Calculator Tool for Determining Greenhouse Gas Emissions for Biosolids Processing and End Use

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A greenhouse gas (GHG) calculator tool (Biosolids Emissions
Assessment Model, BEAM) was developed for the Canadian
Council of Ministers of the Environment to allow municipalities
to estimate GHG emissions from biosolids management. The
tool was developed using data from peer reviewed literature and
municipalities. GHG emissions from biosolids processing
through final end use/disposal were modeled. Emissions from
nine existing programs in Canada were estimated using the
model. The program that involved dewatering followed by
combustion resulted in the highest GHG emissions (Mg CO_2e
100 Mg^{-1} biosolids (dry wt.). The programs that had digestion
followed by land application resulted in the lowest emissions
(−26 and −23 Mg CO_2e 100 Mg^{-1} biosolids (dry wt.). Transportation
had relatively minor effects on overall emissions. The greatest
areas of uncertainty in the model include N_2O emissions
from land application and biosolids processing. The model
suggests that targeted use of biosolids and optimizing processes
to avoid CH_4 and N_2O emissions can result in significant
GHG savings.

Introduction

Wastewater treatment systems often constitute the single
largest use of electricity within municipal governments with
3% of electricity use in the U.S consumed in water and
wastewater treatment (*1*). GHG emissions from wastewater
treatment have been classified as one of the larger minor
sources of emissions (*2*). Energy use is often considered to
be the primary source of GHG emissions related to wastewater
(*3−6*). A recent re-examination of initial estimates resulted
in a greater than 100% increase in emissions of N_2O and CH_4
(*7*). Biosolids treatment and end use can constitute up to
40% of total emissions associated with wastewater treatment
(*8*). A range of different stabilization and end use technologies
are widely available, each with different associated costs and
environmental impacts (*9, 10*).

Decisions on end use/disposal of municipal biosolids have
traditionally been based on cost, regulatory, environmental,
and public acceptance considerations. Environmental con-
cerns have generally focused on contaminants in the biosolids
(*11−14*). Understanding the GHG emissions associated with
different biosolids management practices is likely to influence
public opinion and municipal decision-making. It can also
be used as a model for management of other residuals
including animal manures.

Different biosolids processing technologies require vary-
ing energy and chemical inputs. Fugitive emissions of CH_4
and N_2O during processing and end use of biosolids can
result in significant debits. End use of biosolids may generate
credits, through energy production, as a substitute for
synthetic fertilizers, and through carbon sequestration in
soils. These factors have been discussed to varying degrees
in previous studies (*9, 15−19*). The Intergovernmental Panel
on Climate Change (IPCC) includes limited discussion of
these factors in separate sections of the documents on waste
management, mitigation, and agriculture (*6, 20, 21*).

There have been few studies that effectively integrated
the potential emissions/sequestration associated with the
full range of biosolids management options, and those have
often neglected fugitive emissions or potential credits
(*4, 5, 9, 22*). The goal of the current study was to create a tool
for modeling and calculating GHG emissions from different
biosolids processing and end use options that includes default
values but also provides for use of site specific data. The tool
was designed to compare the GHG impact of different
biosolids management options. Data provided by nine
participating municipalities with different biosolids process-
ing and end use programs were put through the model.

Materials and Methods

Biosolids management was divided into categories for solids
processing and stabilization, and end use and disposal.
Default values for each unit process, including inputs, energy
use, and fugitive gas emissions, were developed based on
values from published literature and data from individual
treatment facilities. Potential credits for each process were
also described. When multiple values were available for a
unit process, preference was given to values from peer
reviewed literature or scientific studies. The range of values
considered for each process is shown in the Supporting
Information (SI). Emissions related to electricity production
were calculated using specific factors for Canadian provinces
(*23*). These ranged from 10 CO_2e (g/kWh) in Manitoba,
Newfoundland, and Quebec to 926 CO_2e (g/kWh) in Alberta.
When available, facility-specific data is used in place of default
values. Emissions/credits from each process were classified
as Scope 1 (direct emissions), Scope 2 (purchased electricity,
heat or steam), Scope 1 and 2 combined, or Scope 3 (indirect
emissions from production of purchased materials and uses
of end products). Carbon dioxide emissions as a result of
aerobic decomposition of biosolids organics were considered
biogenic in origin and not considered in the model. Calcula-
tions were made and are reported on a per dry Mg biosolids
produced. Individual unit processes and values for munici-
palities will be discussed.

