STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
PO Box 47600, Olympia, WA 98504-7600 • 360-407-6000

STATE ENVIRONMENTAL POLICY ACT

Determination of NonSignificance

September 27, 2024

Lead agency: Washington State Department of Ecology

Agency Contact: Emily Kijowski, emily.kijowski@ecy.wa.gov, 360-789-6590

Agency File Number: NA

Description of proposal: – Reissue the Statewide General Permit for Biosolids Management (General Permit) with a term of 5 years. If issued, Ecology will use the General Permit to implement Chapter 173-308 of the Washington Administrative Code (WAC) and to oversee the management of all forms of biosolids generated, treated, stored, transferred from one facility to another, sold or given away, applied to the land for beneficial use, and disposed through incineration or landfilling within the jurisdiction of the State of Washington (Department of Ecology [DOE], 2007). There are about 376 facilities subject to the General Permit currently.

The flexible nature of the General Permit enables Ecology to include additional or more stringent requirements for each individual facility and land application site as necessary if requirements in rule or permit are not stringent enough to effectively protect human health and the environment. These additional requirements can be described as further efforts to mitigate impacts to human health or the environment. They are prescribed based on site-specific characteristics using guidance like the Biosolids Management Guidelines, derived from research and real-world experience from universities and regulatory entities.

Washington's biosolids program is based on the standards established by the U.S. Environmental Protection Agency (EPA) in 40 CFR Part 503 (U.S. Environmental Protection Agency [EPA], 1993) and is authorized by state law in Chapter 70A.226 RCW (DOE, 1992). The law establishes biosolids as a valuable commodity and directs Ecology to maximize beneficial use while protecting human health and the environment. Ecology developed rules for the state biosolids program in Chapter 173-308 WAC Biosolids Management that meet or exceed federal rules in 40 CFR 503 implemented by EPA.

The proposed General Permit differs structurally from the previous iteration of the General Permit issued in 2015. The General Permit categorizes facilities into two primary groups: those without active biosolids management programs, and those with active biosolids management programs. The proposed General Permit is organized into three distinct sections: Baseline, Active Septage Management, and Active Biosolids Management.

Regardless of the permit sections a facility is subject to, all facilities subject the general permit are also subject to project-level SEPA review on their project specific actions as a part of the permit application process.

Location of proposal: –The permit is applicable statewide in all areas subject to the jurisdiction of the State of Washington

Applicant/proponent: Washington State Department of Ecology, Solid Waste Management Program, PO Box 7600, Olympia, WA 98504-7600. Program reception phone: 360-407-6900

Determination: The Washington State Department of Ecology has determined that this proposal will not have a probable significant adverse impact on the environment. An environmental impact statement (EIS) is not required under RCW 43.21C.030(2)(c). We have reviewed the attached Environmental Checklist with consideration of the proposed general permit and biosolids permit program implemented under Chapter 173-308 of the Washington Administrative Code. This information is available at: https://ecology.wa.gov/Biosolids-permit-actions

This determination is based on the following findings and conclusions:

The state biosolids program is based on and meets or exceeds the requirements of the federal biosolids management program implemented by U.S. EPA under 40 CFR Part 503. Beneficial use is the primary means of management in Washington, and nationwide. Biosolids that meet appropriate standards for beneficial use do not pose a significant risk to human health or the environment when used in accordance with applicable rules, guidelines and permit requirements. The permit authorizes landfilling and incineration when biosolids do not meet applicable standards. The permit program implemented by Ecology allows the agency to impose additional or more stringent requirements for individual facilities and sites, as required, following review of a permit application, additional environmental review, and public hearings if required.

