A Greenhouse Gas Emissions Analysis
of
Biosolids Management Options
for
Merrimack, NH

Ned Beecher, MS
Executive Director
North East Biosolids and Residuals Association

April 2008

North East Biosolids and Residuals Association (NEBRA)
Tamworth, NH 03886
www.nebiosolids.org

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An Excel spreadsheet detailing all calculations used in this analysis is available from NEBRA, Tamworth, NH USA (info@nebiosolids.org).

Executive Summary

Since 1984, the Town of Merrimack wastewater treatment facility (WWTF) has been committed to the beneficial reuse of its wastewater solids. In 1994, it chose to replace the open aerated static pile compost facility with a new enclosed in-vessel composting facility that provided for more effective odor control and improved compost quality. In 2002, the treatment plant received a first place award from the U. S. Environmental Protection Agency (U. S. EPA) for its beneficial use program. Compost generated from the WWTF is recognized as superior quality and has been used to refurbish the great lawn at New York Central Park, for construction of the Boston Red Sox Teddy Ebersol ball fields, and in the landscaping of the Rose Kennedy Greenway over the Boston central artery.

After fourteen years of operation, significant renovations of the existing composting facility are required. Thus the Town faces the options of making the capital investments to continue composting or abandoning composting in favor of landfill disposal. Landfill disposal is available at Waste Management's Turnkey Recycling and Environmental Enterprises (TREE) facility located in Rochester, NH. Although choosing the landfill disposal option will require an upgrade to the WWTF dewatering facilities, the operational costs of bringing Merrimack wastewater solids to the landfill appear to be lower than continued composting.

The purpose of this study was to add additional information to the evaluation of the two biosolids options being considered by the Town of Merrimack: continued composting vs. landfill disposal. Specifically, this study analyzed the options with regard to energy consumption and greenhouse gas (GHG) emissions. The scope of this analysis did not include the wastewater treatment operations, only the biosolids management occurring after dewatering. In the analysis, calculations were made of the energy consumed and GHG released from all activities associated with making, distributing, and using compost in comparison with transportation and landfill disposal of the wastewater solids. Current GHG accounting principles developed by the International Panel on Climate Change (IPCC), U. S. EPA, and others were used in the assessment.

The results of this analysis indicate that the current composting operation requires significantly more energy consumption than landfill disposal. For example, the current composting operation accounts for approximately 735 kWh equivalent of energy consumption per dry ton of wastewater solids processed. If the Town upgraded its dewatering system (as would be required to bring the solids to the landfill) and continued composting, the amount of energy consumed in the composting operation would be reduced to approximately 568 kWh equivalent per dry ton of processed solids. In contrast, landfill disposal will account for significantly less energy consumption: approximately 261 kWh equivalent per dry ton of processed solids. In other words, the future composting option would result in energy use 2.2 times greater than the energy use required for landfill disposal.

Despite the greater use of energy to perform composting, composting accounts for less GHG emissions than landfill disposal. Calculations indicate that current composting operations account for an estimated total of 1,529 Mg carbon dioxide (CO_2) equivalent emissions. Future composting operations, with improved dewatering, would account for a total of 1,094 Mg CO_2 equivalent emissions, a decrease of about 29%. In contrast, future landfill disposal would account for an estimated total of 3,754 Mg CO_2 equivalent emissions, 2.5 times as much as the current composting operation and 3.4 times as much as the composting option with improved dewatering.

This difference in total greenhouse gas emissions is driven, almost entirely, by the fact that landfill disposal will release to the atmosphere significantly more methane than composting. Operations at landfills create anaerobic conditions in which wastewater solids readily generate methane. Calculations used in this study took into consideration the fact that a high percentage of methane is eventually captured at the TREE landfill and is used to generate electricity. The important fact is, however, that fugitive emissions of methane are difficult to avoid in the active landfilling operation.

If Merrimack were to choose the upgraded composting option, rather than the landfill option, an estimated 2,660 Mg of carbon dioxide equivalent emissions would be avoided each year, which equates to taking almost 500 passenger cars off the road.

Introduction

The Town of Merrimack, New Hampshire, currently composts the wastewater solids (sewage sludge) produced at its municipal wastewater treatment facility (WWTF) and has been doing so, by one process or another, on and off since 1984. In October 1994, the current enclosed, IPS in-vessel, agitated composting system began operations. This facility includes fifteen 220’ by 6.5’ bays where compost is turned daily by overhead mechanical turners. The operating capacity is designed for 225 cubic yards per day of a mix that currently consists of wastewater solids and sawdust. The Merrimack compost system is entirely enclosed in a 40,000 square foot building to which negative air pressure is applied. All air from the building is discharged to the atmosphere through at 15,000 square foot biofilter. The compost is retained in the active, enclosed compost operation for 21 days. It is then cured in uncovered, outdoor windrows. After at least 30 days, the cured compost is screened. Finished compost is then stored in separate uncovered windrows. These storage windrows are occasionally turned and moved.

After 14 years of operation, the Merrimack Department of Public Works (DPW) is considering upgrading its biosolids management system. Initial analyses have indicated a need to improve the wastewater solids dewatering system, which is currently a belt filter press that produces a material that is about 20% solids (80% water). The final disposition of the wastewater solids is also being reviewed, and two options are being considered seriously – continued composting (which may require some improvements to the current facility) or trucking dewatered solids to the Waste Management Turnkey Recycling and Environmental Enterprises (TREE) landfill in Rochester, NH. DPW staff are assessing new dewatering technologies (centrifuges, screw presses), any needed upgrades for continued composting, and the monetary and energy costs likely to be encountered in the operations of each option.

This paper provides an analysis of the energy consumption and greenhouse gas (GHG) emissions of the current biosolids composting operation and the two future options under consideration: composting with improved dewatering and landfill disposal.

What are biosolids?

Wastewater solids (sewage sludge) contain the particles of waste that settle in primary clarifiers and the particles and micro-organisms that settle out in secondary clarifiers at a WWTF. Wastewater solids are a complex mixture of:

- water – when dewatered and treated, the material is usually 18 – 30 % solids;
- organic matter (40% - 80%) – complex organic (C-containing) molecules like proteins, fats, carbohydrates, etc.;
- inorganic solids: fine silt, clay particles, simple elements
- trace amounts of a diversity of natural and synthetic organic and other chemicals and heavy metals of natural and anthropogenic origin; and
- a diversity of micro-organisms, including small amounts of human and animal pathogens (disease-causing organisms).

Composting is one of the prescribed ways by which wastewater solids are treated to reduce pathogens and create a useable, beneficial *biosolids* product. Biosolids are treated and tested wastewater solids that can be used as soil amendments and fertilizers.

Sustainable Management of Biosolids

The recognized resources in wastewater solids are:

- water
- organic matter – like animal manures and composts, because of their abundant organic matter and biological activity, treated wastewater solids help build healthy soils;
- plant and animal nutrients – wastewater solids contain 4 – 6% nitrogen and phosphorus, plus a little potassium; in addition to these three macronutrients needed by all plants, biosolids contain micronutrients like copper, nickel, and zinc; and
- energy – the complex organic molecules in biosolids store energy that can be released through oxidation and other processes.

The recent history of the management of wastewater solids has been slowly working toward maximizing the beneficial uses of these resources while managing and mitigating potential risks. Thus, today, direct application of treated solids (biosolids) to agricultural lands is the leading use of biosolids in the U. S. Composting biosolids, which requires more energy and cost, is a wide-spread practice and produces a high quality, Class A, product that is widely accepted in soil products markets around the country. Another kind of widely distributed Class A product is heat-dried pellet fertilizer, such as that made in Lawrence and Boston, MA; producing this kind of product generally requires even greater energy and cost. These uses of biosolids as soil amendments and fertilizers puts to use their organic matter and nutrients. In some cases (such as at Nashua, NH), the energy value of biosolids is also tapped through anaerobic digestion and use of the resulting biogas (methane) to generate heat and/or electricity. The most sustainable biosolids management programs are those that

- maximize the use of the resources in wastewater solids (organic matter, nutrients, energy);
- minimize contaminants and other potential negative environmental and public health side-effects (including release of greenhouse gases) through careful control of the original waste-stream, monitoring and testing, and best management practices; and
- does these with the least cost in terms of fossil fuel energy, other non-renewable resource inputs, and greenhouse gas emissions.

Some scientists suggest that composting may represent the best and highest use for wastewater solids (Brown et al., in press). Composting maximizes the use of nutrients and organic matter and reduces trace chemicals and pathogens.

Carbon Emissions Accounting

Concerns with global climate change caused by anthropogenic emissions of carbon dioxide (CO_2) and other greenhouse gases (GHG) have stimulated development of systems that measure and track greenhouse gas emissions from diverse sources. Our analysis applied current GHG accounting principles developed by the International Panel on Climate Change (IPCC), U. S. EPA, and others.

Wastewater, wastewater solids (sewage sludge), and other organic wastes are of interest in carbon emissions accounting mostly because of their potential contribution to the generation of methane (CH_4) and nitrous oxide (N_2O). None of these wastes contain significant amounts of fossil carbon (C) – that is, C from petroleum, coal, and similar materials. Wastewater solids and the amendments in compost are composed of actively cycling, or biogenic, carbon. It is generally accepted that carbon that is actively cycling in the biosphere (through plants, animals, and wastes) has no net impact on overall long-term levels of carbon in the atmosphere. Thus, no matter how these materials are managed, any CO_2 they release over the short term is not added to GHG emissions calculations.

