

BIOSOLIDS AND GLOBAL WARMING: EVALUATING THE MANAGEMENT IMPACTS

GLOBAL warming is one of, if not the greatest, environmental threat currently facing our society. Global warming is thought to be caused by elevated emissions of gases that trap heat in the atmosphere. In 1997, 160 of the world's developed nations met and adopted the Kyoto Protocol in an attempt to reduce emissions of greenhouse gas responsible for global warming. Although the United States has not signed the protocol, local agencies and private companies have begun to understand the impact of their daily operations on the carbon balance and global warming. A bill, the McCain-Lieberman Climate Stewardship Act, will soon be introduced in the Senate to begin concrete actions in the U.S. to control global warming.

King County, Washington prides itself on being an environmental steward. As such, it has taken steps to understand how its various programs impact global warming. As part of this goal, King County asked the University of Washington to conduct a carbon accounting of its current biosolids management program. Carbon accounting measures the amount of greenhouse gases released or stored as a result of our activities. The accounting is done in terms of tons of carbon or tons of carbon dioxide gas (see sidebar). Included was an evaluation of the impact of a range of both disposal and end use options for biosolids on global warming. The results from this process were encouraging. It seems as though appropriate management of a biosolids program is one way that a municipality can accrue carbon credits and reduce the impact that their operations have on the environment. The Washington State Department of Ecology advocates responsible beneficial reuse of biosolids, but may allow land-filling on a temporary or emergency basis. This makes the findings of the King County carbon accounting even more significant.

Employing carbon accounting to understand the impact of King County's biosolids program on CO₂ emissions and carbon sequestration is a complicated process. Of the many possible approaches, the most straight-forward involves a strict accounting of the fertilizer value of the biosolids and the CO₂ gained or lost by using biosolids in lieu of commercial fertilizers. However, this approach does not consider land use, impact of biosolids on soil carbon, C accounting for other disposal or beneficial use options, or what types of crops are grown on biosolids fertilized soils. In other words, the potential to maximize carbon sequestration using biosolids as a tool is not captured by this approach. For that reason, we will attempt to describe the potential impact of different biosolids use or disposal options on carbon accounting for the County. Keep in mind that carbon accounting is not a precise science. There is often disagreement on how particular practices affect carbon balances. In addition, the range of factors that must be considered for the accounting to be truly accurate is large and complex. Because of

A case study of the King County, Washington biosolids program provides tools to evaluate the CO₂ emissions and carbon sequestration of various management options.

Part I

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these factors, there may be flaws in this description.

CAUSES OF GLOBAL WARMING

To best understand how biosolids can relate to global warming, a basic summary of what is known about global warming is necessary. Global warming results when gases in the atmosphere are able to retain heat that is radiated from the surface of the earth as infrared light. The light is absorbed as energy and gradually released. The atmosphere consists primarily of oxygen and nitrogen gas. Both of these gases are incapable of absorbing this heat energy and so are not involved in the warming process. However, other gases such as CO₂ are able to absorb this heat energy and reradiate it back in all directions. The end result is this energy does not leave the earth's atmosphere. A large portion remains in the lower region of the atmosphere, making it warmer. In addition, less reaches the upper portion of the atmosphere, leaving it cooler. Some gases are more efficient at absorption than others. These pose more of a threat to global warming than CO₂. Methane is a case in point. One molecule of methane (CH₄) is 23 times more effective at absorbing heat and therefore 23 times more of a concern than one molecule of CO₂. Table 1 provides characteristics of three primary greenhouse gases — carbon dioxide, methane and nitrous oxide (N₂O) — including their pre- and post-industrial atmospheric concentrations, persistence time in the atmosphere, and their CO₂ equivalence.