The General Permit checklist highlighted that the information with respect to PFAS, microplastics and other contaminants that may be present in biosolids is incomplete and the research is ongoing regarding these emerging contaminants in biosolids. More information is needed to determine if there is risk to human health and the environment from these contaminants associated with land application of biosolids that warrants regulatory action. It is apparent that the EPA and many researchers are working hard to fill in information gaps as they have previously done with emerging contaminants in biosolids in the past. Ecology has also undertaken its own sampling study to further its understanding of PFAS in biosolids generated in Washington state. Implementing regulatory action without risk-based guidance from EPA could interfere with established goals and benefits of biosolids recycling and may not provide demonstrated risk-reduction for human health and the environment.

Washington’s wastewater treatment systems provide a necessary service and generate biosolids during the treatment process as a byproduct. Thus, biosolids generation will continue and the material needs to be managed sustainably. In light of the unavailable or incomplete information, we must weigh the need to manage biosolids with the severity of possible adverse impacts that could occur should Ecology proceed with issuing the general permit (WAC 197-11-080).

In making this determination, we scrutinized the existing research, including the information available about PFAS in Washington state, and the fact that there are no know PFAS manufactures in Washington state. We have seen isolated events in other states where elevated PFAS levels in biosolids are a direct result of dumping or discharging of PFAS from manufacturers into municipal wastewater treatment plants. In most cases the contamination events occurred years ago and the land application practices employed would not be allowed in Washington state. In addition, not having any PFAS manufacturers in Washington makes this even more unlikely to occur in the state. Although the study of PFAS in Washington biosolids was small, it highlighted that a facility with known industrial inputs and impacts from historical AFFF contamination generated biosolids with PFAS levels lower than those calculated from a national average of industrially impacted biosolids.

The research on these contaminants to date and information currently available show us that it is very unlikely that current biosolids land application practices constitute a major source of PFAS exposure for humans or the environment. We also can reasonably assume, based on the absence of PFAS manufacturing in Washington and on Washington-specific PFAS sampling data, that the likelihood for biosolids to have elevated PFAS levels, or land application thereof to lead to elevated soil, groundwater or animal byproducts is unlikely.

Current alternatives to land application that have been suggested are disposing of biosolids via landfilling or incineration at a sewage sludge incinerator. Both disposal options also present environmental impacts themselves. Landfilling and incineration at a sewage sludge incinerator will not effectively destroy PFAS, microplastics or any other contaminants of concern, and both release contaminants with environmental impacts as well. Incineration of PFAS may work for other applications, such as AFFF at incinerators specifically designed to handle this material. Sewage sludge incinerators were not designed with this same intent. Research has found that minimizing landfilling of biosolids (that is, maximizing responsible land application) can significantly decrease the Greenhouse Gas (GHG) emissions from biosolids management (Brown et al., 2010). Diverting biosolids from land application by instead disposing of them in landfills or incinerating them at sewage sludge incinerators will lead to increased GHG production from municipalities across the state.

Landfilling of biosolids in Washington is extremely difficult due to regulations implemented to divert organic waste, such as biosolids, from landfills in an effort to curb unnecessary GHG. (Organics Management Law, 2022) (Organic Material Management, 2024) There are only a few landfills in the state of Washington that will accept biosolids. Washington state currently has four sewage sludge incinerators that can process biosolids, with this number likely reducing soon due to aging facility technology and more stringent air emissions regulations being implemented since their initial construction. Beyond these logistical obstacles, the landfills and sewage sludge incinerators in Washington do not have adequate capacity to accept the biosolids generated annually.

The state biosolids program is based on and meets or exceeds the requirements of the federal biosolids management program implemented by U.S. EPA under 40 CFR Part 503. Beneficial use is the primary means of management in Washington, and nationwide. The permit authorizes landfilling and incineration when biosolids do not meet applicable standards. The Biosolids Rule and General Permit incorporate mitigation efforts throughout. Biosolids that meet appropriate standards for beneficial use do not pose a significant risk to human health or the environment when used in accordance with applicable rules, guidelines and permit requirements.

