

Protecting Our Water Environment



Metropolitan Water Reclamation District of Greater Chicago

***MONITORING AND RESEARCH
DEPARTMENT***

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***A GREENHOUSE GAS ACCOUNTING OF THE
METROPOLITAN WATER RECLAMATION DISTRICT
OF GREATER CHICAGO'S BIOSOLIDS END USES:
EVALUATION OF YEARS 2001 AND 2008***

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BIOSOLIDS END USES: EVALUATION OF YEARS 2001 AND 2008

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TABLE OF CONTENTS

	<u>Page</u>
LIST OF TABLES	iii
ABSTRACT	1
INTRODUCTION	2
Short-Term Carbon Cycle	2
Greenhouse Gas Emission	2
Nitrous Oxide	2
Methane	3
CO ₂ Emission	3
Carbon Credit Potential	3
MATERIALS AND METHODS	5
Biosolids and Uses	5
Dewatered Biosolids	5
Lagooned, Air-Dried Biosolids	5
Existing Greenhouse Gas Protocol	7
RESULTS AND DISCUSSION	9
Landfill Daily Cover	9
Landfill Final Cover	9
Farmland Application	9
Fertilizer Off-Sets	9
Nitrous Oxide	13
Methane	14
Soil Carbon	14

TABLE OF CONTENTS (Continued)

	<u>Page</u>
Mineland Reclamation	16
Urban Use	16
SUMMARY	19
REFERENCES	22

LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
1	Utilization of Metropolitan Water Reclamation District of Greater Chicago Biosolids in 2001 and 2008	6
2	Average Chemical and Physical Characteristics of Biosolids Generated at the Metropolitan Water Reclamation District of Greater Chicago	6
3	Balance Sheet Estimates of Greenhouse Gas Emissions for the Metropolitan Water Reclamation District of Greater Chicago's Disposal of Dewatered Biosolids in Landfill	10
4	Balance Sheet Estimates of Greenhouse Gas Emissions for the Metropolitan Water Reclamation District of Greater Chicago's Utilization of Air-Dried Biosolids as Landfill Final Cover	11
5	Balance Sheet Estimates of Greenhouse Gas Emissions for the Metropolitan Water Reclamation District of Greater Chicago's Utilization of Dewatered Biosolids as Farmland Fertilizer	12
6	Balance Sheet Estimates of Greenhouse Gas Emissions for the Metropolitan Water Reclamation District of Greater Chicago's Utilization of Air-Dried Biosolids for Mineland Reclamation in 2001	17
7	Balance Sheet Estimates of Greenhouse Gas Emissions for the Metropolitan Water Reclamation District of Greater Chicago's Utilization of Air-Dried Biosolids as Urban Turf Fertilizer	18
8	Greenhouse Gas Emissions for the Metropolitan Water Reclamation District of Greater Chicago's Biosolids Use Programs in 2001 and 2008	20
9	Summary of Greenhouse Gas Emissions for Each of the Metropolitan Water Reclamation District of Greater Chicago's Biosolids End Uses	21

ABSTRACT

Biosolids generated at the Metropolitan Water Reclamation District of Greater Chicago (District) include lagoon-aged, air-dried materials and centrifuge-dewatered biosolids. Air-dried biosolids are generally used as soil amendments and as fertilizer topdressing for establishment and maintenance of turf on recreational areas in the Chicago metropolitan area. The air-dried biosolids are also used for landfill final cover and have been used at the Fulton County land reclamation site. Dewatered biosolids are used mainly as fertilizer on farmland in nearby counties, and some are utilized as landfill daily cover. This report details estimates of the carbon (C) credits and debits for each of the District's end uses of biosolids for both 2001 and 2008. Debits are due to fossil fuel use and fugitive gas emissions, while credits arise from avoiding the use of fertilizer by biosolids and soil C sequestration. The utilization of dewatered biosolids in landfills showed a C debit due to the nitrous oxide (N₂O) and methane (CH₄) emissions. The beneficial use of biosolids as farmland and turf fertilizer and landfill final cover resulted in C credit primarily through biosolids as a replacement for fertilizer and C sequestration. The aging of biosolids is the major factor controlling the differences in credits among the beneficial use practices. Estimates presented herein show that, despite the higher consumption of fuel for transportation to farmland, the utilization of unaged, air-dried biosolids still leads to higher greenhouse gas (GHG) credits than the distribution of aged, air-dried biosolids in urban areas.