Carbon dioxide is produced naturally through aerobic respiration. All creatures that use carbon as a food source and breathe will release CO₂. Atmospheric CO₂ is consumed naturally through photosynthesis. All

Table 1. Characteristics of gases contributing to global warming

	CO ₂	CH ₄	N ₂ O
Atmospheric concentration	ppm	ppb	ppb
Preindustrial	280	700	270
Current	370	1745	314
Atmospheric lifetime (years)	5-200	12	114
Per molecule ratio of radiative forcing (CO ₂ equivalent)	1	23	296

fixed carbon on earth was initially derived from plants using energy from the sun to reduce carbon from the atmosphere. There are two carbon cycles. The rapid cycle involves atmospheric carbon that is fixed by plants and returned to the atmosphere after the plant material is eaten. Biosolids fit into this cycle. The long-term cycle involves release of carbon deposits from the earth into the atmosphere. Examples include burning of fossil fuels and deforestation.

Methane (CH₄) is generated naturally as well as anthropogenically. Wetlands are the primary natural source of methane, producing 120 to 175 Tg CH₄ per year. Natural sources of methane are generally not included in global warming calculations. Anthropogenic emissions originate from rice paddies, natural gas drilling and transmission, coal mining, enteric fermentation, manure, and solid waste disposal. These sources of methane are taken into account for global warming calculations.

Finally, nitrous oxide (N₂O) is produced microbially in both the denitrification and nitrification portions of the N-cycle. It also is produced by nitrogen fertilizer use, which adds to the pool of nitrogen that is subject to nitrification and denitrification reactions. Animal waste, as it also contains N, also contributes to the generation of atmospheric N₂O.

KYOTO PROTOCOL

The most significant policy step to control emissions of these gases was codified in the Kyoto protocol. While this pact has set the standard internationally, it has not been officially adopted in the U.S. Despite that fact, it is used as a guide for controlling CO₂ emissions. The Kyoto protocol lists policies or practices that can contribute to the reduction of greenhouse gas emissions. Those potentially pertinent to biosolids advocate energy efficiency, protection and enhancement of sinks and reservoirs of greenhouse gases, reforestation, sustainable forest management and agriculture, development and use of new and renewable forms of energy, reducing transport-based emissions and reduction of methane emissions through recovery and use in waste management.

To date, our understanding of the factors involved in global warming is very limited. This is a highly complex field and a wide range of sources of greenhouse gases as well as natural fluctuations have to be taken into

account to fully understand what is happening in the atmosphere. In addition, we are uncertain about what effects global warming will have both in the near and long term. What is generally agreed upon is that the earth is getting warmer and that this is at least partially the result of what us humans are doing here on the earth's surface. It is also generally agreed that this is not a good thing, with views on the consequences ranging from manageable to catastrophic. As a consequence of what we know, the vast majority of the developed nations are attempting to identify ways to reduce emissions of greenhouse gases. It is likely in the near future that carbon credits, accruing from reduced emissions or increased sequestration, will be assigned a monetary value. Industries and countries will start trading sequestered carbon. Municipalities will evaluate how their programs increase or decrease carbon emissions. And biosolids can play a role in the carbon balance.

BIOSOLIDS AND THE CARBON BALANCE

The carbon present in municipal wastewater treatment and released into the atmosphere as CO₂ is not considered to be a portion of the greenhouse gases responsible for global warming. This carbon represents the breakdown of recently fixed C and is considered to be part of the biological or rapid carbon cycle. For example, a corn plant fixes CO₂ as it grows and by doing so, sequesters carbon. However, shortly after that carbon is fixed, the corn plant gets eaten and the fixed C is released by a person or a cow as CO₂, reentering the atmosphere. Greenhouse gases other than CO₂, including CH₄ or N₂O, are factored in the balance as they are not considered to be part of the biological carbon cycle. In addition, fossil fuels used in treating wastewater or managing biosolids can be considered. However, biosolids have the potential to be a source of energy or carbon credits by providing an alternative to practices that make use of carbon reserves such as fossil fuels used in manufacturing commercial fertilizers.