Aerobic Digestion. Aerobic digestion (activated sludge
treatment, aerated lagoons, and trickling filters) is unlikely
to be a source of significant CH_4 or N_2O emissions except for
controlled nutrient removal via nitrification (*6*). The model
includes default values for electricity use for aeration and
mixing based on a sludge retention time of 15 days (*10*).

Storage Lagoons. Anaerobic lagoons storing organic
residuals have been identified as sources of CH_4 (*6*). Both
temperature and depth of the lagoon will influence the

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potential for CH_4 release. Minimal emissions are predicted at temperatures less than 15 °C for nonaerated lagoons. Emissions of 0.12 and 0.40 kg CH_4 kg BOD are predicted for lagoons less and greater than 2 m in depth, respectively (6). Aerated lagoons will have minimal CH_4 emissions. Emissions from electricity consumption by aeration blowers or mechanical mixers are included in the model.

Anaerobic Digestion. Anaerobic digestion is generally used to meet regulatory requirements for volatile solids (VS) reduction (10). The CH_4 generated during digestion can be flared or used to provide heat and power for facilities. In the model, total CH_4 is calculated as a function of the total VS destruction (10, 24). Biogas yields from VS destruction average 0.9 m^3/kg VS destroyed (25).

Digesters require energy for heating and operating pumps and mixers. Default values for electricity requirements and heat loss, based on a typical heat loss of 4.62 m^3 of natural gas/m^3 sludge treated (10), are included in the model. There are potential fugitive emissions from combustion or flaring of digester gas. A range of values for gas flare efficiency have been reported (2, 3). The model uses a default value of 0.3% (26). Emissions of N_2O from incomplete combustion are minimal per Mg dry biosolids (between 0.004 and 1.7 g N_2O/kg CH_4 burned) (3, 6). The model includes default values for VS destruction and composition of biogas and uses U.S. EPA values for biogas conversion to electricity.

Thickening, Conditioning, and Dewatering. Emissions from thickening, conditioning, and dewatering include emissions from polymer production and electricity use. Polymer manufacturing emissions (Scope 3) are approximately 9.0 Mg CO_2eq/Mg polymer (27). A default dosage of 5 kg of polymer per Mg dry solids was used (23). Centrifuges use considerably more electricity than belt filter presses. Default values in the model reflect this difference: 101.4 kWh for centrifuges and 4.9 kWh for presses, per Mg dry sludge treated (28).

Thermal Drying. Rotary dryers are the most common drying systems used in North America, generally operating at 340−370 °C (23). Default electricity for drying was set at 214 kWh/Mg dry solids, based on biosolids thermal drying data from Windsor, Ontario. Default fuel use for drying was calculated based on energy required to evaporate water from sludge and initial and final solids content (10).

Alkaline Stabilization. Lime stabilization is used to meet pathogen reduction prior to land application or landfill disposal. If the lime is processed specifically for biosolids stabilization, its production has significant embedded, supply chain (Scope 3) carbon emissions (9). The model uses a supply chain cost of 0.9 Mg CO_2e/Mg lime (27). If the liming agent used is a residual from another process, these debits do not apply. Use of lime stabilized biosolids in soils displaces agricultural lime and emissions associated with its use. IPCC estimated emissions of 0.12 Mg CO_2e per Mg agricultural limestone applied to the soil (20). The model includes production emissions for total quantity of lime used (9, 28, 29). Credits for displacement of agricultural lime are also included.

Composting. Composting results in emissions from energy use and fugitive gas release. Different systems have different energy requirements with lowest requirements associated with windrows (5 L of fuel per dry Mg feedstock) and highest for in-vessel systems (90 kWh per dry Mg) (16). The model includes fuel requirements for mixing (18.3 kg CO_2e) and turning (14 kg CO_2e) per dry Mg feedstock (16, 30). Average energy consumption, including requirements for aeration and odor control across 16 in-vessel composting facilities, was 40 kWh per Mg of waste, based on operating near full capacity (31, 32). The model also includes aerated static pile and windrow systems.