INTRODUCTION

Short-Term Carbon Cycle

Each year, approximately ten percent of the carbon dioxide (CO₂) stored in the atmosphere cycles through the terrestrial system. This C is assimilated by plants through photosynthesis, with a portion of this being consumed by animals and another fraction becoming part of soil organic matter. As this fixed C decomposes (either through aerobic respiration or anaerobic respiration), approximately the same quantity of CO₂ is released back into the atmosphere. This process is generally referred to as the short-term C cycle. As part of the short-term C cycle, releases of CO₂ from decomposition of C in biosolids is not counted in the GHG balances and are not considered in C accounting.

Biosolids management can, however, impact the C cycle when the decomposition of biosolids results in the release of gases other than CO₂. For example, if the nitrogen (N) in the biosolids is released to the atmosphere as N₂O rather than nitrogen gas (N₂), this decomposition process will count as a GHG debit. Another example of a GHG debit associated with biosolids management is the release of CH₄ when biosolids are allowed to decompose under anaerobic conditions.

Greenhouse Gas Emission

Nitrous Oxide. Nitrous oxide can be formed at two points in the N cycle. When organic N is mineralized and transformed from ammonia to nitrate (NO₃⁻), there is a potential for N₂O to be released as a by-product. Nitrous oxide can also be formed during denitrification, as NO₃⁻ is reduced to N₂. The latter reaction occurs under anoxic conditions and is generally considered to be the primary source of N₂O from soil systems or cases where organic materials are being used as a microbial energy source. Nitrogen is used in these reactions as an electron acceptor for mineralization of C. Both sufficient N and organic matter are required for these reactions to occur. For releases pertinent to biosolids, N₂O emissions have been documented from landfills, agricultural fields, and compost piles. It can also be formed chemically during combustion reactions. Incineration of biosolids has been shown to release significant quantities of N₂O to the atmosphere. As N₂O has 296 times the global warming potential of CO₂, releases of small amounts of this gas can have very large impacts on GHG accounting.

Research on N₂O emissions from each of these potential end uses for biosolids has provided a general understanding of conditions where N₂O release would be expected. In general, N₂O emissions from biological N transformations are increased in the presence of a readily available C source and conditions of low oxygen. Examples of this type of condition in an agricultural setting include poorly drained soils with high organic matter or compost piles that have a low C:N ratio and high moisture content. However, our understanding of factors controlling the formation of N₂O is limited enough that it is not possible to quantify precisely the potential release for each different biosolids end use scenario. For example, a single study of N₂O emissions

from landfills in Sweden where biosolids were used as final cover showed emissions ranging from -0.011 to 35.7 mg N₂O-N m⁻² h⁻¹, while emissions from landfills where mineral soils had been used ranged from -0.0017 to 1.07 mg N₂O-N m⁻² h⁻¹ (Börjesson and Svensson, 1997). Literature on the release of N₂O from composting operations shows a release ranging from below detection limits to 4.6 percent of initial N content (Fukumoto et al., 2003; Lopez-Real and Baptista, 1996). Two studies conducted on poorly drained grasslands in Scotland show the release of N₂O from biosolids ranging from 0.3 percent to 4.3 percent of total N (Ball et al., 2004; Jones et al., 2007). Data from a study of fluidized bed biosolids mono-combustion facilities in Japan showed N₂O emissions ranging from 1.52 to 6.4 kg N₂O Mg⁻¹ dry biosolids (Suzuki et al., 2003). The data on the N₂O release from these studies indicate that its emission is quite variable. Reducing the potential for N₂O release is critical to minimizing potential GHG debits associated with different biosolids end use options.

Methane. Methane is a by-product of respiration under anaerobic conditions. Carbon is used as the electron acceptor for reactions where C is also used as an energy source. Emissions of CH₄ from different biosolids end use options are much better understood than emissions of N₂O. The use of biosolids to replace fertilizers in agriculture has limited potential for CH₄ release as soils are generally well aerated. Emissions have been documented for composting operations with the bulk of emissions occurring during the initial period after pile construction. These emissions are easily controlled by adjusting the moisture in the pile as well as by covering the pile with finished compost (Brown et al., 2008; United States Environmental Protection Agency [USEPA], 2006). Methane is also released from landfills where biosolids are used as either daily or final cover. When biosolids are used as daily cover, they are usually applied as a thick layer of high-moisture material over compacted solid waste. The anaerobic conditions within this layer of biosolids supports an active microbial community that can decompose organic C and release CH₄.