Processing biosolids can either work to consume energy (drying and aerobic digestion), or as a source of energy (anaerobic digestion with methane collection). Biosolids can be landfilled to increase carbon reserves. However, landfilled biosolids will decompose under anaerobic conditions and generate methane. Unless methane is efficiently harvested, this can have a net negative result on CO₂ balances. Biosolids have value as fertilizer. By using biosolids, synthesis of commercial fertilizers and associated energy use is avoided. There are transportation costs associated with use of biosolids as fertilizer, which have the potential to take away from credits gained. Biosolids are used to fertilize a range of crops. For many crops, their life-cycle (as a fertilizer) is short enough that they are not considered in the C balance. However, for forestry and potentially for restoration sites, there is the potential to generate C credits for biosolids application.

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Biosolids also can be used to grow bioenergy crops, which can generate C credits for the fossil fuel use avoided. Finally, biosolids can also be used to increase total soil C, a major sink for carbon.

The range of different options for biosolids and the potential impact of these options on greenhouse gas emissions are evaluated below. A comparative carbon accounting of the current King County biosolids program is included — without considering the micronutrient value of biosolids or the benefit of building soil carbon reserves. Part II takes those factors into account, assessing the impact on CO₂ mitigation.

ENERGY COSTS OF LANDFILLING BIOSOLIDS

Solids from a wastewater treatment facility can be landfilled either prior to, or after, digestion and stabilization. In either case, there is a high potential that methane will be generated as a result of anaerobic decomposition of wastewater BOD. The rate and amount of methane generated will depend on a number of factors. Lab studies have evaluated methane generation from components of municipal solid waste (Eleazer et al., 1997). In this study, grass produced about half as much CH₄/g as the food waste. Over 80 percent of each material had decomposed by the end of the study. The actual decomposition rates of materials in a landfill will vary based on several factors including moisture content, nutrient status, pH, and temperature (Hilger and Barlaz, 2003). If wetter conditions persist, more methane will be produced. However acid pH and high nitrogen content will decrease rates of methane production.

Methane formed from the decomposition of landfilled materials can do one of three things: Stay under the cap in the landfill; Escape into the atmosphere; or Be harvested for flaming or biogas capture and use. These three alternatives are not mutually exclusive and the relative balance between the three will determine the net carbon balance associated with this disposal option.

Methane not harvested that comes into contact with the cover material in the landfill could potentially be oxidized or converted to CO₂ before release into the atmosphere. There is conflicting data on the extent of CH₄ oxidation by landfill cover soils. In a laboratory study, changes in moisture content resulted in a nearly 5-fold change in methane oxidation rates (Boeckx and Van Cleemput, 1996). Temperature also caused changes in the rate of methane oxidation. Adding ammonia fertilizer to the soil resulted in a decrease in CH₄ production with an increase in N₂O production. The same bacteria that can produce methane are also able to use the added N and produce nitrogen gas.

Another study found that landfill cover soils can not only oxidize all of the CH₄ that reaches the surface soil from below, they are also able to oxidize CH₄ from the atmosphere (Bogner et al., 1997), thus releasing carbon. No methane was released from the landfill soil as measured by sampling stations locat-

CARBON ACCOUNTING EXPLAINED

THE United Nations Framework Convention on Climate Change (UNFCCC) was developed by the international community in response to the recognition that greenhouse gas emissions have been increasing over the last 200 years as a result of anthropogenic activities. As the potential environmental effects of this increase become better understood, the urgency of appropriate carbon accounting becomes more obvious. Carbon accounting keeps track of the volume of greenhouse gases that are either generated or sequestered as a result of human activity. Carbon accounting measures the amount of greenhouse gases released or stored as a result of our activities. The accounting is done in terms of tons of carbon or tons of carbon dioxide gas. Under the auspices of the UNFCCC's, a meeting was held in Kyoto in 1997. The subsequent Kyoto protocol calls for industrialized nations to reduce their greenhouse gas emissions by five percent by 2008-2012. An integral part of this goal is developing an understanding of our greenhouse gas emissions and sequestration through carbon accounting. The United States is the only industrialized nation that has not signed the Kyoto protocol.

ed across the surface of the landfill from the period (June to December) when the chambers were monitored. When methane collection wells at the landfill were shut down for a two day period, CH₄ concentrations underneath the cap increased by three orders of magnitude but there was no subsequent increase in CH₄ flux from the surface of the soil. The microorganisms that change the methane into CO₂ were present in high enough numbers in the landfill cover soil to convert all of the methane into CO₂ before the methane was released into the atmosphere. In a US EPA emissions inventory, the amount of methane oxidized from landfills was assumed to be 10 percent (US EPA, 1998).