Methane emissions during composting have been reported (16). The Clean Development Mechanism (CDM) protocol for composting requires oxygen measures to document the absence of CH_4 (33). Studies have shown that CH_4 is oxidized in the upper portion of the windrow, with compost used to oxidize CH_4 (34). Storage of finished compost releases trace quantities of CH_4 and N_2O (35). Regulations for composting biosolids require internal pile temperature of 55 °C, which is associated with aerobic decomposition.

Nitrous oxide has also been detected during composting (up to 4.6% of total N released as N_2O) with increased emissions resulting from low C:N ratios and high moisture content (36, 37). Emissions are reduced by maintaining pile temperature at 55° and by incorporating finished compost into the pile (36, 38, 39). Default values for N_2O and CH_4 emissions are provided for piles with excess moisture and low C:N ratios. The model reduces emissions when a compost cover or biofilter is used.

End Use or Disposal

Landfill. In the model, fugitive emissions are the major debits associated with landfilling. Landfills are considered a significant source of CH_4 (2, 40). Decomposition rates are accelerated in sanitary landfills (41−43). Protocols exist for diversion of biosolids from landfills to composting facilities (6, 33). The decay rate constant for biosolids from the CDM protocol for CH_4 generation in warm wet environments (0.40) was used for default value as these temperatures are characteristic of sanitary landfills (33, 41, 42). Default values included consideration of gas collection efficiency and onset of collection systems (44−49). Nitrous oxide emissions from landfilled biosolids have also been reported (40, 44, 50, 51). The model includes a default debit for N_2O emissions equivalent to emissions from compost. The range of values associated with landfill gas emissions are reported in the SI. Biosolids used as a component of manufactured soil material for final landfill cover are considered as an agricultural application and not included in the landfill disposal section of the model.

Combustion. There is growing interest in combustion of biosolids as a disposal/end use option. Multiple hearth or fluidized bed technologies are the most prevalent, with higher efficiency in fluidized beds (52). There was insufficient data on pyrolysis/gasification facilities to model emissions from these facilities. Because of the high moisture content in biosolids, combustion operations often require supplemental energy. Use of waste heat will decrease energy requirements. The model uses the Btu value, percent solids, and the amount of energy required to evaporate water from sludge to calculate a default balance for combustion (10).

Fugitive Emissions. The IPCC default value of 4.85×10^{-5} kg CH_4 emitted/dry kg wastewater solids burned, was used in this model (6). Combustion temperature is the primary variable controlling N_2O emissions, with higher emissions observed at lower temperatures. The IPCC default value for N_2O release from combustion is based on moisture content with limited information provided on percent solids for each category and limited data forming the basis for the values (6, 53, 54). A study of emissions from fluidized bed combustion facilities for monoincineration using continuous monitoring showed significantly higher emissions factors ranging from 1520−6400 g N per dry Mg biosolids (19). The emissions were described as a function of total N in the material using the equation:

$$\eta = 161.3 - 0.140 T_f$$

where η is the % of total N that is volatilized as N_2O, and T_f is the average highest freeboard temperature from the fluidized bed facilities. There is limited published data on cocombustion of coal or MSW and biosolids (54). There was no published data for emissions from multiple hearth