CO₂ Emission. The utilization of biosolids involves the transportation of biosolids to site and spreading and incorporation to land. The combustion of fuel for those operations produces CO₂. Both urban/agricultural use and landfilling of biosolids can cause such CO₂ emissions, as transport is needed for both uses with additional requirements for spreading and/or incorporation for urban and agricultural use.

Carbon Credit Potential

Biosolids can have a positive impact on the C cycle when they are used as a replacement for N fertilizer in farmland or as the final cover in landfills to establish vegetation. The production of chemical fertilizers is a highly energy-intensive process. When organic sources of fertilizer are used as a substitute, there is a potential GHG credit for the averted emissions associated with fertilizer production. The potential credits associated with the use of biosolids are the increases in soil organic C. The use of organic soil amendments has been shown to increase soil C reserves. Increasing soil C reserves has the potential to be a low-cost means to sequester C.

Increased C in soils has also been associated with improved soil physical properties and increased plant productivity.

Credits associated with biosolids end use are highly dependent on many factors, which make them more difficult to estimate and are likely to vary based on site-specific conditions. These credits are generally significantly higher than debits associated with the transportation of biosolids, suggesting that despite a high level of uncertainty, it is important to estimate credits with different biosolids end use options. As more data becomes available, the level of uncertainty will be reduced.

In the evaluation presented in this report, the end uses for biosolids produced by the District in 2001 and 2008 are evaluated to provide a general GHG balance for the program. The basis for the estimates and a description of the uncertainties are provided. The values have been estimated using the most quantitative information available.

MATERIALS AND METHODS

Biosolids and Uses

Dewatered Biosolids. The District produces dewatered biosolids cake by anaerobic digestion followed by centrifuging. The mesophilic anaerobic digestion (>15 days, >95°F) significantly reduces volatile solids (VS) and pathogens (defined in 40 Code of Federal Regulations Part 503 Rule [USEPA, 1994]). The centrifuging, aided with the addition of polymers, increases the biosolids solids content to 20 – 30 percent. Approximately 5 kg of polymer is used to condition each Mg of dry solids in typical dewatering processes (Tchobanoglous et al., 2003). The dewatered biosolids were mainly used on farmland as fertilizer. Some of this product was used in landfill as daily cover or co-disposed with municipal solid waste.

Lagooned, Air-Dried Biosolids. The process used to produce air-dried biosolids at the District includes long-term storage (at least 18 months) of anaerobically digested liquid or centrifuge-dewatered biosolids in lagoons followed by air-drying (>60 percent solids) of the biosolids on large paved beds. Producing an air-dried material offers the biosolids program a wide range of benefits, including the development of a diverse, local customer base. The air-dried biosolids were used as a source of nutrients for turf grass in golf courses and athletic fields in the Chicago metropolitan area. The product is also used as landfill final cover for establishing vegetation. In 2001 some air-dried materials were hauled to Fulton County for land reclamation (Table 1).

The quantity and properties of biosolids utilized in 2001 and 2008 were summarized in Table 1 and Table 2, respectively.

From a GHG perspective, the air-dried product has two additional benefits: First, since the product is drier than the dewatered cake, the volume of biosolids to be transported is reduced. Second, the hauling distance is reduced because the dry product can be used locally, and the dewatered cake is used on farmland that is usually located at a greater distance than the local market. However, there are two factors that suggest that there may be additional debits associated with the production of air-dried materials. The lagooned biosolids are placed on paved beds for drying at a thickness of up to 18 inches, which can result in anaerobic conditions and the release of fugitive GHGs. The considerable loss of N that occurs during drying is most likely due to fugitive emissions. The dried product contains about two percent total N, about half that of the dewatered biosolids cake. For each metric ton of biosolids, a loss of 50 percent of the total N is roughly 20 kg N. If ten percent, or 2 kg, of that N volatilizes as N₂O, the carbon-equivalent debit is about 600 kg. The N₂O is elevated within the biosolids piles, though air sampling has not shown significant N₂O emissions (Bellucci et al., 2010). Nevertheless, debits associated with possible GHG emissions, along with biosolids air-drying, were not included in the report, as data were not available for conducting a calculation.

TABLE 1: UTILIZATION OF METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO BIOSOLIDS IN 2001 AND 2008

Biosolids Use	2001	2008
	-----Dry Tons-----	
Dewatered Biosolids		
Farmland Fertilizer	128,132	97,146
Landfill Daily Cover	35,733	26,451
Landfill Co-Disposal	12,698	1,968
Class A Air-Dried		
Urban Reclamation	3,095	20,048
Mineland Reclamation	22,000	NA
Landfill Final Cover	1,490	46,545
Total	203,148	192,158

NA = Not applicable; no biosolids applied.