This DNS is issued under WAC 197-11-340. Ecology will not act on this proposal for 14 days from the date below. Ecology will accept written comments from Friday September 27, 2024 through 11:59 pm Friday, October 11, 2024. Ecology prefers online comment submission via the eComment form (link below). Written comments by mail must be postmarked by 11:59 pm Friday, October 11, 2024.

Online eComments form (preferred): https://swm.ecology.commentinput.com?id=rM4PhRNKm

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Date September 27, 2024

References

A full list of references is provided below. The first reference document below is not readily available online (identified with an asterisk (*)) and is included in Appendix A.

Ecology will also provide electronic copies of all references upon request.

1. *Brown, S., Beecher, N., & Carpenter, A. (2010). Calculator Tool for Determining Greenhouse Gas Emissions for Biosolids Processing and End Use. Environmental Science and Technology, 44, 9509-9515, https://doi.org/10.1021/es101210k
2. Organics Management Law, SSHB 1799, 67th Legislature, 2022 Regular Session. (Wa. 2022). https://lawfilesext.leg.wa.gov/biennium/2021-22/Pdf/Bills/Session%20Laws/House/1799-S2.SL.pdf?q=20220526135441
3. Organic Material Management. SSHB 2301, 68th Legislature, 2024 Regular Session. (Wa. 2024). https://lawfilesext.leg.wa.gov/biennium/2023-24/Pdf/Bills/Session%20Laws/House/2301-S2.SL.pdf?q=20240408111253
4. U.S. Environmental Protection Agency. (1993). *Standards for the use or disposal of sewage sludge (40 CFR Part 503)*. Retrieved from https://www.epa.gov/sites/default/files/2020-02/documents/fr-2-19-1993-sewage-sludge.pdf
5. Washington State Department of Ecology. (1992). Chapter 70A.226 RCW. Municipal Sewage Sludge-Biosolids. https://app.leg.wa.gov/RCW/default.aspx?cite=70A.226
6. Washington State Department of Ecology. (2007). Chapter 173-308 WAC. Biosolids Management. https://apps.leg.wa.gov/wac/default.aspx?cite=173-308

APPENDIX A: Full Text of Cited Reference

Appendix A contains the full text of the following references:

Brown, S., Beecher, N., & Carpenter, A. (2010). Calculator Tool for Determining Greenhouse Gas Emissions for Biosolids Processing and End Use. Environmental Science and Technology, 44, 9509-9515, https://doi.org/10.1021/es101210k

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 concerns 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 varying 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 processing 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. Calculations were made and are reported on a per dry Mg biosolids produced. Individual unit processes and values for municipalities 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_2e/kWh	treatment processes	end use/disposal	GHG emissions Mg CO_2e/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_2O 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_2O release (*60*). The IPCC default factor for N_2O 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_2O 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_2e/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