TABLE 1. Data from Nine Municipalities Used to Model Greenhouse Gas Emissions

municipality	population served	wastewater treated (MLD)	weighted GHG emissions for electricity generation g CO$_2$e/kWh	treatment processes	end use/disposal	GHG emissions Mg CO$_2$e/100 Mg dry solids
TB, Ontario	100 000	70	181	• anaerobic digestion • centrifuge dewatering	biosolids/soil landfill cover	46
AN, Quebec	330 000	295	10	• rotary press dewatering	• incineration/heat recovery • ash recycling	148
LA, Quebec	271 600	254	10	• rotary press dewatering • rotary drum high temperature drying	• landfilling dewatered cake • cement kiln incineration	49
WI, Ontario	181 350	161	181	• centrifuge dewatering • rotary drum high temperature drying	agricultural land application	10
MO, New Brunswick	125 000	79	352	• centrifuge dewatering • polymer addition • alkaline stabilization • composting	land application	5
VA, British Columbia	980 000	436	20	• gravity thickening • dissolved air • floatation thickening • anaerobic digestion • centrifuge dewatering	restoration land application	−23
HX, Nova Scotia	54 000	27	733	• anaerobic digestion • Fournier press dewatering • alkaline stabilization	agricultural application	28
NA, British Columbia	25 000	10	20	• gravity thickening • aerobic digestion • centrifuge dewatering	silvicultural land application	12
HA, Ontario	165 000	96	181	• dissolved air floatation thickening • anaerobic digestion • polymer addition • belt filter press dewatering	liquid and dewatered biosolids agricultural application	−26

furnaces. These facilities have more frequent start-up and shut-down with associated temperature fluctuations (*52*). For this study, no distinction is made between mono- and cocombustion of biosolids or types of facilities. Nitrous oxide emissions are calculated using the equation presented above with reduction factors for drier biosolids. The model emissions factors for combustion at 850 °C, are similar to emissions from the IPCC default. The ash resulting from combustion can be used as a soil amendment or for cement manufacture. Beneficial use of ash is given a credit based on the quantity of lime or phosphorus it displaces (*9*).

Direct Land Application

The model includes CO$_2$ emissions debits for transport and land application.

Fugitive Emissions. Biosolids are generally applied to aerobic soils to meet the N requirements of a crop. Previous work has shown minimal CH$_4$ release, even in poorly drained soils (*15, 55*). The model includes CH$_4$ emissions for storage prior to land application. A number of studies have quantified N$_2$O release from soils, with higher emissions on poorly drained soils in warmer climates (*56−59*). A majority of emissions associated with the production of agronomic crops has been attributed to N$_2$O release (*60*). The IPCC default factor for N$_2$O emissions for fertilizer, compost and biosolids use are 1% of the total N added. Published literature generally reports lower emissions for biosolids compared to fertilizer (*15, 57, 61, 62*). The range of emissions is shown in the SI. The current model considers N$_2$O emissions from biosolids as equivalent to synthetic fertilizer for biosolids applied as a fertilizer replacement.

Offsets from Land Application. Using biosolids in lieu of synthetic fertilizers results in avoidance of Scope 3 emissions due to energy use from production of synthetic fertilizers. Different values for emissions have been reported (*9, 30*). For this model, we used default values of 4 and 2 kg CO$_2$e/kg for N and P respectively, with no distinction made between total and available nutrients (*30, 63, 64*). As biosolids supply additional macro- and micronutrients, default values were considered conservative. Offsets associated with increased soil organic matter are included in the model. Increases in soil carbon have been observed in biosolids amended soils
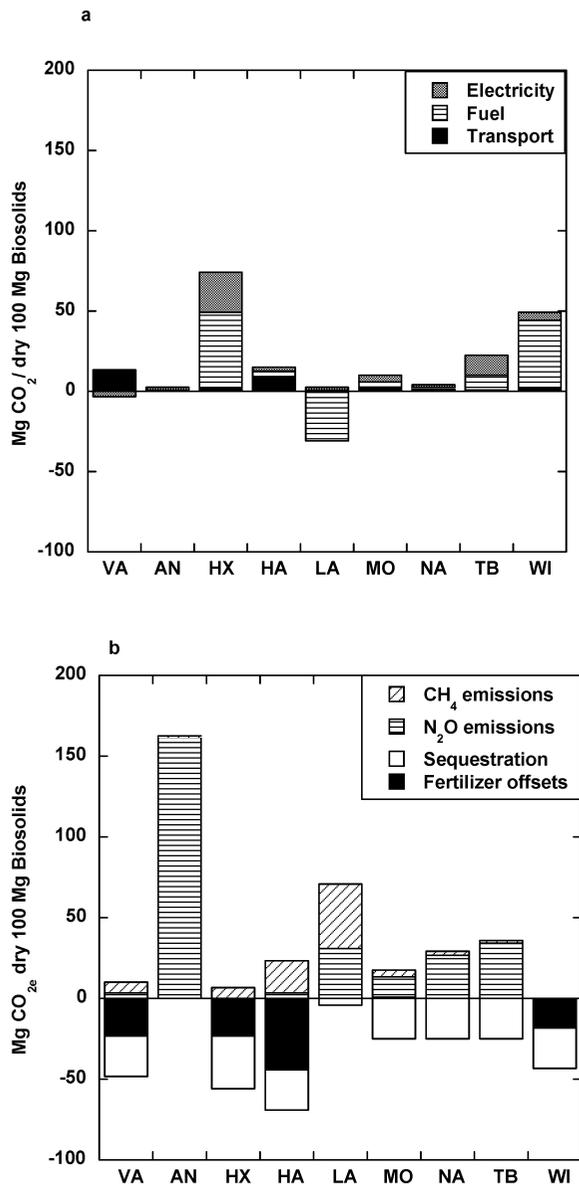
FIGURE 1. Greenhouse gas emissions or credits associated with (a) electricity, fuel and transport and (b) fugitive gas emissions, carbon sequestration, and fertilizer offsets for nine biosolids programs in Canada. Emissions include province-specific weighting factors for electricity.