TABLE 2: AVERAGE CHEMICAL AND PHYSICAL CHARACTERISTICS OF BIOSOLIDS GENERATED AT THE METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

	Class A Air-Dried		Dewatered	
	2001	2008	2001	2008
Total Solids (%)	70.2	71.3	25.9	25.3
Total Volatile Solids (%)	35.4	38.1	54.2	52.5
Total Kjeldahl N (%)	1.87	2.22	4.29	4.18
NH ₃ -N (%)	0.40	0.20	0.43	0.54
NO ₃ -N (%)	0.044	0.031	ND ²	0.007
Total P (%)	2.20	2.13	2.52	1.94
Bulk Density (dry g/cm ³) ¹	0.69	ND	0.30	ND

¹Source: Calculated from data in Simmons (2003).

²Not determined.

Existing Greenhouse Gas Protocol

Although the United States Environmental Protection Agency (USEPA) excluded agricultural practices from the GHG accounting in its initial rulemaking, other entities have started to quantify debits and credits associated with the management and use of organic materials. The Intergovernmental Panel on Climate Change (IPCC) has some default assumptions for emissions associated with biosolids use and disposal. These include N₂O emissions from the land application of biosolids and the combustion of biosolids. According to the IPCC, emissions of N₂O from the land application of biosolids are similar to the emissions from chemical fertilizers and composts (one percent of total N) (DeKlein et al., 2006). Default IPCC emissions from the combustion of biosolids are 900 g N₂O per metric ton of wet biosolids and 990 g N₂O per metric ton of dry biosolids (Sabin et al., 2006). With respect to agriculture, the IPCC refers to the use of biosolids and other organic sources of nutrients as a method to both increase soil C stores and offset the energy requirements for the production of chemical fertilizers (Smith et al., 2007). No default values are given for either potential offset, though there will likely be protocols for soil C sequestration and for fertilizer replacements in the near future. The N₂O emission from land-filled biosolids is limited to dewatered biosolids, and it was calculated as 1.5 percent of total N, which is the value used for composting (Brown et al., 2008).

The Chicago Climate Exchange (CCX), the Clean Development Mechanism (CDM) and the Climate Registry (Clean Development Mechanism, 2008; McComb, 2009) use a protocol (Equation 1) to estimate C credits for biosolids that are diverted from landfills to compost operations. The basis for the credits in the protocol is the CH₄ emissions that are avoided by removing materials with a high CH₄ generation potential to an outlet where they will decompose aerobically. Factors that contribute to the quantity of CH₄ that is released from landfilled biosolids include: the time period from when waste is deposited in a cell and active gas collection begins, the level of treatment of the biosolids, whether biosolids are mixed with other materials prior to being used as daily cover, and the nature of the material used. It is likely that the CH₄ generation potential of biosolids will vary based on the level of treatment the material has received prior to landfilling. Reduced VS following anaerobic digestion will reduce the total quantity of CH₄ that can be released from the landfilled material. Current United States (U.S.) regulations for sanitary landfills constructed after 1991, and containing a minimum quantity of waste, require that gas collection begins at two to five years after the waste is deposited in a cell (USEPA, 2006). The current USEPA's estimate of CH₄ oxidation rates by landfill cover soils is ten percent. The USEPA recognizes that certain types of cover materials, such as composts, are likely to oxidize a significantly higher portion of total CH₄ (USEPA, 2006). Recent studies suggest that this is the case and that the ten percent default value for oxidation may be overly conservative (Chanton et al., 2009; Scheutz et al., 2009).

As shown in Equation 1, a number of correction factors are included in the protocol that reduce the credits per ton of material diverted. These include the decay rate constant for the substrate that is adjusted in the CDM protocol for the climate at the landfill site and the CH₄ oxidation factor for gas at the landfill. These factors are included to assure that the credits granted under the protocol are sufficiently conservative. The potential for the protocol to accurately reflect GHG credits increases with the quantity of data available for developing the protocol. In developing the protocol, the available data were used to improve the accuracy of the protocol for

conditions in U.S. landfills (LeFebvre et al., 2000). The single decay rates for each substrate were used in the protocol assuming the climate is warm (mean annual temperature >20° C) and wet (ratio of the mean annual precipitation/potential evapotranspiration >1). Similar to N₂O, the CH₄ emission was considered to be zero when air-dried materials are used.