What is accounted for in GHG emissions calculations are:

- CO_2 emissions from burning of fossil fuels, which, in the wastewater management field, occurs during the treatment and processing of wastewater and wastewater solids;
- Emissions of methane, which has 23 times greater intensity as a greenhouse gas than does CO_2;
- Emissions of nitrous oxide (N_2O), which has 296 times more effect than CO_2; and
- Any non-fossil, cycling carbon (C) that is sequestered.[1]

This study estimated the net emissions of CO_2, CH_4, and N_2O and the amounts of sequestered carbon (C) associated with the

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[1] How long non-fossil carbon must be sequestered to be considered to have significant impact on reducing global warming is a matter of discussion. Research shows that a molecule of carbon dioxide (CO_2) remains in the atmosphere for up to 200 years. If, instead, non-fossil, or biogenic, carbon can be sequestered in the terrestrial environment and not contribute to CO_2 in the atmosphere, then it is considered to be a net benefit – a credit – in carbon accounting. Given the range of time CO_2 remains in the atmosphere, a conservative target for sequestration of C that is likely to truly reduce atmospheric CO_2 and the greenhouse effect is 100 years (Recycled Organics Unit, 2007).

two leading proposed options for the future management of Merrimack wastewater solids. In this analysis, as is the standard practice, total GHG emissions are expressed in terms of megagrams (Mg, or metric tons) carbon dioxide equivalents (CO_2 equiv).

This analysis focuses on…

- charging each biosolids management option with CO_2 released when fossil fuels are burned during operations;
- charging each biosolids management option with any methane or nitrous oxide emissions to the atmosphere,
- crediting each biosolids management option with any significant amount of carbon sequestered (maintained in organic materials for about 100 years) that would otherwise have been released to the atmosphere as CO_2 according to the assumed norm; and
- crediting each biosolids management option whenever it results in the displacement of fossil fuel use (e.g. using biosolids-generated methane) or the displacement of the use of other resources that cause carbon emissions (e.g. peat, synthetic nitrogen fertilizer).

The Scope of the Analysis

The basic wastewater treatment processes at Merrimack are not part of this analysis. While these involve considerable use of energy for pumps, aeration blowers, etc., and wastewater treatment is known to be a source of methane and nitrous oxide emissions, whichever biosolids management option is chosen will not change these processes and their energy consumption and GHG emissions.

This analysis assumes that a new dewatering system will be required to meet the needs of the landfill disposal option, mostly because the current ~9,500 wet U. S. tons per year of solids production cannot be efficiently transported the longer distance to the landfill (J. Taylor, pers. comm.). Creating a higher solids content will reduce the total mass, allowing for a fewer number of truck trips to the landfill.

If composting were to continue, it would not be necessary to upgrade the current belt filter press dewatering system. However, a dewatering upgrade would be likely anyway (J. Taylor, pers. comm.), although it may not have to be done as quickly. At other treatment plants, replacement of aging belt filter presses have usually created more energy efficient operations (mostly due to reducing the volume of solids to be handled), while also improving the work environment for operators.

This analysis focuses on the current composting operations, but makes a prediction of GHG emissions impacts for a future operation that includes centrifuge dewatering prior to composting. Changes in electricity use will be the most significant direct impact of installing a centrifuge, and this is incorporated in the calculations. Polymer use will also change, but this was not included in this analysis; this change, like centrifuge electricity use, will be equal for both the future composting or landfill disposal options.

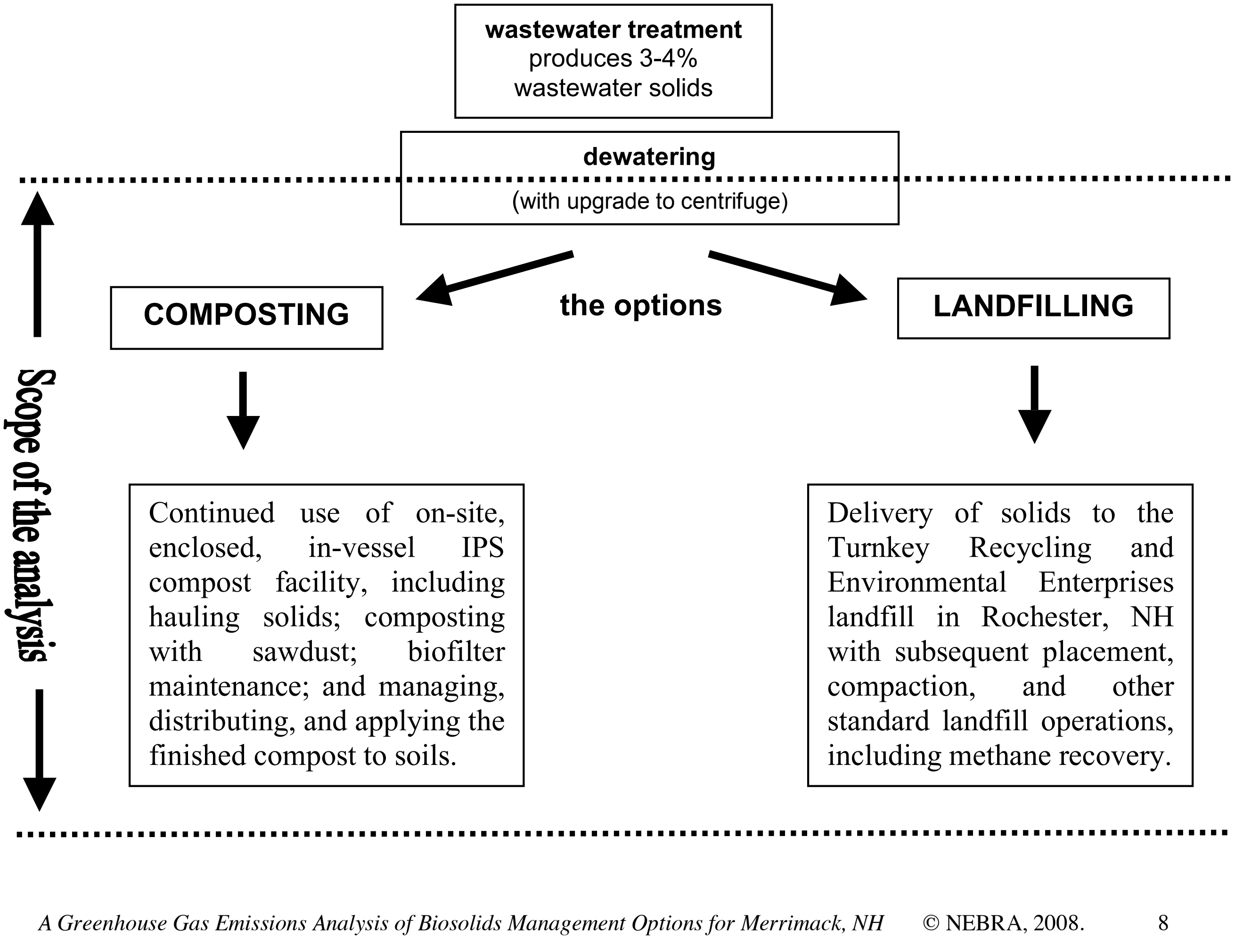
Within the composting operation, a significant benefit of improved dewatering would be a reduction in the amount of sawdust amendment required. Sawdust is becoming continually more difficult and costly to obtain (J. Taylor, pers. comm.). An increase in the percent dry solids created by centrifuge dewatering would also reduce the number of composting bays needed to process Merrimack solids and would thus reduce the use of electricity and the amount of fuel used by equipment such as front end loaders.

In summary, the process point at which the two potential future biosolids management options diverge is *after* the assumed upgraded dewatering, at the point when the wastewater solids are deposited into a truck that will convey them either a short distance to the WWTF's composting facility or to the TREE landfill in Rochester, NH (Figure 1).

GHG emissions analyses vary in how they deal with the energy consumption and GHG emissions attributable to suppliers, vendors, customers, and other actions. When organizations calculate their carbon footprints, they may include only the energy use and GHG emissions of things they own and the activities that are conducted by their employees. Thus, when an employee rents a car for business, the fuel use and emissions from the use of that car are not included in that organization's carbon footprint (they would be "charged," instead, to the rental car company).

However, for this current analysis of energy use and carbon emissions for the Merrimack biosolids management options, we included the use of any equipment and the actions of

Figure 1: The scope of the analysis



Continued use of on-site, enclosed, in-vessel IPS compost facility, including hauling solids; composting with sawdust; biofilter maintenance; and managing, distributing, and applying the finished compost to soils.

Delivery of solids to the Turnkey Recycling and Environmental Enterprises landfill in Rochester, NH with subsequent placement, compaction, and other standard landfill operations, including methane recovery.

any person required to get the biosolids management job done. Ultimately, the Town of Merrimack has control of this entire scope, albeit through vendors and contractors for some aspects of the operations.

We have included in this analysis all ancillary GHG emissions costs and benefits associated with each option that we believe to be significant (Table 1).

What is Significant and What is Not?

Because of the much greater impacts on atmospheric warming caused by methane and nitrous oxide, any process that produces these gases has far greater importance in carbon emissions accounting (Table 1). The most significant aspects of the Merrimack biosolids management options, with regards to impacting total greenhouse gas emissions, are discussed below; included is discussion of why each factor is or is not significant in the specific case of the Merrimack options:

- *potential methane release during composting* - While methane (CH_4) may be generated in some composting operations, the extensive aeration and agitation in the Merrimack operation reduces any likelihood that anaerobic conditions required to generate methane will occur. Data collected at other composting facilities using the same IPS technology indicate that oxygen levels in the active composting bays remain consistently above 5% (pers, comm. R. Nicoletti). In addition, the active composting operation at Merrimack is enclosed, and the air from the composting area is treated through a biofilter that oxidizes (i.e. breaks down) methane. The only part of the composting operation at Merrimack that may produce methane is during outside curing and storage; estimates for methane generation during this stage of the operations are included in this analysis.

- *nitrous oxide release during composting* - Nitrous oxide (N_2O) has been measured from some composting operations, and its release from biofilters has been measured. However, as with methane, the high level of aeration in the enclosed Merrimack active composting area reduces the risk of N_2O generation, and we have assumed zero emissions during that process. However, similar to methane, we estimate some N_2O release during curing and storage of the compost.

- *using sawdust for energy instead of in compost* – To produce a high quality compost, Merrimack uses 18,000 cubic yards of sawdust each year (about 700 cubic yards of wood chips per year are used in biofilter maintenance as well). If this woody material were burned for electricity production instead, it would displace fossil fuels that might have been used to create the same amount of electricity, thus reducing the associated fossil carbon emissions. Our analysis takes this into account.