KING COUNTY LANDFILLING CALCULATIONS

It is possible to estimate the effect on carbon sequestration if King County were to landfill all of the biosolids (anaerobic stabilized secondary cake) generated. Certain assumptions have to be made to complete this estimate. The information presented above shows there are no absolute numbers for determining the amount of CH₄ that would be generated by the landfilled biosolids and what portion of that would actually enter the atmosphere. Nor does it show the portion of the CH₄ that would come into contact with the landfill cover soils, and either be released to the atmosphere or be oxidized.

The landfill nearest to King County that would accept biosolids is the Columbia Ridge Transfer Station in Arlington, Oregon, operated by Waste Management, Inc. According to Chris Haines, facility manager, approximately 15 percent of the total methane generated is being captured and flared. The remainder is released into the temporary cover soil, where it either remains as methane and is released to the atmosphere or is oxidized to CO₂ and released to the atmosphere. An application has been submitted to the State of Oregon to irrigate the material in the landfill, which would increase the rate of methane production and make gas capture and beneficial use financially viable. If this permit is approved, it is likely that energy recovery and use would begin in the near future. However, for this estimate, the current practices at the landfill are being used.

Two other factors need to be calculated before estimating carbon sequestration resulting from landfilling all of King County's biosolids:

Transportation: Before trying to estimate the amount of methane that biosolids would generate in the landfill, the amount of energy it takes to get them there has to be calculated. For this and all other estimates, we will consider that the trucks used to transport the biosolids get 6 miles/gal, and that 21.6 lbs of CO₂ is released for each gallon of diesel consumed. For a King County truck, that translates to approximately 360 lbs of CO₂ per 100 miles traveled. The landfill is approximately 250 miles from Seattle, thus each truck would burn 1,800 lbs of CO₂ for each round trip to the landfill. If each truck

We will assume that the methane generation capacity of the biosolids is equivalent to 250 ml CH₄ g⁻¹.

carries 30 wet tons of biosolids, 4,280 trucks are needed to transport all of the biosolids produced in 2002 to this facility — generating 3,850 tons of CO₂ or 3500 Mt of CO₂.

Methane Generation: We will assume that the methane generation capacity of the biosolids is equivalent to 250 ml CH₄ g⁻¹, which is in the middle of rates reported for grass clippings and food waste (Eleazer, 1997). In addition, we will assume that 50 percent of the dry weight of the biosolids is organic. We will also assume that the methane production rate is reduced by the low C:N ratio of the biosolids, and that a portion (5 percent) of the decomposition of the organic matter in the biosolids results in the formation of N₂O (Borjesson and Svensson, 1997).

The total dry weight of biosolids produced in 2002 was 27,221 dry tons. Dividing by two to take into account the portion of the biosolids that is inorganic, gives a total organic mass of 12,375 metric tons. Here we assume that 95 percent of the organic fraction of the biosolids would produce CH₄ as it decomposed and the remaining five percent would produce N₂O.

If the biosolids produced by King County in 2002 had gone to the landfill, they would potentially have produced 2099 Mt of CH₄ and 23.5 Mt N₂O. To express that in terms of CO₂ production, this amount of methane is equivalent to 132,750 Mt of CO₂ and the nitrous oxide is equivalent to 7,000 Mt CO₂.

LANDFILLING — WHAT'S THE NET?

The next factor to consider is the fate of the gases generated in the landfill from biosolids decomposition. Based on the annual temperature at the landfill site, we will assume that the oxidation of methane by the cover soil is 50 percent of the maximum. If 15 percent of the CH₄ generated is flared, and of the remainder, 25 percent is oxidized, that means 64 percent of the CH₄ generated in the decomposition of the biosolids will be released to the atmosphere. In addition, we will assume that all of the N₂O is released to the atmosphere. This means that if all of the biosolids produced in King County in 2002 had gone to the landfill, a total of 85,000 Mt of CO₂ would have been released to the atmosphere from the landfill site. As noted in Table 2, if transport and N₂O are included in the calculation, the total gas release is over 95,000 Mt CO₂.