Equation 1. The equation calculating total carbon credits for the landfilling methane avoidance at both the CCX and the CDM.

$$BE_{CH_4,SWDS,y} = \phi \cdot (1 - f) \cdot GWP_{CH_4} \cdot (1 - OX) \cdot \frac{16}{12} \cdot F \cdot DOC_1 \cdot MCF \cdot \sum_{x=1}^y \sum_j W_{j,x} \cdot DOC_j \cdot e^{-k_j(y-x)} \cdot (1 - e^{-k_j})$$

Where:

$BE_{CH_4,SWDS,y}$ = Methane emissions avoided during the year y from diverting waste disposal from the solid waste disposal site (SWDS) during the period from the start of the project activity to the end of the year y (tCO₂e)

ϕ = Model correction factor to account for model uncertainties (0.9)

f = Fraction of methane captured at the SWDS and flared, combusted or used in another manner (zero for the first three years). An average gas-recovery efficiency is 75 percent based on the USEPA average (USEPA, The Climate Registry Local Government Protocol, 2008).

GWP_{CH_4} = Global Warming Potential (GWP) of methane, valid for the relevant commitment period (21)

OX = Oxidation factor (reflecting the amount of methane from SWDS that is oxidized in the soil or other material covering the waste (0.10)

F = Fraction of methane in the SWDS gas (volume fraction) (0.5)

DOC_1 = Fraction of degradable organic carbon (DOC) that can decompose

MCF = Methane correction factor (1)

$W_{j,x}$ = Amount of organic waste type j prevented from disposal in the SWDS in the year x (metric tonnes) (monitored)

DOC_j = Fraction of degradable organic carbon by weight in the waste type j

k_j = Decay rate for the waste type j

J = Waste type category (index)

X = Year during the crediting period: x runs from the first year of the first crediting period ($x = 1$) to the year y for which avoided emissions are calculated ($x = y$)

Y = Year for which methane emissions are calculated

Estimates of emission debits related to transport are calculated based on emissions per unit of energy produced by fossil fuel combustion and are used to determine the emissions associated with each practice. This approach has been used in GHG accounting for biosolids management (Rosso and Chau, 2009).

RESULTS AND DISCUSSION

Landfill Daily Cover

Landfilling of biosolids as daily cover results in significant GHG debits ([Table 3](#)). However, several steps could be used to reduce the total debit while still maintaining landfilling as an end use option. For example, mixing biosolids with clean fill or another mineral soil material prior to use as daily cover would significantly reduce the CH₄ and N₂O generation potential of the material. The goal with any mixture would be to make the daily cover aerobic, which could significantly reduce the potential for CH₄ and N₂O emissions.

Landfill Final Cover

The solids content of biosolids used for final cover in both 2001 and 2008 was about 70 percent ([Table 4](#)). The air-drying process resulted in a loss of 50 percent of the total N from the biosolids cake. The cover consisted solely of biosolids applied at a very high rate (30 cm depth) and directly seeded with grasses. For this estimate, this type of application is treated as a beneficial use with credits similar to agricultural applications. These include credits for the fertilizer content of the biosolids as well as for soil C sequestration. There are currently no debits taken for fugitive emissions. It should be noted that when biosolids are applied at this high rate, there is the potential for both CH₄ and N₂O emissions when biosolids become saturated with water. Gas measurements from the surface of the landfill at different times of the year, particularly after significant rainfalls, may be needed to verify that this approach is appropriate. Alternatively, biosolids can be mixed with a soil material (such as clean fill or dredged material) prior to use as a final cover to reduce the potential for saturated soil conditions and associated release of fugitive gases.

Emissions resulting from transportation to the landfill for air-dried materials are minimal. The average distance to landfill sites for the District is about 20 miles. Therefore, transport-related emissions for 2001 and 2008 were about one to two percent of credits associated with soil C credits from use of the biosolids.

Farmland Application

Fertilizer Off-Sets. A substantial portion of the District's biosolids are used in farmland application in which the biosolids serve as an alternative to chemical fertilizer primarily containing N, phosphorus (P), and potassium ([Table 5](#)). Based on the average hauling distance of 46 miles and fuel use at 17.4 L per truckload, transport and application debits for biosolids totaled approximately 14 Mg CO₂ per day for 2001 and 11 Mg CO₂ per day for 2008. Using the CO₂ equivalents for fertilizer production of 3.96 kg CO₂ per kg N and 2 kg CO₂ per kg P (Recycled Organics Unit, 2006), the daily credits associated with the use of biosolids in 2001 were 60 Mg CO₂ per day for N and 18 Mg CO₂ per day for P. In this calculation, the total N and P in