- *carbon sequestered in soil* – There is considerable discussion in research literature regarding the degree to which use of compost leads to permanent or semi-permanent sequestration of carbon in the soil. It is widely agreed, however, that this is a significant positive impact of compost use, and we have estimated a credit for the composting option.

- *methane generation from landfill disposal of wastewater solids* – Landfills produce methane, and wastewater solids are the kind of material most likely to produce methane in significant volumes in relatively short periods of time after they are landfilled. Methane generation from solids in the landfill has the single largest impact on our carbon emissions analysis.

Table 1: Identifying the Most Significant Aspects of the Solids Management Options

In performing the following analysis, the net carbon dioxide equivalents of each option are accounted for from the following sources:

	Additions of fossil CO2 equivalent to the atmosphere from Merrimack solids management		**Relative importance in greenhouse gas emissions resulting from Merrimack solids management**
Composting option		**+ *or* -**	
Composting operations	electricity	+	some
	diesel fuel	+	some
	natural gas	+	minimal; not much is used
	methane & N2O from active composting	+	potentially **LARGE**, but not likely in this case, due to enclosed active composting
	storage of solids prior to composting	+	potentially some; not included in this analysis because of short storage time (~ 1 day)
	methane & N2O from sawdust storage	+	not likely; assumed to be zero
	not using sawdust for composting, but burning it for energy	-	potentially **LARGE**, but only if sawdust would be burned for energy instead
	methane and N2O from curing & storage	+	potentially **LARGE**
Compost transportation and marketing	diesel fuel	+	some
	gasoline	+	minimal
Compost placement	diesel	+	minimal
Compost use	displaced fertilizer	-	some
	displaced peat		some
	sequestered carbon (C) in soil	-	**LARGE**
	displaced other nutrients (P, K, micro)	-	minimal; not included in this analysis

	displaced fungicide/herbicide	-	minimal; not included in this analysis
	displaced need for irrigation	-	some; not included in this analysis
	induced N2O release from soil	+ or -	potentially some, but chemical fertilizers that compost might replace would likely induce more
Landfill disposal option			
Solids transportation	diesel fuel	+	some
Landfill operation	diesel fuel	+	some
	fugitive methane from solids decomposition	+	**LARGE**
	fugitive methane from other MSW due to solids present	+	potentially some; difficult to estimate; not included in this analysis
	fugitive N2O from solids decomposition	+	Likely minimal; difficult to estimate; not included in this analysis
	sequestered carbon (C) in landfilled solids	-	potentially some

Which Option Uses More Energy?

The data from utility bills for energy used by Merrimack in 2007 allowed for the calculation of total energy used in terms of kilowatt-hour equivalent per dry ton of processed solids. Kilowatt-hour equivalents are a way to look at all energy uses – diesel, natural gas, gasoline, and electricity – in a common unit. (EPA, 2004; DOE-EIA, 2007). Using the same process and calculations, it was also possible to estimate the likely total kilowatt-hour equivalent of all of the energy needed to operate the two future options: composting with centrifuge dewatering or landfilling with centrifuge dewatering.

The results of this comparison (Table 2) indicate that the current composting operation requires more energy consumption than either of the likely future options. Changing to centrifuge dewatering should reduce energy consumption considerably, from 735 to 568 kWh equivalent per dry ton processed solids. Bringing the solids to the Rochester landfill, after centrifuge dewatering, would likely further reduce energy consumption by about 46%.

These results underscore the fact that composting is an energy-intensive operation. Research has shown that, on average, active composting utilizes on the order of 100 kWh equivalent energy for each ton of compost output (Brinton, 2008). The current basic composting operations at Merrimack utilize approximately 181 kWh equivalent energy for each *wet* ton of compost output, not including solids dewatering, curing, loading, screening, marketing, biofilter maintenance, and delivery of the compost. If all energy costs associated with all of these aspects of the Merrimack composting operations are included, the energy use is 375 kWh equivalent per wet ton of compost output.

Because the composting operations are enclosed and highly mechanized, e.g forced aeration and daily mechanical agitation, energy consumption at Merrimack is likely greater than other operations. However, the greater mechanization results in a more efficient control over the process and a more highly aerobic condition in the composting process, which minimizes the opportunity for the production of methane.

By upgrading to a centrifuge dewatering system, Merrimack's composting operation equivalent energy consumption could be reduced from 181 to 140 kWh per wet ton of compost output (considering only the basic composting operation). Similarly, the all-inclusive total energy costs associated with the composting operations could be reduced from 375 to 290 kWh equivalent energy per wet ton of compost output.

It is important to note that the estimates on energy use per wet ton of compost output do not include calculations of the energy saved by various uses of compost (these kinds of credits are calculated for greenhouse gas emissions – see below). If one considers the amount of energy needed to synthesize nitrogen fertilizer and the fact that compost use displaces the need for some fertilizer, it becomes apparent that the total per-wet-ton energy used in producing compost is offset, to some extent, by avoided energy consumption elsewhere when the compost is used. Other benefits of compost use provide similar offsets, including the reduced needs for peat, herbicides and fungicides, and irrigation.

Table 2: Energy Uses of Current and Future Options

Operation	**Energy use / day** (avg. over 365 days in 2007)	**kWh equivalent / dry ton solids**	**Notes**
CURRENT COMPOSTING			
Belt filter press operations	66 kWh	13	estimated, based on 11 hp engine x run time
Moving & mixing solids, moving compost, screening, managing storage piles, loading trucks with compost	22.0 gallons diesel fuel	178	9855 total gals /year diesel used for moving all compost (including out-of-town solids) by 3 front loaders, dump trucks, and power screen
Transporting sawdust (necessary compost feedstock)	13.6 gallons diesel fuel	110	
Compost facility operations (aeration, turning, biofilter)	1331 kWh	215	based on utility bills showing 2007 consumption
Compost facility heating (mixing area and office)	49.2 cubic feet	15	22,000 cubic feet of natural gas were consumed in '07.
Biofilter maintenance	1.4 gallons diesel fuel	12	wood chip delivery and placement every 2.5 years

Marketing compost	0.06 gallons gasoline	2	calculated based on marketer estimates for 2007
Compost delivery by marketing company	13 gallons diesel fuel	103	calculated based on actual delivery miles in 2007
Compost delivery by Town from WWTF	0.11 gallons diesel fuel	1	some landscapers and soli product marketers pick up and deliver
	1.1 gallons gasoline	42	most locally sold compost goes in private pickups
Compost application	5.5 gallons diesel fuel	44	calculated based on measured details from typical compost use project
TOTAL **Current Composting**		**735**	
UPGRADED COMPOSTING			
Increased electricity use for centrifuge dewatering	+374 kWh	+74	estimate based on expected horsepower and run time
1/3 less energy use due to higher solids content (change from 20% - 30% solids)	-33%	– 240	Estimate assumes a total reduction in energy use and credits of 30% over current composting operations.
TOTAL **Upgraded Composting**		**568**	
LANDFILL DISPOSAL AT ROCHESTER, NH			
Centrifuge dewatering	440 kWh	87	estimated and equivalent to dewatering line for upgraded compost option
Transportation of wastewater solids to landfill	19.5 gallons diesel fuel	158	Based on estimated diesel fuel used for 316 roundtrips of 106 miles at 4.7 miles per gallon.
Landfill dozer/compacter operations attributable to Merrimack solids	1.93 gallons diesel fuel	16	2 machines run 10 hours per day, consuming 400 gallons times 0.48% of waste that is Merrimack's
TOTAL **Landfill disposal**		**261**	

The amount of energy consumed contributes only part of the total carbon emissions attributable to a particular operation, for two main reasons:

1. If some or all of the fuels and/or electricity used are from renewable sources (e.g. biofuels or wind power), then that portion is not considered to be contributing carbon emissions; and
2. Carbon emissions accounting includes more than the carbon

dioxide (CO_2) released from burning of fossil fuels. In fact, far more important to the bottom line in carbon accounting are the gases methane and nitrous oxide.

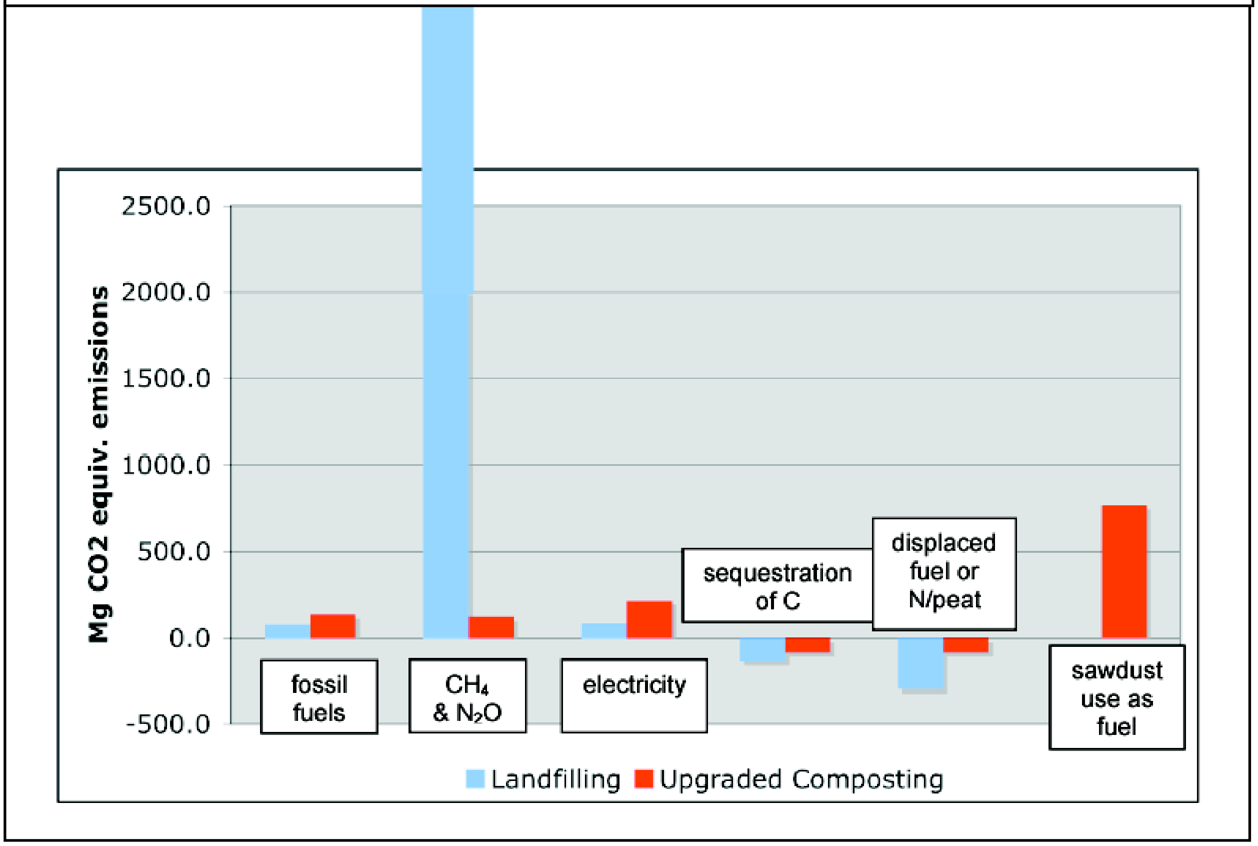
Which Option Has Greater Greenhouse Gas Emissions Impacts?