If the operating process at the landfill changes and gas is harvested for energy use, this balance will change. If, instead of flaring a portion, the methane was harvested for energy recovery, this would count as an energy credit rather than a debit. For the purposes of this estimate, we can assume that collection efficiency would be the same as release efficiency. In this case, landfilling biosolids would generate a net carbon credit of 94,430 Mt CO₂ (Table 3).

THE INCINERATION OPTION

Incineration is an alternative disposal option for municipal biosolids. Energy recovery

from incinerating biosolids is possible. The energy requirements and potential energy recovery for incineration are described in different engineering texts (Owen, 1982; Metcalf and Eddy, 2001). Energy requirements increase with increasing water content in the biosolids. In addition, the energy value of the sludge decreases with increasing sludge stabilization. For example, an average heating value of raw primary biosolids is 25,000 kJ/kg of total solids. This decreases to 12,000 kJ/kg total solids for anaerobically digested primary biosolids (Metcalf and Eddy, 2001).

If one includes the heat requirements for all of the other components of the biosolids in addition to the water, the energy generated by incineration is most likely negative for anaerobically digested cake with a moisture content greater than 80 percent. For King County, this disposal option for biosolids would involve a net cost of carbon, rather than a gain in carbon credits.

LAND APPLICATION TO MEET FERTILIZER REQUIREMENTS

Biosolids often are applied to meet the N and P requirements of annual crops. In the Northwest, fertilizer application in commercial forestry operations also is common. In this scenario, biosolids can be considered as a substitute for commercial fertilizers and the energy costs associated with manufacturing commercial fertilizers can be avoided. With this end use, biosolids can be considered as a carbon sink, or a greenhouse gas credit. To calculate the scope of this sink, the energy requirements for N and P fertilizer production must be taken into account.

With nitrogen fertilizer production, atmospheric N is fixed and processed into commercial fertilizers using the Haber-Bosch process — an energy intensive process that consumes a great deal of fossil fuel. In fact, producing the chemical equivalent of one unit of nitrogen requires 1.4 units of carbon (Cole et al., 1993; Izuarralde et al., 1998; Schlesinger, 2000; Sitting;1979).

Phosphate fertilizer is produced by crushing phosphate rock and then spraying it with either sulfuric acid or phosphoric acid. This is also an energy intensive process. Expressed on the same basis as nitrogen and taking into account transportation costs, about 3 units of carbon are required to manufacture, transport and apply 1 unit of P as P₂O₅ fertilizer.

Biosolids are generally applied to meet the N needs of a crop. Total N in biosolids generally ranges from 4 to 6 percent, with available N being only a small portion of the total. For King County biosolids, total N averaged 5.9 percent at the West Point Treatment Plant (WPTP) and 7.2 percent at the South Treatment Plant (STP). Of this, 17.5 percent



Table 2. CO₂ impacts of landfilling biosolids with no energy recovery

	Gas	
	CH ₄ (Mt)	N ₂ O (Mt)
Amount generated	2100	23.5
CO ₂ equivalent	132750	6940
Portion released	64%	100%
Bottom line	CO ₂ (Mt)	
Transport	3500	
Methane	85000	
N ₂ O	6941	
Total gas released	95400 Mt CO ₂	

of the total N is present as NH₃, and 82.5 percent is present as organic N (King County, 2002). About 25 percent of the organic N is available for plant uptake in the year following biosolids application. An average N application rate for most agronomic crops is 165 kg ha⁻¹. With the available N content of the

King County biosolids, this would translate into an application that would have 433 kg total N. On a dry weight basis, this would equal 7.34 Mg of WPTP biosolids and 6 Mg of STP biosolids. Assuming 21 percent solids, this would amount to a wet application of 35 Mg of WPTP and 28.6 Mg of STP biosolids.