TABLE 3: BALANCE SHEET ESTIMATES OF GREENHOUSE GAS EMISSIONS FOR THE METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO'S DISPOSAL OF DEWATERED BIOSOLIDS IN LANDFILL¹

	2001	2008
Biosolids Characteristics		
Quantity going to landfill (Mg/day-wet)	512	307
Density (kg/m ³)	300	300
Solids content (%)	25.9	25.3
Quantity going to landfill (Mg/day-dry)	132.6	77.7
Have the biosolids been digested prior to disposal?	Yes	Yes
Total nitrogen (%-dry weight)	4.29	4.18
TVS (%-dry weight)	54.2	52.5
Organic carbon (%-dry weight)	31.4	30.5
Organic carbon (Mg/day-dry weight)	41.6	23.7
Methane correction factor for landfill	1	1
Quality of soil cover at landfill	No Cover	No Cover
Oxidation of methane by soil cover	0	0
Methane captured at landfill and combusted after three years	0.75	0.75
Percent of captured methane used to generate electricity	0	0
Fraction of degradable organic carbon (DOC) in biosolids	0.87	0.87
Decomposition loss of decomposable DOC in three years	0.57	0.57
Fuel Use		
Hauling and applying biosolids to land (L-diesel fuel/day)	698	419
CO ₂ emissions from diesel used (Mg/day)	1.94	1.16
Methane Emissions		
CH ₄ released from first three years after landfilling (Mg/day)	12.40	7.04
CH ₄ released after three years (Mg/day)	2.34	1.33
Fugitive CH ₄ from combusted CH ₄ (Mg/day)	0.021	0.012
CO ₂ emissions equivalents from released CH ₄ (Mg/day)	310	176
Nitrous Oxide Emissions		
N ₂ O emitted from landfilled biosolids (Mg/day)	0.134	0.077
CO ₂ emissions equivalents from released N ₂ O (Mg/day)	41.6	23.7
Residual Carbon		
Undecomposed carbon of landfilled biosolids (Mg CO ₂ /day)	-19.9	-11.3
CO₂-Equivalent Emissions (Mg/year)	121,801	69,176

¹Co-disposal and daily cover.

TABLE 4: BALANCE SHEET ESTIMATES OF GREENHOUSE GAS EMISSIONS FOR THE METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO'S UTILIZATION OF AIR-DRIED BIOSOLIDS AS LANDFILL FINAL COVER

	2001	2008
Biosolids Characteristics		
Quantity going to land application (Mg/day-wet)	6	179
Solids content (%)	70.2	71.3
Quantity going to land application (Mg/day-dry)	4.21	128
Density (kg/m ³)	690	690
Type of biosolids to be land applied	Digested	Digested
Total nitrogen (%-dry weight)	1.87	2.22
Total phosphorus (%-dry weight)	2.20	2.13
Volatile solids (%-dry weight)	35.4	38.1
Organic carbon (%-dry weight)	20.5	22.1
Biosolids CaCO ₃ equivalence (%-dry weight)	0	0
Average number of days biosolids is stored prior to land application	0	0
Will biosolids replace commercial fertilizer where it is applied?	Yes	Yes
Is lime in biosolids derived from a waste product (e.g. cement kiln dust)	NR ¹	NR
Will the lime in biosolids replace purchased lime where it is applied?	NR	NR
Fine-textured (% of land application area)	50	50
Coarse-textured (% of land application area)	50	50
Fuel Use		
Hauling and applying biosolids to land (L-diesel fuel/day)	8.0	244
CO ₂ emissions from diesel used (Mg/day)	0.030	0.677
Methane Emissions		
CH ₄ emitted from storage of biosolids prior to land application (Mg/day)	0	0
CO ₂ emissions equivalents from released CH ₄ (Mg/day)	0	0
Nitrous Oxide Emissions		
N ₂ O emitted from storage of biosolids prior to land application (Mg/day)	0	0
CO ₂ emissions equivalents from released N ₂ O (Mg/day)	0	0
Carbon Sequestration		
From biosolids residual C (Mg CO ₂ /day)	-0.635	-20.7
From soil C sequestration (Mg CO ₂ /day)	-0.738	-22.4
Fertilizer Off-Set Credits		
From nitrogen applied to soil (Mg CO ₂ /day)	-0.315	-11.3
From phosphorus applied to soil (Mg CO ₂ /day)	-0.185	-5.44
Calcium Carbonate Debit		
From CaCO ₃ applied to soil (Mg CO ₂ /day)	0	0
CO₂-Equivalent Emissions (Mg/year)	-675.5	-21,597

¹NR = not relevant.