Landfill disposal will lead to larger greenhouse gas emissions than continued composting. Our best estimates, using equivalent assumptions for each option, are as follows (see also Table 3). Note that one Mg (mega gram) is one metric ton, equivalent to 1 million grams or 1,000 kilograms or 1.102 U. S. tons.

- Current composting operations emit an estimated total of 1,529 Mg CO_2 equivalent emissions.
- Future composting operations (with centrifuge dewatering) would emit an estimated total of 1,094 Mg CO_2 equivalent emissions, a decrease of about 29 %.
- Future landfill disposal would emit an estimated total of 3,754 Mg CO_2 equivalent emissions, 2.5 times as much as the current composting operation and 3.4 times as much as the future composting option.

More precision in these estimates is difficult to attain, because of uncertainties in the details of each operating system and the necessity of making assumptions (see notes,

Figure 1. Greenhouse Gas Emission (CO_2 equivalents) estimated for different aspects of Merrimack wastewater solids management by landfill disposal (blue, left) or upgraded composting (red, right).



below, for details regarding assumptions and calculations). These results are consistent with other analyses that have found that properly-managed composting operations are likely to produce less greenhouse gas emissions than landfill disposal (Recycled Organics Unit, 2007; Brown and Leonard, 2004).

In this analysis, we assumed the following regarding the landfill option:

- only a fraction of the methane that may be generated from landfilled Merrimack wastewater solids is captured (much of the methane is fugitive);
- 100% utilization for electricity generation of the Merrimack wastewater solids methane that is captured at the landfill;[2] and
- some (5%) of the carbon in landfilled Merrimack wastewater solids is sequestered.

The TREE landfilling operations at Rochester are efficient – we have generally assumed a methane capture rate of 79%. This efficiency is above the average: U. S. EPA has generally used 75%, but other analyses have placed the average efficiency within the range of 20% to 90%, with an average of perhaps 35% (S. Brown, pers. comm., Anderson, 2006). However, landfill operations are less controlled than other forms of putrescible waste management, such as anaerobic digestion and composting (especially enclosed composting such as that at Merrimack). As waste is deposited in a landfill and compacted, it is exposed to the atmosphere. Collection of any emissions, including methane, will not occur in the active waste dumping area for anywhere from several months to a year. During that time, wastewater solids are highly likely to become anaerobic and to begin generating methane that cannot be captured.

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[2] Currently, 50% of Rochester landfill gas is utilized. Most of the methane captured is from the closed landfill areas, which have the highest capture efficiencies (up to 90+%, B. Howard, pers. comm.). Less of the methane from quickly putrescible wastewater solids is likely to be captured, because capture efficiency is lower in the active disposal area, which is where wastewater solids will release methane. In the future, a greater percentage – approaching 100% - of the landfill gas from Rochester will be utilized. In late 2008, the University of New Hampshire plans to complete its renewable energy project that involves construction of a pipeline from the TREE facility to the campus in Durham, where burning the methane will generate heat and electricity. In our calculations we have assumed 100% use of captured Merrimack-derived methane for this purpose and given the landfill option credit for the displaced fossil fuel use. These assumptions serve to minimize the total projected greenhouse gas emissions of the landfilling option.

Table 3: Total Estimated Greenhouse Gas Emissions for Current and Future Options

Operation / Emissions Source	**CO2 Equivalent Emissions** numbers > 0 are debits numbers < 0 are credits (Mg / year)	**Notes**
CURRENT COMPOSTING		
Dewatering / electricity (belt filter press)	12.52	Estimated (J. Taylor) based on 11 HP engine and measured run hours.
Moving & mixing solids and compost, screening, moving storage piles, loading trucks with compost, etc. / diesel fuel	81.2	9855 gallons per year diesel is used by 3 front loaders, dump trucks hauling solids to compost, power screen - includes all pre- and post-composting front loader work.*
Composting operation (aeration, ventilation, turning, biofilter, etc.) / electricity	206.18	Based on actual electricity use by the composting facility in 2007*.
Space heating (office and enclosed compost area) / natural gas	1.02	
Transporting sawdust	50.06	About 18,000 cubic yards of sawdust are used each year in the composting operations.* This equates to about 1.5 cubic yards per wet ton of wastewater solids.
Biofilter maintenance (transporting & replacing wood chips / diesel fuel	5.34	The biofilter that treats air from the enclosed processing facility has it wood chip media changed every 2.5 years.
Alternative use of 30% of sawdust & woodchips for electricity generation / lost credit for displaced fossil fuel use	1157	Sawdust and wood chips have several markets. We assume that 30% of the sawdust used each year by Merrimack composting might instead be used for electricity generation. Other uses of sawdust will likely result in soil carbon sequestration, as with composting.
Compost curing & storage / methane (CH_4) emissions	18.77	Compost is stored outside, in large piles, as it cures and before it is sold and distributed. Several different calculations, based on literature, were used and averaged to reach this estimate.*
Compost curing & storage / nitrous oxide (N_2O) emissions	169.77	As with the methane emissions estimate above, several different calculations, based on literature, were used and averaged to reach this estimate.*

Compost marketing / gasoline	0.18	Estimated total gas used in marketing operations provided by Agresource, the contract marketer.*
Compost distribution by contractor / diesel fuel	46.97	Agresource estimated 5954 gallons of diesel were used to deliver Merrimack compost to end use sites in 2007.* Most Merrimack compost is delivered in this way.
Compost distribution locally / diesel fuel	0.41	Some local contractors transport Merrimack compost to local end use sites.*
Compost distribution locally / gasoline	3.64	Most of the 2500 cubic yards of compost distributed locally is picked up in small pick-ups.*
Compost placement at end use site / diesel fuel	20.12	Estimated by Agresource based on measured fuel use at a compost utilization site in 2007.*
Carbon sequestration in soil due to compost use /	– 122.96	The amount of carbon sequestration attributable to compost use is difficult to estimate with precision; there are many factors that affect C sequestration in soils. This estimate was reached through several calculations, based on literature,, the results of which were averaged.*
Displacement of N fertilizer use / displaced fossil fuel use	– 47.10	Nitrogen (N) fertilizer requires copious amounts of energy to produce and transport. This estimate* assumes that 80% of the N supplied by compost actually displaces an equivalent amount of N fertilizer.
Displacement of peat use / displaced release of sequestered C	– 74.34	When compost is used, it often replaces any need to use peat. Mining peat releases fossil carbon. This estimate assumes that 30% of Merrimack compost* displaces peat.
TOTAL **Current Composting**	**1529**	
UPGRADED COMPOSTING		
Dewatering / electricity (centrifuge)	83.48	Based on increased electricity use by centrifuge operations estimated by J. Taylor.
Decrease in total composting operations' use of all fuels, electricity, and credits	a reduction of – 518.13	Estimate assumes a total reduction in energy use and credits of 30% over current composting operations. This is because the dryer material produced by the centrifuge will reduce volume and mass of solids to be managed by ~ 1/3.

TOTAL Upgraded Composting	**1094**	
LANDFILLING AT ROCHESTER, NH		
Centrifuge dewatering / electicity	83.48	Based on increased electricity use by centrifuge operations estimated by J. Taylor.
Transportation of wastewater solids to landfill / diesel fuel	72	Based on estimated diesel fuel used for 316 roundtrips of 106 miles at 4.7 miles per gallon.
Landfill dozer/compacter operations attributable to Merrimack solids	7.1	2 machines run 10 hours per day, consuming 400 gallons times 0.48% of waste that is Merrimack's
Fugitive methane (CH_4)	4018.2	Estimate based on several different calculations, derived from literature and analysis of the TREE facility operations, the results of which were averaged.
Carbon (C) sequestration	– 132.3	Estimate assumes 5% of C in landfilled Merrimack solids will be sequestered in landfill, rather than converted to CO_2 and CH_4.
Credit for use of landfill methane for generating electricity	– 294.79	Estimate assumes that 100% of generated and captured methane from Merrimack solids is used to offset fossil fuels in electricity generation.
TOTAL Landfilling	**3,754**	

*All data on energy and other resources used has been adjusted to account only for the proportion of the composting operation that is attributable to the Merrimack wastewater solids. Total measured energy and other resources used by Merrimack for the composting operations in 2007 included processing of 414 dry tons of wastewater solids from other towns; the proportions of energy and resources used to process these out-of-town solids are not included here.

How Significant Are These Emissions?

Current composting operations at Merrimack's WWTF have a total "carbon footprint" of approximately1,529 Mg. This is equivalent to the estimated annual carbon dioxide emissions from 283 average U. S. passenger cars or the estimated annual emissions from the electricity used by 203 average U. S. homes (Table 4). The estimated carbon emissions from proposed future landfill disposal of Merrimack solids would be about 2.5 times greater, or the equivalent of 700 cars.

Stated another way, if Merrimack were to choose the upgraded composting option, rather than the landfill disposal option, an estimated 2,660 Mg of carbon dioxide equivalent emissions would be avoided each year, which equates to taking almost 500 cars off the road. The same reduced greenhouse gas emissions benefit could be derived by growing 6,890 tree seedlings for 10 years.