We can also assume that applying biosolids to meet the N needs of the crop would also supply the P needs. Generally P is applied at the same rate (kg ha⁻¹) as N to meet the fertilizer needs of the crop. Although there has been a great deal of research on P bioavailability in different

types of biosolids (e.g. Elliot et al., 2002), for this estimate, we will assume that by applying biosolids to meet the N needs of the crop, the P needs will also be met. We will also assume that the N requirements for



An assumption was made that a truck transporting biosolids to a beneficial use site (as well as the landfill) releases 21.6 lbs of carbon for each gallon of diesel consumed.

forestry are equivalent to the N requirements of agronomic crops. For this estimate, we are not taking into consideration the micronutrient or the potassium fertilizer content of the biosolids because micronutrients are not routinely applied to agricultural soils and the potassium content of biosolids is generally low. However, if these were figured into the estimate, the credits associated with using biosolids instead of commercial fertilizer would increase.

For energy calculations, we've assumed that the C requirements for producing and applying commercial fertilizer N and P are as stated above and that biosolids are applied at a rate sufficient to supply 165 kg ha⁻¹ N which will supply the same amount of P. For 2001, about 109,000 wet Mg or 23,000 dry Mg were applied to agricultural fields and 1,500 Mg were applied to forest sites. King County applied biosolids to a total of 3,650 ha of land at a fertilizer rate in 2001. The energy savings achieved by using biosolids instead of commercial N and P fertilizers come to 1.5 Mg of CO₂ per ha treated.

This carbon credit gained by using biosolids as a fertilizer source to replace commercial N and P has to be altered to factor in the CO₂ costs for transporting biosolids to the site. For this analysis, the CO₂ costs for land application (meaning the fuel use associated with spreading the biosolids on each hectare of land) of the biosolids are not being considered. They would be a very small fraction of the cost of bringing materials from the treatment plant to the application site and so would not have a significant impact on the calculations. For King County, the average one-way haul distance for biosolids used on agricultural land is 205 miles, or 410 miles round-trip. For forest application, the one way haul distance averages 55 miles, with a round trip equal to 110 miles. This significantly reduces the CO₂ credit for agricultural sites with only a minor reduction for forest sites (see Table 4).

For King County, using biosolids as a substitute for commercial fertilizers results in a net savings in CO₂ for both agricultural and forest application sites. To maximize this savings, it would be advantageous to reduce the haul distance for the material. This would require higher application to forest lands or identification of agricultural sites with a shorter haul distance. This estimate did not take into account the micronutrient value of the biosolids. In addition, it did not take into account the potential for biosolids addition to soils to increase soil carbon reserves. It is possible that the fertilizer value of the biosolids combined with the potential to increase soil carbon reserves would further add to CO₂ mitigation. This will be discussed in Part II, along with a total assessment of the CO₂ credits and debits associated with landfilling biosolids versus recycling on agricultural land and in forests. ■

When land applied for beneficial use, biosolids can be considered as a carbon sink, or a greenhouse gas credit.

Table 3. CO₂ impacts of landfilling biosolids with all methane captured for energy recovery

	CO ₂ (Mt)
Transportation	-3500
Methane emission	84,959
Methane currently flared	19,900
Nitrous oxide emission	-6,941
Total credit	94,430



A portion of the biosolids generated in King County is land applied to forest sites. Energy savings achieved using biosolids instead of commercial N and P fertilizers come to 1.5 Mg of CO₂/ha treated.

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Table 4. CO₂ savings with biosolids land application to forestry and agricultural sites

	CO ₂ Saved Per ha ¹	CO ₂ Saved Per dry ton Biosolids
Forest sites		
CO ₂ credit:	1.5	
CO ₂ transport cost:	-0.22	
Net Credit:	1.3	0.18
Agricultural sites		
CO ₂ credit:	1.5	
CO ₂ transport cost:	-0.82	
Net Credit:	0.7	0.1

¹Based on a 6.67 Mg ha application

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