TABLE 5: BALANCE SHEET ESTIMATES OF GREENHOUSE GAS EMISSIONS FOR THE METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO'S UTILIZATION OF DEWATERED BIOSOLIDS AS FARMLAND FERTILIZER

	2001	2008
Biosolids Characteristics		
Quantity going to land application (Mg/day-wet)	1,355	1,052
Solids content (%)	25.9	25.3
Quantity going to land application (Mg/day-dry)	351	266
Density (kg/m ³)	300	300
Type of biosolids to be land applied	Digested	Digested
Total nitrogen (%-dry weight)	4.29	4.18
Total phosphorus (%-dry weight)	2.52	1.94
Volatile solids (%-dry weight)	54.2	52.5
Organic carbon (%-dry weight)	31.4	30.5
Biosolids CaCO ₃ equivalence (%-dry weight)	0	0
Average number of days biosolids is stored prior to land application	25	25
Will biosolids replace commercial fertilizer where it is applied?	Yes	Yes
Is lime in biosolids derived from a waste product (e.g. cement kiln dust)	NR ¹	NR
Will the lime in biosolids replace purchased lime where it is applied?	NR	NR
Fine-textured (% of land application area)	50	50
Coarse-textured (% of land application area)	50	50
Fuel Use		
Hauling and applying biosolids to land (L-diesel fuel/day)	4,927	3,825
CO ₂ emissions from diesel used (Mg/day)	13.7	10.6
Methane Emissions		
CH ₄ emitted from storage of biosolids prior to land application (Mg/day)	0.266	0.202
CO ₂ emissions equivalents from released CH ₄ (Mg/day)	5.59	4.24
Nitrous Oxide Emissions		
N ₂ O emitted from storage of biosolids prior to land application (Mg/day)	0.0126	0.0095
CO ₂ emissions equivalents from released N ₂ O (Mg/day)	3.90	2.96
Carbon Sequestration		
From biosolids residual C (Mg CO ₂ /day)	-56.7	-41.6
From soil C sequestration (Mg CO ₂ /day)	-69.6	-52.8
Fertilizer Off-Set Credits		
From nitrogen applied to soil (Mg CO ₂ /day)	-60.2	-44.5
From phosphorus applied to soil (Mg CO ₂ /day)	-17.7	-10.3
Calcium Carbonate Debit		
From CaCO ₃ applied to soil (Mg CO ₂ /day)	0	0
CO₂-Equivalent Emissions (Mg/year)	-66,074	-47,975

¹NR = not relevant.

biosolids were used rather than the plant available forms, as the biosolids N and P left after the first year's cropping could still be used during the subsequent croppings. It is likely this calculation over-estimated the P fertilizer credit due to the lower P availability in biosolids as compared to chemical fertilizer.

Nitrous Oxide. Land application of biosolids may also be a source of N₂O emissions. One study suggested that between 31 and 59 percent of all GHG emissions associated with growing a corn crop in the Midwest U.S. resulted from N₂O emissions (Kim and Dale, 2008). As an organic source of N, biosolids are likely to have different N₂O release rates in comparison to chemical fertilizers. Although the accounting does not give credits or debits for N₂O emissions, the high level of uncertainty relating to N₂O emissions suggests that this is an area that deserves more attention. If the biosolids can be tailored to reduce N₂O emissions, there is a potential for additional GHG credits for fertilizer substitution. However, if the use of biosolids results in increased N₂O emissions, any credits associated with fertilizer displacement are likely to be negated.

The IPCC gives direct and indirect default emission factors for N₂O for fertilizer use. The default value of one percent of the total N emitted as N₂O is used for application of chemical fertilizer, compost, and municipal biosolids. A higher emissions factor (two percent) is used for cattle, pig, and chicken manures. The IPCC also encourages the use of manures as a means to reduce N₂O emissions from agricultural soil (Metz et al., 2001). Results from research have generally showed lower N₂O emissions from biosolids-amended soils in comparison to soils receiving chemical fertilizers (Scott et al., 2000).