Table 4: Carbon emissions from common sources (http://www.epa.gov/cleanenergy/energy-resources/calculator.html)

Source of emissions	**Assumptions**	**Mg CO_2 equivalent emissions**
Avg. U. S. passenger car	22 mpg, 13,600 miles/year, 618 gallons gasoline/year	5.46 / vehicle / year
One barrel of oil		0.43 / barrel
Electricity use of one average U. S. home per year	1,392 lbs. CO_2 per MWh delivered	7.55 / home
CO_2 sequestered by 100 tree seedlings grown for 10 years	23.2 lbs. C is absorbed per tree over 10 years	– 3.86
One home barbecue propane canister		0.024 / canister

Minimizing Energy Use and Greenhouse Gas Emissions From Each Option

Composting

The enclosed, in-vessel composting utilized at Merrimack allows for careful control of the composting process, an advantage over other forms of composting. This level of control is also significant in comparison to landfill disposal. By optimizing the composting process – keeping properly high C:N ratios, dry feedstocks, and adequate consistent aeration – it is possible to eliminate methane and nitrous oxide emissions or reduce them to very low levels. Biofiltration of the air from the active composting operations helps; however, further analysis and understanding of the potential for nitrous oxide (N_2O) emissions from the biofilter would be needed to ensure minimal emissions of this powerful greenhouse gas. If N_2O emissions are found, it may be relatively easy to reduce them; for example, a scrubber that reduces the levels of ammonia entering the biofilter could be effective.

The downside of the active, enclosed, in-vessel composting process is its large demand for electricity. This results in overall higher energy costs for the composting option, in comparison to landfill disposal. However, in the future, it may be possible to further optimize composting operations to reduce energy consumption. For example, replacing blowers with more energy efficient units could reduce demand. Ultimately, it may also become possible to purchase or produce renewable energy, which, while not reducing energy consumption, would reduce total greenhouse gas emissions.

Optimizing composting operations at Merrimack can also be enhanced by utilizing the facility's full capacity. Currently, Merrimack processes only about one-half (~31 wet tons per day) of the design capacity of 60 wet tons per day. The energy required to increase to operating at full capacity would be more than that used in current operations, but the per-ton energy costs would be lower due to efficiencies of scale. With the upgraded composting option, the percentage of the facility's capacity taken up by Merrimack solids would be reduced by almost 1/3, resulting in additional excess capacity that could be sold to other towns. If regulatory, political, and social circumstances would allow for increased importation into Merrimack of wastewater solids or other compostables, the Merrimack compost facility could become far more energy-efficient on a per-ton basis, provide a regional solution, and generate some revenue (tipping fees) for the Town.

If the capacity of the facility cannot be filled with outside materials, Merrimack might consider utilizing it for further treating its own biosolids compost; that is, the curing phase could occur in the enclosed facility. The compost could remain in the composting bays for as much as 45 to 50 days (based on current operations). After the initial 21 days of active composting, agitation could be reduced in frequency, so additional energy costs (from that and additional ventilation run time) could be moderate. In return, keeping the material indoors longer may reduce the fugitive methane and nitrous oxide emissions possible with outdoor curing. Measurements of actual emissions from the current outdoor curing piles and the biofilter would have to be conducted so as to determine the true value of this change in operations.

Lastly, a change in the amendment used for composting could have a significant impact on energy consumption and GHG emissions. Sawdust is a valuable commodity that is in demand in energy markets as well. Thus, its use for the composting at Merrimack results in significant carbon debits. Many composting operations use ground green and wood waste as an amendment. Merrimack currently stores, at its transfer station, and then occasionally burns, its residents' green and wood wastes. It is likely this material could be processed into a suitable compost amendment using a similar amount of fuel as is used to deliver sawdust to the compost facility. Making this change would remove the debit on the Merrimack composting carbon accounts that is due to taking some sawdust away from use as a fossil-fuel alternative. However, it must be noted that green and wood wastes are heterogeneous and more challenging to handle than delivered sawdust, and the quality of the final compost product may be affected if this amendment were not well managed.

Landfilling

Emissions from landfill disposal of wastewater solids may be difficult to avoid, because the material is highly and quickly putrescible and prone to emitting methane. Nonetheless, there may be potential at the TREE facility to further increase methane recovery, and it may be that new techniques will be found for managing waste in the active landfilling area. Considerable research is being conducted regarding bioreactor landfills and maximizing the capture and use of methane to offset fossil fuel consumption.

As with the composting option, landfill operations – which already use less fossil fuel energy –will likely be able to reduce GHG emissions in the future by utilizing renewable energy sources such as biofuels or electricity from renewable sources to run trucks, dozers, and compactors.

Is There Money To Be Made From Carbon Credits?

Avoiding the production of methane from highly putrescible materials like wastewater solids may be an opportunity for composting operations to generate carbon credits. This will depend on how carbon accounting is formalized over the coming years. If landfill disposal is considered the status quo for the management of wastewater solids, then composting can be considered an option that reduces methane generation, resulting in carbon credits for the owner of the composting facility.

Markets for carbon offsets are being developed around the country. With this year's adoption by the New Hampshire legislature of the Regional Greenhouse Gas Initiative a carbon offset market is certain, beginning in 2009. Under New Hampshire's system, marketable offsets will probably be defined as sources of CO_2-equivalent reductions in greenhouse gas emissions that began in 2006 or later and are from sectors of the economy other than the electricity-generating sector (J. Fontaine, NH DES, pers. comm.). Offsets have already brought cash to, for example, farms that have switched to managing their manures in anaerobic digesters, thus reducing fugitive methane emissions and displacing fossil fuel use by burning the methane.

Over the past year, carbon offsets have been priced from about \$2 to \$5 / Mg CO_2 equivalent, with a late March 2008 price of about \$5.70 (Chicago Climate Exchange, 2008). At the current price, the market is saying that Merrimack's choice of upgraded composting over landfill disposal is worth about \$15,000. It is expected that the market price will rise as states – and possibly the federal government – increase requirements for reductions of emissions.

However, a critical aspect of the developing carbon offset markets is the idea that offsets will likely only be allowed for *new*, verifiable, reductions in GHG emissions. By composting its solids, Merrimack has already been "doing the right thing" in minimizing GHG emissions. Therefore, if the rules develop as expected, it is unlikely that Merrimack will be able to benefit monetarily from marketable carbon offsets if the Town continues with composting.

Conclusion

Fossil fuel energy (fuels and electricity) is currently used to manage Merrimack wastewater solids. This fuel use releases carbon dioxide (CO_2) to the atmosphere. In the near future, either of the two proposed solids management options being considered by Merrimack will continue to utilize fossil fuel energy. These will continue to produce greenhouse gas (GHG) emissions. However, to the extent either option can utilize alternative, renewable sources of energy, Merrimack can reduce this aspect of its carbon emissions footprint.

While concerns about the greenhouse gas emissions from fossil fuels are important and should be a concern, the greatest potential impacts of managing wastewater solids are the potential emissions of the far more powerful greenhouse gases methane and nitrous oxide. The strictly controlled processes of a composting operation allow for the minimization of methane and nitrous oxide releases. By comparison, active landfilling operations are inherently less controllable and, therefore, the control of methane generation and capture is more challenging. Even state-of-the-art bioreactor landfill systems are unlikely to be able to recover high enough percentages of methane from quickly putrescible materials such as wastewater solids to avoid significant GHG emissions.

This analysis has been conservative in terms of giving the landfilling option the benefit of the doubt. As noted by the Recycled Organics Unit paper (2007, p. 38) "As identified in a US EPA, (1998) emissions study, composting processes are "greenhouse neutral" when other factors such as carbon sequestration in soil are considered…. [I]t is probable that composting processes are in fact beneficial to the environment by reducing greenhouse gas emissions (directly and indirectly) and also by reducing landscape degradation and improving plant growth in soils."

While it is beyond the scope of the current study, it is important to mention these other environmental benefits of composting as a way of managing putrescible residuals such as wastewater solids. Benefits include:

- reductions in concentrations of trace synthetic chemicals found in wastewater solids (composting decomposes many);
- proven benefits to soils when compost is used (e.g. improved soil ecology, reduced erosion, more resilient turf);
- reductions in the use of synthetic fertilizers, herbicides, fungicides, and irrigation water; and
- improved crop health.

See further discussion of these benefits under "Compost Use" in the notes, below.

Completing this analysis of a real-life composting operation compared to a real-life landfill disposal system has provided a clear picture of likely greenhouse gas emissions associated with these two options. Existing composting operations and the distribution and use of compost consume a greater amount of energy but generate significantly less GHG emissions than the landfill disposal option. Improvements to the existing dewatering operations would further reduce the energy use and GHG emissions associated with either option.

If sustainability, in terms of reducing global warming impacts, are a priority, then current knowledge indicates that landfill disposal of highly putrescible materials such as wastewater solids is a less desirable option. Research is continuing on bioreactor landfills and their potential to efficiently generate and capture methane. Such systems may yet prove manageable and efficient enough to reduce fugitive methane emissions to negligible levels. But even the best landfilling system does not take advantage of the soil-building nutrients and organic matter found in wastewater solids. And it will probably always be more efficient to manage those putrescible residuals that are already separated from solid waste (e.g. wastewater solids), with highly-controllable systems such as anaerobic digesters or composting.

Acknowledgements

This analysis required collection of data from a variety or sources and consultation with many people. Appreciation is hereby extended to those who provided critical local, real-world data for this project, especially Jim Taylor, superintendent of the Merrimack WWTF; Dr. Geoffrey Kuter of Agresource, Inc.; and Bill Howard, landfill engineer at Waste Management Turnkey Recycling and Environmental Enterprises. Thanks also to Bill Smagula (Public Service of New Hampshire), Richard Nicoletti (IPS Composting Systems/Siemens), Joe Fontaine (NH Dept. of Environmental Services), and Charley Hanson (Resource Management, Inc.). Dr. Sally Brown, Research Associate Professor at the University of Washington, provided essential input. This project was conducted and funded by the North East Residuals and Biosolids Association, with support from IPS Composting Systems/Siemens and Agresource, Inc.