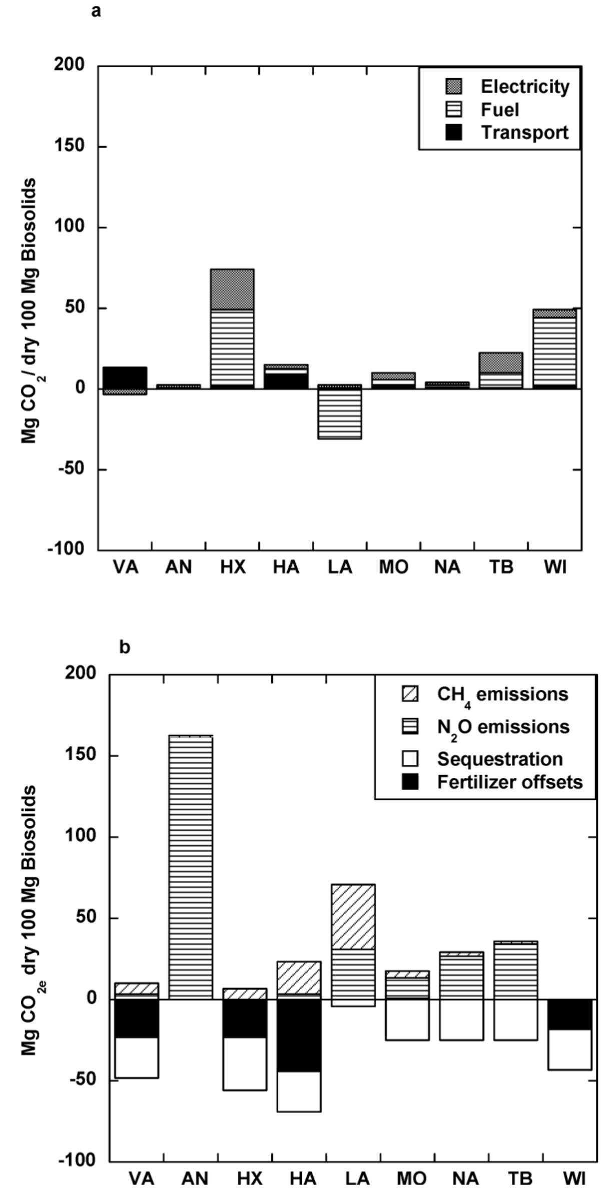

FIGURE 1. Greenhouse gas emissions or credits associated with (a) electricity, fuel and transport and (b) fugitive gas emissions, carbon sequestration, and fertilizer offsets for nine biosolids programs in Canada. Emissions include province-specific weighting factors for electricity.

(*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}).

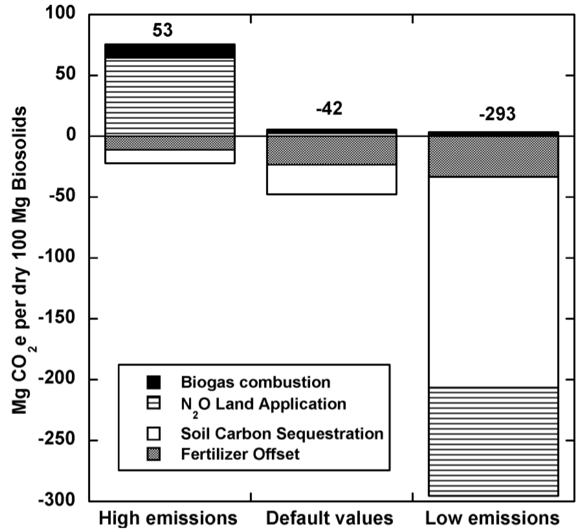

FIGURE 2. High, low, and default emissions factors for VA showing range of reported values for fertilizer offsets, soil carbon sequestration, CH_4 emissions from flaring biogas, and N_2O emissions following land application. Transport and electricity use are not included.

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_2e 100 Mg^{-1} biosolids (dry wt.)			
electricity	Mg CO_2e 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_2O 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_2e for electricity in both provinces are also similar at 20 and 10 g CO_2e 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_2e 100 Mg^{-1} biosolids (dry wt.)] in comparison to AN [0.2 Mg CO_2e 100 Mg^{-1} biosolids (dry wt.)]. VA derives a negative net GHG balance of −303 Mg CO_2e 100 Mg^{-1} biosolids (dry wt.) from anaerobic digestion with heat and electricity generation and −48 Mg CO_2e 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_2e 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_2e 100 Mg^{-1} biosolids (dry wt.). According to the model, increasing the combustion temperature to 880 °C effectively eliminated N_2O. 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_2O emissions. This resulted in emissions per dry 100 Mg biosolids decreasing from 144 to −4 Mg CO_2e. As a result of this study, the municipality has increased the burn temperature at its facility to minimize N_2O 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_2e, emissions of CH_4 and N_2O have the potential to negate benefits associated with biosolids use or disposal. Focusing solely on CO_2e 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_2O emissions). The factors with the greatest potential impact on net emissions include all sources of N_2O.

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_2O 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*).

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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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