FIGURE 2. High, low, and default emissions factors for VA showing range of reported values for fertilizer offsets, soil carbon sequestration, CH_4 emissions from flaring biogas, and N_2O emissions following land application. Transport and electricity use are not included.

(18, 65, 66). The current model provides a default credit of $25 \, Mg \, CO_2e \, 100 \, Mg^{-1}$ biosolids (dry wt.). The range of reported values for fertilizer offsets and soil carbon sequestration are provided in the SI.

Applying the Model. Data from nine wastewater treatment facilities across Canada was applied to the spreadsheet. The facilities were selected to represent different treatment processes and end use/disposal programs. This enabled a direct comparison of different biosolids management scenarios with regard to GHG emissions. The programs evaluated, treatment and end use for biosolids, and associated GHG emissions are shown in Table 1.

Total GHG emissions per dry Mg of biosolids ranged from a low of $-26 \, Mg \, CO_2e \, 100 \, Mg^{-1}$ biosolids (dry wt.) for HA (anerobic digestion, polymer addition, belt filter press dewatering followed by liquid and dewatered land application) to $144 \, Mg \, CO_2e \, 100 \, Mg^{-1}$ biosolids (dry wt.) for AN (rotary press dewatering followed by incineration with heat recovery and ash recycling). This difference was observed despite the fact that emissions associated with electricity
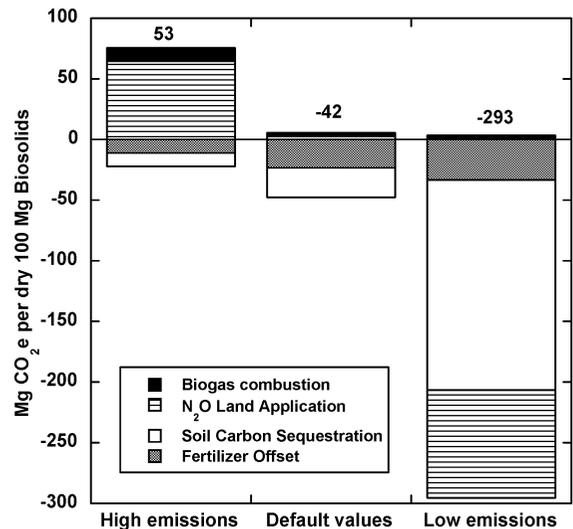
use in HA were significantly higher ($181 \, g \, CO_2e \, kWh^{-1}$) than those in AN ($10 \, g \, CO_2e \, kWh^{-1}$).

The bulk of emissions and credits for the different programs were associated with indirect factors. This illustrates the importance of considering a full range of potential GHG impacts when evaluating different biosolids treatment and end use options. Emissions associated with energy and transport are shown in Figure 1a. Emissions associated with fugitive gas release, credits from soil carbon sequestration, use of ash, fertilizer offset credits, or credits for heat recovery are shown in Figure 1b.