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NOTES

1. **General Assumptions Used in Analysis of Both Options**
2. **The Composting Option - Assumptions and Calculations**
3. **The Landfilling Option - Assumptions and Calculations**

An Excel spreadsheet detailing all calculations used in this analysis is available from NEBRA, Tamworth, NH USA (info@nebiosolids.org).

1. General Assumptions Used in Analysis of Both Options

Wastewater Solids Production

In 2007, the Merrimack WWTP produced an average of 26 wet U. S. tons of dewatered wastewater solids per day, averaged over 365 days (typically, there is no dewatering on Sundays). At an average measured solids content of 19.4%, this equaled 1,841 dry U. S. tons for the year. It is the processing of this material for which estimates of energy use and greenhouse gas emissions were generated.

During 2007, the Merrimack compost facility also took in 414 dry U. S. tons of solids from other New Hampshire WWTPs. Altogether, these and Merrimack's solids produced 12,265 cubic yards of compost. Because all Merrimack composting operation data for 2007 includes the out-of-town solids, calculations of sawdust, biofilter media, and energy uses have been reduced proportionally using the ratio 1841/2255 (dry U.S. tons Merrimack solids / dry U. S. tons Merrimack and out-of-town solids). In this way, the results presented in this analysis pertain only to the management of Merrimack solids.

Merrimack wastewater solids data, 2007:

Wastewater solids generated	26 wet tons / day
	1,841 dry U.S. tons / year
Percent solids	19.4% average
Volatile solids (VS)	80%
Carbon (C) content	54% of volatile solids assumed

Merrimack finished compost data, 2007:

Total compost produced (including out-of-town solids)	12,265 cubic yards
Percent solids	54% average
Bulk density	720 lbs. / cubic yard
Volatile solids (VS)	72.5%
Carbon (C) content	54% of volatile solids assumed
Total Kjeldahl nitrogen (TKN)	2.1 % average

Energy sources

The U. S. Environmental Protection Agency (EPA) estimates that, in the U. S., 3% of energy costs are attributable to water and wastewater treatment operations. Wastewater treatment facilities utilize a significant percentage of the electricity used by municipalities. Within the wastewater treatment process, a majority of the electricity is used by pumps for moving wastewater and solids and by blowers used to aerate treatment processes.

Merrimack obtains a separate accounting of electricity used in its composting operations, making it easy to separate the electricity costs of those operations from the wastewater treatment facility operations (electrical use for dewatering, however, had to be estimated; see Table 2).

There are published emissions equivalent factors for electricity use based on U. S. averages. However, for this analysis, we obtained an estimate from Public Service of New Hampshire (PSNH) of the percentages of each type of fuel used to generate the electricity that likely flows to Merrimack (B. Smagula, pers. comm.). This mix includes 50% coal, 10% natural gas, 5% oil, 10% nuclear, 10% hydro, 10% wood, and 5% other. Thus, CO_2 emissions estimates for the electricity used in the Merrimack composting operation are unusually precise: 0.52 kg fossil CO_2 emissions / PSNH-sold kWh.

The other three significant sources of fossil fuel energy used in the Merrimack composting operations are natural gas, diesel fuel, and gasoline. The landfilling option involves use of diesel fuel for transportation, placement, and compaction of the wastewater solids. Common published emissions factors were utilized for calculating CO_2 emissions from these sources (U. S. EPA, 2004):

- natural gas: 0.12 lbs. CO2 / cubic foot

- diesel fuel: 22.23 lbs. CO2 / gallon
- gasoline: 19.37 lbs. CO2 / gallon

Transporting solids

In the late 1990s, roll-off containers were the trend in New Hampshire for biosolids hauling operations. Today, there are more tractor-trailers in use for this purpose, mostly because they are lighter and can haul larger loads – good for energy efficiency. Dump trailers have been in use for some time, but they create some operational challenges and are being replaced with live floor or belt-floored trailers. These trailers can haul up to 30 tons of biosolids at a time and average 4.7 mpg (C. Hanson, pers. comm.). Additional estimates of mileage for trucks transporting wastewater solids or biosolids compost were obtained from Merrimack (J. Taylor, pers. comm.) and Agresource (G. Kuter, pers. comm.); they estimated 4.5 mpg and 5 mpg, respectively. For this analysis, a consistent truck mileage of 4.7 was used for all calculations for both options.

2. The Composting Option - Assumptions and Calculations

Methane and nitrous oxide release from composting operations

The IPCC Group III notes (Ch. 10, p. 602) that "CH_4 and N_2O can both be formed during composting by poor management and the initiation of semi-aerobic (N_2O) or anaerobic (CH4) conditions; recent studies also indicate potential production of CH_4 and N_2O in well-managed systems (Hobson *et al.*, 2005)." In contrast, however, Brown et al. (in press) agree with the Recycled Organics Unit (2006) in arguing that well-managed composting operations are careful to maintain aerobic conditions (through controlling moisture levels and aeration) during all composting operations, because it enhances degradation and stabilization. They also argue that, with N-rich wastes, like wastewater solids, the generation and presence of ammonia reduces the potential for methane generation, because of ammonia's toxicity to methanogens.

For outdoor windrow or static pile composting operations, it may be necessary to more carefully assess the release of CH_4 and N_2O from a composting operation. But, in this case, the Merrimack active compost operation is indoors and, if continued, will remain indoors. Essentially all composting process air is captured and treated through a biofilter, which is assumed to oxidize any CH_4 to CO_2. Any N_2O generated may or may not be treated in the biofilter, and this is an area of uncertainty. Nitrous oxide emissions have been measured from biofilters. Presumably, such emissions could be controlled by reducing the volume of ammonia in the air entering the biofilter, which is commonly done with an air scrubber. Further research on this topic at operating composting and biofilter operations is needed.

Besides the biofilter, there are two parts of the Merrimack composting operation where CH_4 and N_2O might be released to the atmosphere: storage of the wastewater solids prior to composting and outside curing and storage of finished compost.

As noted by Brown et al. (in press), several studies show that untreated animal residuals with low C:N ratios and high moisture content – which are considered representative of wastewater solids – are well-suited for developing low-oxygen and anaerobic conditions that promote N_2O and CH_4 generation, respectively. Almost all of the emissions of these gases from these materials tend to occur during storage prior to composting or other treatment. At Merrimack, however, wastewater solids are stored for a day, at the most, before they are placed inside the composting building. Thus, we assume negligible methane or nitrous oxide emissions from this step in the process.

The outside curing and storage of Merrimack's compost is another potential stage during which methane and nitrous oxide could be produced and emitted. However, studies show that any CH_4 production is greatest during the beginning, active stages of composting: "Methane was detected in both windrows during the first 60 days of the process with over 50% being released by day 30" (as quoted in Brown et al., in press). Essentially, the potential for CH_4 generation parallels the CO_2 flux and the rate of biological activity in the composting process (as long as aeration remains consistent). Factors that increase the likelihood for CH_4 generation include lower C:N ratios, wetter material, and other factors that encourage anaerobic conditions. Brown et al. (in press) argue that control of moisture in the composting and curing material is probably the most important factor in controlling greenhouse gas emissions. "In all of the studies where GHG emissions have been detected from the surface of the compost piles, the % moisture of the feedstocks has been at or above the maximum levels for appropriate aeration." In summary, the Merrimack compost is thoroughly aerated and agitated during the most active composting process – for 21 days. It is likely that essentially no methane and little N_2O are generated during this period – and, any that are generated may be treated in the biofilter (which is effective in oxidizing methane, but may not be as effective with reducing N_2O).

Studies of N_2O generation from composting of manures and biosolids suggest that the generation of this gas is also most likely to occur at the beginning of the process, when the available nitrogen, volatile solids, biological activity, and low-oxygen sites are at their maximum. However, studies have also found N_2O production later in the process (e.g., after 30 days).

Finally, studies cited by Brown et al. (in press) indicate that the size of piles makes a difference in potential greenhouse gas generation, with larger piles producing greater emissions (likely due to greater potential for developing pockets of anaerobic conditions in larger piles). In addition, these authors point out that, while CH_4 and N_2O are generated within compost piles, their release to the atmosphere is reduced by "the active microbial community on the surface of the piles that will either oxidize (CO_2) or reduce N_2O gases before they are emitted," as noted by U. S. EPA (2002).

Thus, additional factors in the Merrimack composting operation that serve to reduce the potential for GHG emissions from curing and storage of compost include:

- Because it is about half sawdust, Merrimack's curing compost has a much higher C:N ratio (perhaps 30:1) than the materials in studies in which significant N_2O emissions were detected. Abundant available carbon decreases the activity of nitrifying (and denitrifying) bacterial activity.
- Piles are moved and broken into minimally, which allows for the aerated surface zone to treat CH_4 and N_2O produced within the piles.

Thus, to estimate the maximum possible release of methane and nitrous oxide from compost storage at Merrimack, this analysis included…

- use of emission factors suggested by Brown et al. (in press): 2.5% of initial C (IPCC: 10 g CH_4 per kg waste dry weight) and 1.5% of initial N (0.6 g N_2O per kg waste dry weight);
- assumption of a 50% of these gases emissions' occurred within the enclosed compost operations and were thus not released to the atmosphere; and
- assumption of a further 50% reduction of emissions by the aerated, biologically-active, upper layers of compost on the storage piles (as recommended by Brown et al, in press).

The final estimates for emissions of CH_4 and N_2O from the curing and storage of Merrimack compost were derived from averages of the results of several calculations using differing factors and assumptions. Two calculations were completed and averaged for CH_4 emissions. Five calculations were completed and averaged for N_2O emissions.

Use of sawdust

Calculation of the GHG emissions due to the use of sawdust in the composting process included the following:

- 75% of the sawdust used at Merrimack came an average 136 miles (one way) from Connecticut in 2007.
- 25% of the sawdust used at Merrimack came an average 15 miles (one way) from New Hampshire in 2007.
- 100 cubic yards of sawdust is hauled each truckload.
- Each truck backhauls another product on ½ of the trips they make bringing sawdust to Merrimack.

