046
	Net GHG reductions (CH ₄ , N ₂ O emissions included)	0.024	0.022

* “-” indicates an emission; “+” indicates a reduction