The wide range of GHG costs associated with electricity use across Canada shows the importance of considering province specific factors as well as future power needs when considering the benefits of an anaerobic digestion facility with energy capture. For provinces with low GHG costs for electricity, use of heat for drying to offset transport emissions could be preferable to generating electricity.

A sensitivity analysis was conducted for two municipalities to see how the range of reported factors would influence the outcomes of this analysis. Midrange values were used for the model as a means to show general trends while remaining conservative considering the high level of uncertainty (Figure 2). Transport and electricity use were not included in this estimate. Uncertainties related to soil carbon sequestration and N_2O emissions were associated with the largest differences in end values. The range in reported values were sufficient to alter the net balance in the VA program from a net credit per dry 100 Mg biosolids of $293 \, Mg \, CO_2e$ (low end factors) to a net emitter of $53 \, Mg \, CO_2e \, 100 \, Mg^{-1}$ biosolids (dry wt.) (high range emissions factors). The default values for VA resulted in a net credit of $42 \, Mg \, CO_2e \, 100 \, Mg^{-1}$ biosolids (dry wt.). For landfilled biosolids, the high-end emissions scenario used high decomposition rates with midrange gas capture efficiency. The low end coupled slower decomposition with more effective gas collection. As collection systems are not required for the first three years after material is deposited, these changes had a low impact on total emissions [range from $32-53 \, Mg \, CO_2e \, 100 \, Mg^{-1}$ biosolids (dry wt.)].

A side-by-side comparison of two of the Canadian programs illustrates the importance of fugitive emissions, energy, minimal impact of transport, and the importance of Scope 3 factors in determining the potential GHG impacts of different biosolids management options (Table 2). VA, a municipality that uses anaerobic digestion followed by land

TABLE 2. Existing and Optimized GHG Emissions/Credits for the VA (Anaerobic Digestion Followed by Land Application) and AN (Dewatering, Combustion with Ash Use in Cement Production) Programs

		VA		AN	
		existing	optimized	existing	optimized
		kWh Mg^{-1} biosolids (dry wt.)			
conditioning	kWh Mg^{-1} biosolids (dry wt.)	5	5	5	5
anaerobic digestion		−1658	−2333	0	0
dewatering		171	171	11	11
combustion		0	0	1113	716
total electricity use		−1482	−2157	1129	732
		Mg CO$_2$e 100 Mg^{-1} biosolids (dry wt.)			
electricity	Mg CO$_2$e 100 Mg^{-1} biosolids (dry wt.)	−3	−4.3	1.1	0.7
polymer		5	5	5	5
fuel/not transport		0.6	0.6	−25	−10
fuel/transport		12.5	2	0.2	0.2
CH$_4$ emissions		7	7	0	0
N$_2$O emissions		3	3	163	0
carbon sequestration		−25	−25	0	0
ash use		0	0	−0.1	−0.1
fertilizer offset		−23	−23	0	0
total emissions		−23	−34	144	−4

application, and AN, an incineration facility, were used for this comparison. These programs feature very different end use options and represent the highest emissions (AN) and close to the lowest emissions of the programs modeled in this exercise. The CO$_2$e for electricity in both provinces are also similar at 20 and 10 g CO$_2$e kWh^{-1}, respectively.

Data from 1 of 5 treatment plants operated by VA was used for this model. The plant treats an average of 436 megaliters per day (MLD). Primary solids are gravity thickened and secondary solids are thickened by dissolved air floatation. Thickened solids are fed to thermophilic anaerobic digesters. Digester gas is burned for heat alone (18%) and heat plus electricity (60%), generating 61 MJ/yr of heat or 20 × 10^6 kWh/yr of electricity. A portion (22%) of the gas is flared. Biosolids are dewatered to 31% solids using polymer and centrifuges. Approximately 40 000 wet Mg of biosolids are generated and land applied with round trip distance to projects of 520−875 km.