Because sawdust is a valuable commodity for a variety of uses, including fuel, this analysis made the assumption that if the sawdust required for the Merrimack composting operation was not used for composting, 30% of it would be used as fuel, offsetting emissions from fossil fuel burning (coal is the fossil fuel assumed to be used instead). This calculation resulted in a large and significant GHG emissions debit against the composting operations.

Use of sawdust in compost that is then applied to soils increases the likelihood that that sawdust will add to sequestered C, in comparison to some other uses the sawdust may have been put to, such as a fuel (home stove briquettes or electricity generation). However, because many alternative uses of sawdust (animal bedding, mulch) involve returning it to soils, we did not claim any extra carbon sequestration credit for the use of sawdust in the Merrimack compost. However, this is a very important aspect of sawdust use, in comparison to the use of sawdust as fuel, where the carbon is immediately emitted as CO_2. It may be preferable, if possible, to use any photosynthetic carbon as an addition to soils for carbon sequestration, rather than using it as a fuel (unless the CO_2 from the burning is captured and sequestered). However, it is unclear as to whether the carbon emissions offsets would be greater from using sawdust for soil C sequestration or for burning in order to offset fossil fuel use – so much depends on the particular local situation, soil management techniques, etc.

Biofilter maintenance:

The biofilter that treats the air from the enclosed composting operation is filled with wood chips. This "media" is completely replaced every 2 to 3 years (2.5 was used in calculations). 2,000 cubic yards are required to do the job. This material comes from area logging operations, assumed to be 15 miles away, on average. In addition to the carbon emissions impacts of transporting these wood chips to Merrimack, the calculation for biofilter maintenance includes the run time of diesel-powered machinery required to remove old wood chips and place the new ones in the biofilter.

Marketing compost:

Fuel used to market compost is negligible. Agresource estimated that they would put on about 500 miles per year visiting Merrimack and customers. Thus, at 20 miles per gallon, this is 25 gallons of gasoline per year.

Agresource leases space and does not have a separate electric bill or heating bill. Given the relative portion of Merrimack compost to their entire operations, we assume that this energy use is negligible, and it was not included in this analysis. Similar office costs at the landfill operation were also not included.

Compost delivery

In 2007 9,765, cubic yards of compost were delivered by Agresource to 36 customers in NH, MA, CT, NY and VT. In order to determine the amount of fuel used to make deliveries, we assumed that all loads average 60 cubic yards and that trucks used fuel at the rate of 4.7 miles per gallon.

Agresource used actual data from their deliveries to arrive at an estimate of 5954 gallons of fuel used to deliver Merrimack compost in 2007 (approximately 0.61 gallons per cubic yard of compost): "For the 13 largest customers (about 80% of the total volume distributed) I calculated the actual mileage from Merrimack to the customer and garage location for the trucking company (a triangle route) and thus was able to calculate total fuel consumed. Miles traveled was determined using an internet calculator (my travel .com). For all other customers I used an average value for miles based on the state in which the customer was located; for example I assumed 150 miles for the smaller Massachusetts customers based on the average values obtained from the largest Massachusetts customers." Because Agresource used 4.5 mpg for mileage, we have recalculated proportionally to make these calculations consistent with the standard mileage rate of 4.7 mpg used throughout this analysis.

Local customers pick up about 2,500 cubic yards of compost. Our estimates for fuel consumption by these customers are based on typical customers and uses identified by Jim Taylor, Superintendent of the Merrimack WWTF.

Compost use:

Merrimack's compost meets the U. S. EPA and State of New Hampshire highest quality standards for biosolids. It is – and will likely continue to be – mostly used for creating quality turf on large areas such as parks, sports fields, and golf courses. Other uses include horticultural applications, such as potting mixes, and in home and business flowerbed, vegetable, and landscaping applications.

The use of Merrimack's compost has tangible benefits in comparison to lawn care, landscaping, mulching, and other practices that utilize alternatives to compost. Generally, compost replaces the need for some or all of the fertilizer needed for healthy turf.

There are additional benefits to compost use that were not quantified and included in our calculations. According to Agresource, the company that markets Merrimack biosolids compost (G. Kuter, pers. comm.):

"Compost is an important component in restoring the health of degraded soils. The environmental benefits obtained from using composts to improve soil properties has been identified by the Sustainable Sites Initiative, a partnership of the American Society of Landscape Architects, the Lady Bird Johnson Wildflower Center, and the United States Botanic Garden, founded to address and define sustainability in land development and management practices.

"The Sustainable Sites Initiative recognizes that healthy landscapes provide valuable services such as climate regulation, clean air and water, and improved quality of life. They are working to develop sustainable practices that, in contrast to conventional land practices, enhance the ability of landscapes to provide these important environmental benefits. Recommendations of the Sustainable Sites Initiative include the use of compost as a sustainable practice to increase organic matter in soils. Compost is a primary replacement for peat that is mined from wetlands and bogs resulting in the destruction of native plant communities.

"Soil organic matter serves a wide range of important environmental functions including:

- Holding plant nutrients and releasing them over time to reduce fertilizer use and the potential for contamination of ground and surface waters;
- Improving soil structure to allow for better infiltration of water, thus reducing run-off and erosion;
- Increasing the diversity of microbial populations in the soil that facilitate the breakdown of soil contaminates and provide for biological control of plant pathogens without the use of pesticides; and

- Improving the ability of soil to hold and store water, reducing needs for irrigation.

"The impact of increased soil organic matter on the ability of soil to hold water can be quantified and can significantly reduce water use. For example, Merrimack compost is typically incorporated into soil at about 30% by volume to increase soil organic matter by about 5%. This increased level of organic matter in the soil will result in the soil holding an additional 1.88 gallons of water per cubic foot of soil. Thus, for a 10,000 square foot lawn, 9,400 gallons of water will be held in the soil for plant use. For example, 13,000 cubic yards of compost will cover an area of 46 acres when used in this manner and thus has the potential to save 1,970,968 gallons of water. This savings is on-going: as water is taken up from the reserves held in the soil organic matter, it is replaced from precipitation. Improved soil structure further improves the infiltration of water, allowing soil reserves to be replenished and reducing the amount lost from run-off."

These additional benefits of compost, some of which include potential reductions in greenhouse gas emissions associated with the use of Merrimack compost, were not included in this analysis.

Application of compost at end use sites:

Agresource provided details on the energy used during application of compost, basing their estimates on one typical 2007 project for which fuel consumption was measured.

Displacing synthetic fertilizer and peat use:

Smith et al. (2001) and Brown et al. (in press) note that between 0.94 and 1.4 Mg, respectively, of fossil C energy is utilized to make, transport, and apply 1 Mg N as nitrogen fertilizer. The higher value was used to calculate the GHG emissions avoided by using the more local source of nitrogen found in Merrimack biosolids compost.

Smith et al. (2001, p. 150) note "each cubic metre of peat replaced by compost will therefore save the emission of about 247 kg of CO2,...". This factor was used, and we assumed that only 20% of Merrimack compost displaced peat use.

One thing to note regarding the two calculations discussed in the previous two paragraphs: in comparison to other calculations for this analysis, these two did not apply only to the Merrimack wastewater solids portion of the compost. This was done because the Merrimack compost exists only because of the Merrimack solids needing management, and, therefore its use as a replacement for fertilizer and peat is reasonably attributable to the Merrimack solids. This makes sense especially for the displacement of N fertilizer, since most of the N in the compost is from the Merrimack solids. It may make less sense for the displacement of peat use, since much of the peat-displacement value in the compost is derived from the sawdust.

Carbon sequestration in soils

Determining the amount of significant carbon sequestration from compost use in soils is difficult, because of the many factors that affect the longevity of the sequestration (e.g. tilling, precipitation, air and soil temperatures, etc.)

Most of the carbon (C) in compost is eventually converted to CO_2, but some remains in the organic matter that is applied to soils. The final estimate for avoided CO_2 emissions (carbon credit) due to soil carbon sequestration is based on an average of four different calculations.

Three calculations of the carbon sequestration credit assumed that 8.2% of compost C remains in the soil for 100 years or more (Recycled Organics Unit, 2007). One of these calculations utilized mass balance calculations derived from lab analysis of the Merrimack compost.

The final calculation of carbon sequestration credit is based on a change in organic matter (OM) content in the receiving soil. Brown and Leonard (2004) cite a study by Cogger in Washington state that found increased OM (2.9%) in soil treated for 10 years with no-till and biosolids, in comparison to similar soils that received nitrogen fertilizer or no fertilizer for the same time period. They also note that the level of "total organic C remained elevated in restored versus undisturbed soils for at least 21 years" following the use of biosolids to reclaim coal mine lands. They recommend using neighboring, undisturbed site soils' organic matter (OM) content as an approximation of the long-term OM content that will be reached by a soil created with biosolids on reclaimed land.

This approach was used to estimate carbon sequestration when biosolids compost is applied to a site with low starting organic matter content. We assumed that when the compost user aims to raise the soil organic matter 3% that, over years or decades, the system may fall back 50%, making for an overall lasting increase of 1.5% (a conservative, low value). This lasting increase in soil carbon is due not only to the carbon applied in the compost, but also to the increased biomass and plant matter stimulated by the compost addition. As expected, calculating carbon sequestration by this means results in an order of magnitude larger value of carbon sequestration than more conservative calculations based on only the carbon found in the compost.