At AN, the treatment plant services approximately 330 000 people with total inflow of 295 MLD. Sludge is dewatered using chemical mixing, flocculation, and settling. It is concentrated in thickening tanks and dewatered using rotary presses and polymer. The dewatered sludge is incinerated in a fluidized bed monocombustion facility at 760 °C. Process heat is used for process and facility heating. External electricity and fuel are also required. The ash (8 Mg per day) is used for cement production at a cement kiln 35 km from the treatment plant.

Emissions per dry Mg biosolids were similar for both municipalities for conditioning, dewatering, and thickening. Transport emissions were higher in VA [12.5 Mg CO$_2$e 100 Mg^{-1} biosolids (dry wt.)] in comparison to AN [0.2 Mg CO$_2$e 100 Mg^{-1} biosolids (dry wt.)]. VA derives a negative net GHG balance of −303 Mg CO$_2$e 100 Mg^{-1} biosolids (dry wt.) from anaerobic digestion with heat and electricity generation and −48 Mg CO$_2$e 100 Mg^{-1} biosolids (dry wt.) from land application of the biosolids for fertilizer replacement and soil carbon sequestration. This credit has the potential to increase with use of all digester gas for electricity generation. Decreasing transport distances would also decrease emissions.

Using the model, biosolids programs for both municipalities were optimized to reduce emissions and maximize credits. Results from this optimization are compared to current estimated emissions in Table 2. GHG credits related to net electricity use and generation were increased 40% for the VA program by expanding electricity production to

include use of all CH$_4$. Reducing the one-way haul distance to 100 km resulted in a reduction of transport GHG emissions by 83%. These two optimization steps resulted in net negative GHG emissions (credits) for VA's biosolids program increasing from −23 to −34 Mg CO$_2$e 100 Mg^{-1} biosolids (dry wt.).

Nitrous oxide was the primary emission associated with the combustion facility, result in a debit of 163 Mg CO$_2$e 100 Mg^{-1} biosolids (dry wt.). According to the model, increasing the combustion temperature to 880 °C effectively eliminated N$_2$O. This temperature increase was estimated to require an additional energy input of 54 GJ/day. This municipality reported using a portion of heat from the combustion process for heating buildings and reducing energy requirements for combustion. The theoretical optimization included increasing the fraction of waste heat used for combustion and increasing combustion temperature to eliminate N$_2$O emissions. This resulted in emissions per dry 100 Mg biosolids decreasing from 144 to −4 Mg CO$_2$e. As a result of this study, the municipality has increased the burn temperature at its facility to minimize N$_2$O emissions.

The BEAM spreadsheet tool provides a means for municipalities to evaluate GHG emissions associated with biosolids treatment and end use, considering both direct and indirect emissions. Because of their high CO$_2$e, emissions of CH$_4$ and N$_2$O have the potential to negate benefits associated with biosolids use or disposal. Focusing solely on CO$_2$e emissions related to energy use results in an incomplete understanding of net GHG emissions. Similarly, the high emissions and/or offset potentials associated with indirect (Scope 3) factors should be considered. The results from this study suggest that limiting considerations of emissions to Scope 1 and 2 factors has a high potential for generating misleading GHG estimates.

It must be emphasized that default factors used in the model for each unit process vary dramatically with regards to level of uncertainty. Factors used in the model range from those that can be predicted with a relatively high degree of accuracy (transport related emissions) to those with a greater degree of uncertainty (soil carbon credits and N$_2$O emissions). The factors with the greatest potential impact on net emissions include all sources of N$_2$O.

Results from applications of the BEAM model suggest that maximizing potential offsets, including energy capture and fertilizer and carbon sequestration value, while minimizing fugitive CH$_4$ and N$_2$O emissions associated with biosolids management practices such as landfilling, low

temperature combustion, or poor compost management, can significantly decrease the GHG emissions from biosolids management programs. The end use options associated with the highest credits were also those with the lowest capitol costs, suggesting a cost-effective means for wastewater treatment agencies to lower their GHG footprints without increasing capitol expenditures (*11*).

Acknowledgments

Supporting Information Available

Additional information including the calculator spreadsheets, tables summarizing the literature for the range of reported values for different parameters, and a flow diagram for the wastewater treatment process. This material is available free of charge via the Internet at http://pubs.acs.org.

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ES101210K