Additional literature supporting this approach includes the following:

- "Depletion of soil organic C (SOC) pool have contributed 78±12 Pg of C to the atmosphere. Some cultivated soils have lost one-half to two-thirds of the original SOC pool with a cumulative loss of 30–40 Mg C/ha (Mg=megagram=10^6 G=1 ton). The depletion of soil C is accentuated by soil degradation and exacerbated by land misuse and soil mismanagement. Thus, adoption of a restorative land use and recommended management practices (RMPs) on agricultural soils can reduce the rate of enrichment of atmospheric CO_2 while having positive impacts on food security, agro-industries, water quality and the environment. A considerable part of the depleted SOC pool can be restored through conversion of marginal lands into restorative land uses, adoption of conservation tillage with cover crops and crop residue mulch, nutrient cycling including the use of compost and manure, and other systems of sustainable management of soil and water resources. Measured rates of soil C sequestration through adoption of RMPs range from 50 to 1000 kg/ha/year. The global potential of SOC sequestration through these practices is 0.9±0.3 Pg C/year, which may offset one-fourth to one-third of the annual increase in atmospheric CO_2 estimated at 3.3 Pg C/year. The cumulative potential of soil C sequestration over 25–50 years is 30–60 Pg. The soil C sequestration is a truly win–win strategy. It restores degraded soils, enhances biomass production, purifies surface and ground waters, and reduces the rate of enrichment of atmospheric CO_2 by offsetting emissions due to fossil fuel." (R. Lal, 2004).
- "Compost applications over 6 y increased the resistant pool of C by 30% and the slow pool of C by 10%. The compost treatment contained 14% greater soil organic C than the fertilizer management…. Proper management of nutrients from compost, cover crops and rotations can maintain soil fertility and increase C sequestration." (Fortuna et al, 2003).

Compost contribution to soil N_2O production?

"Nitrous oxide is produced naturally in soils through the processes of nitrification and denitrification. Nitrification is the aerobic microbial oxidation of ammonium to nitrate, and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas (N_2). Nitrous oxide is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbial cells and ultimately into the atmosphere.

The IPCC notes that "in most soils, an increase in available N enhances nitrification and denitrification rates which then increase the production of N_2O. Increases in available N can occur through human-induced N additions or change of land-use and/or management practices that mineralise soil organic N" (Klein et al., 2007). One of the main controlling factors in this reaction is the availability of inorganic N (e.g. ammonia, nitrate, nitrite) in the soil.

Compost, which has a relatively high C:N ratio compared to N fertilizer or manures or sewage sludge, is less likely to produce an abundance of inorganic N in the soil. The release of N from an organic source, like compost, is mediated by microbial activity, which parallels, over the growing season, the growth rate of plants and their uptake of available inorganic N. Thus, we assumed no net increase of N_2O emissions from compost use, especially in comparison to the alternatives – such as N fertilizer – that would be used in place of compost. Compost use may, in fact, reduce N_2O emissions in comparison to use of chemical fertilizer N.

3. The Landfilling Option – Assumptions and Calculations

Background information regarding the Turnkey Recycling and Environmental Enterprises Facility, Rochester, NH (TREE)

According to Bill Howard, engineer for the TREE facility in Rochester, NH, the facility accepts about 1 million tons of waste each year. Five to six percent of this is non-hazardous industrial and municipal wastewater solids. These materials are mixed with solid waste (lots of paper) as it is placed in the active landfill cell. TREE has 3 landfills @ Rochester - 2 are closed (49-acre Aug 79 - Aug 92 and 51-acre Jun 90 - Oct 97). Both of the two closed landfills have gas capture. The third landfill was started in 1995 and is 106 acres, plus another 27 acres that extends over the closed Turnkey #1 landfill. Expansions are being completed in spring 2008 and after 2008. Regarding fugitive methane: their composite calculation is that all landfill operations are achieving 87% collection efficiency (closed areas with geomembrane final cover achieve 90 - 99% efficiency; clay cover achieves 85%). The active landfill area of 60-70 acres with a temporary cap on part of it has an estimated 75% efficiency. The active landfilling operation works this way: waste is placed; after 30 feet of depth is reached (about 180 days), horizontal collectors are functional. Takes a year before vertical wells are installed. After about 50 - 60 feet of depth is reached, air from the collection system begins to have methane. Rate of air withdrawel is slowly increased as methane content begins to climb to a steady state of about 50 - 60%. Leachate is recycled. Current operations at TREE are not focused on maximizing methane generation. TREE currently produces 9 MW of electricity with 2 generators (they run 4 engines also); half of this electricity is used internally; the rest is sold on the grid. This uses about one-half of the biogas currently being produced (~4,300 cfm); the other half is flared (closed and open flares that have a capacity to deal with 7,000 - 8,000 cfm). EPA's default estimate for methane capture efficiency at landfills is 75% (see EPA AP42, chapter 2). Bill "It's reasonable to assume that all VS goes to methane eventually (food waste, biosolids, - the rapidly degradable wastes)".

Transportation of solids to the TREE facility in Rochester, NH

Merrimack produced 9,490 wet tons of wastewater solids in 2004. For the landfill disposal option, it is assumed that the WWTF will install a centrifuge that will increase the percent solids of the material. This will result in a 30% reduction in the mass of wastewater solids produced. It was assumed that a truck will carry 20 tons of solids at a time, requiring 316 truckloads to haul a year's Merrimack solids. The round-trip distance from the Merrimack WWTF to the TREE facility in Rochester is 106 miles; it was assumed that the trucks – which would probably be owned and operated by Merrimack – would not back-haul anything from the landfill area.

Greenhouse gas emissions from the landfill

For this analysis, five calculations were made for the fugitive methane emissions from placing Merrimack wastewater solids in the TREE landfill at Rochester, NH. The results of these five calculations (with a range of 27 to 579 Mg CH_4) were averaged. Many of the calculations assumed a capture rate, at least after the first 6 months, of about 80%, the rate identified by Bill Howard, engineer at the TREE facility. One calculation assumed different rates of capture over time. The calculation that yielded the lowest value for fugitive methane emissions was based on Yazdani et. al (2006) estimates of methane releases from an engineered bioreactor landfill. The calculation that yielded the highest value was based on U. S. EPA (2006) models for methane generation from landfilled food discards (a similar, highly putrescible waste).

There is a lack of research looking specifically at methane production from highly putrescible materials, such as wastewater solids, during the time they are dumped in an active landfill area. However, individuals consulted for this project, and the implications in the literature, all concur with the assumption that wastewater solids will likely become anaerobic and generate significant amounts of methane within several months or a year of being landfilled.

Landfills are a significant source of methane, a powerful greenhouse gas, as noted in the following:

According to the IPCC, "overall, the waste sector contributes <5% of global GHG emissions." Worldwide wastewater CH_4 emissions equaled 590 Mg CO_2 equivalent per year in 2005. Wastewater N_2O emissions equaled 100 Mg CO_2. Landfills contributed 520 – 750 Mg CH_4. (Chapter 10, IPCC group III, p. 596**)**

"Because landfills function as relatively inefficient anaerobic digesters, significant long-term carbon storage occurs in landfills…. Landfill CH_4 is the major gaseous C emission from waste; there are also minor emissions of CO_2 from incinerated fossil carbon (plastics)….. Landfill methane can be released to the atmosphere directly, oxidized by aerobic methanotrophs in cover soils, and escape longer-term lateral migration and internal storage.

"It is important to stress that both the CH_4 and N_2O from the waste sector are microbially produced and consumed with rates controlled by temperature, moisture, pH, available substrates, microbial competition and many other factors. As a result, CH_4 and N_2O generation, microbial consumption, and net emission rates routinely exhibit temporal and spatial variability over many orders of magnitude, exacerbating the problem of developing credible national estimates (Chapter 10, IPCC group III, p. 589).

During the past two decades, GHG emissions from landfills have been declining in developed countries, as less biodegradable waste is landfilled and gas recovery improves. "By 2010, GHG emissions from waste in the EU are projected to be more than 50% below 1990 levels due to these initiatives (EEA, 2004)." In developing countries, GHG emissions from waste are expected to increase, as more waste is generated and landfilled (Chapter 10, IPCC group III, p. 597).

Regulatory agencies are increasingly requiring landfill operations to capture methane emissions from landfills. The following excerpts discuss methane capture and mitigation:

"Intensive field studies of the CH_4 mass balance at cells with a variety of design and management practices have shown that >90% recovery can be achieved at cells with final cover and an efficient gas extraction system (Spokas *et al.*, 2006). Some sites may have less efficient or only partial gas extraction systems and there are fugitive emissions from landfilled waste prior to and after the implementation of active gas extraction; thus estimates of 'lifetime' recovery efficiencies may be as low as 20% (Oonk and Boom, 1995), which argues for early implementation of gas recovery."

The keys to best methane recovery rates include: horizontal collection system placed concurrently with filling of cells, monitoring and remediation of edge and piping leaks, installation of secondary perimeter extraction systems, and frequent monitoring and repair of the final cover.

Part of strategy for reducing the potential for fugitive methane emissions from a landfill is utilization of a living soil cover that is microbially active: "Recent field studies have demonstrated that oxidation rates can be greater than 200 g/ m^2/d in thick, compost-amended 'biocovers' engineered to optimize oxidation (Bogner *et al.*, 2005; Huber-Humer, 2004)…. A secondary benefit of CH_4 oxidation in cover soils is the co-oxidation of many non- CH_4 organic compounds, especially aromatic and lower chlorinated compounds, thereby reducing their emissions to the atmosphere (Scheutz *et al.*, 2003a)" (Chapter 10, IPCC group III, p. 600). The same effect was discussed, above, with regards to the ability of the aerated surface part of a compost curing pile to oxidize CH_4 that may be generated deeper in the pile.

While most current landfills were not designed to manage significant portions of putrescible (organic) and wet wastes, there has been recent interest in bioreactor landfills that utilize such wastes to increase methane production and the rates of waste breakdown. While such landfills may improve overall methane generation and capture, they are unlikely to do much better than conventional landfills when it comes to capturing methane from highly putrescible materials such as wastewater solids. This is because no methane capture happens during the several months of active landfilling.

Research regarding an engineered pilot bioreactor landfill project notes: "The time from initiation of filling to completion of coverage and initiation of full enhancement is assumed to be 3.5 years. During the time to full enhancement, the waste stream entering up to year 3.5 generates about 7% of the methane potential of a year's entering waste (average of 1.75 years' waste x kinetic coefficient of 0.04 yr-1). This gas is captured with 80% efficiency but may be flared as the most convenient early option. After start of enhancement, starting at year 3.5 once the gas capturing cover is in place, the modeled generation rises to 70% of full potential in 5 years and 90% of full potential within 10 years" (Yazdani et al., 2006).

The time periods required to establish high rates of methane recovery are longer than the likely time period during which wastewater solids placed in the active landfill cell with generate methane that is released directly to the atmosphere.