The rate of N₂O emissions from a site also depends on site-specific characteristics. In a study conducted on a well-drained soil in Denmark, Peterson (1999) observed N₂O emissions across different fertilizer and manure treatments ranging from 0.14 to 0.64 percent of total N added (below the default IPCC value of one percent total N). On a poorly drained grassland site in Scotland, emissions from soils that had received high loading rates of biosolids (3,066 kg N/ha) were 4.3 ± 0.5 percent of total N in year one and 1.3 ± 0.2 percent of total N in year two with rainfall of 1,107 mm and 718 mm in years one and two, respectively (Jones et al., 2007). Rochette et al. (2008) measured N₂O emissions from a single site on soils of two different textures. Emissions in the clay soil ranged from 12 to 45 kg N₂O/ha over the three-year period of the study. Emissions in the loam soil ranged from 1.0 to 1.1 kg N₂O/ha over the same period. In general, if soils are aerated (soil is well drained or coarse-textured), there is a low potential for N₂O emissions.

Emissions will also vary based on rainfall and temperature. Levels of emissions tend to be higher in warmer months; however, emissions have also been measured from soils over the winter as well as after a thaw (Jones et al., 2007). In a field study in Scotland, emissions were highest in the summer following manure and biosolids application in June (Jones et al., 2007). Emissions increased after rainfall events and were also detected in the winter following heavy rains. Peterson (1999) observed the highest N₂O fluxes in fertilizer- and manure-amended soils in the spring when soils were saturated and crop growth was slow. Ball et al. (2004) noted fluxes after rainfall events. In this study, a range of biosolids products was compared to chemical N

and a cattle-manure slurry. Nitrous oxide release continued over a longer period in organic-amended soils, but total emissions were lower than those from plots that had received chemical N. These results suggest that N₂O fluxes are highest as the organic N in manures or biosolids is mineralized and is then available over time from denitrification in anaerobic soil microsites or after high rainfall when soil moisture is high.

In summary, poor drainage prevalent in fine-textured soil appears to be the primary factor that contributes to elevated N₂O release. Site-specific factors, including the percentage of time that soil moisture is greater than 60 percent, the clay content of the soil, and the relative position of a field (e.g., low lying areas) will all determine the extent of N₂O release (Grant et al., 2006). The research findings suggest that because denitrification occurs under anoxic or anaerobic conditions, restricting applications to coarser textured soils would reduce the potential for N₂O emissions. Wet conditions will also tend to increase N₂O emissions.

For the current accounting, as biosolids are applied to meet the agronomic rate for N and as the IPCC default values for biosolids and chemical fertilizer N are identical, no credits or debits were added to the balance. Research on N₂O emissions from biosolids versus urea applied at different times of the year to different soil types are encouraged so that emissions from biosolids-amended soils can be quantified and compared to sites receiving chemical N.

Methane. Methane is produced only under severely reducing conditions. As biosolids are typically only applied to aerobic soils, the potential for methane emissions from land application is minimal. Regulatory concerns about nutrient runoff from biosolids-amended sites restrict applications to well-aerated soils. Because of this, CH₄ release from the land application of biosolids is considered negligible. Previous work has shown minimal CH₄ release even in poorly drained soils (Ball et al., 2004). The scenario where CH₄ emissions from the land application of biosolids can most likely occur is during storage prior to application. If biosolids are stored on site for lengthy periods prior to land application, it is possible that CH₄ can be released. For this scenario, no debits were taken for CH₄ emissions. The District's general practice is to limit the duration of storage prior to application, which limits both N₂O and CH₄ emissions.

Soil Carbon. When biosolids are land applied, they add organic C to soils. Carbon stored in soils amounts to approximately 2,500 Pg C (petagram = 10¹⁵ g or 10⁹ Mg) in the top two meters of the soil surface (Lal, 2004). In contrast, the atmosphere contains 760 Pg of C and all living matter 560 Pg C. The release of C from soils from 1850 - 1998 is estimated to be 136 ± 55 Pg C as a result of land-use change, deforestation, and soil cultivation (IPCC, 2000). This statistic suggests that increasing soil C through the use of biosolids is a potential approach to sequester atmospheric C. There is a protocol in place at the CCX for credits associated with increased soil C as a result of conversion to no-till management practices. A recent study showed that when biosolids amendments are incorporated into a no-till management scheme, rates of C accumulation are significantly accelerated (Spargo et al., 2008).

Data from a mineland reclamation site in Fulton County that received long-term biosolids application for agricultural production show a net soil C sequestration in the surface soil of

approximately 0.23 Mg CO₂ per Mg biosolids (Tian et al., 2009). Other studies have also shown that the land application of biosolids increases the organic C of the soil (Pepper et al., 2008; Rufus Chaney, personal communication; Sally Brown, unpublished data). Increases in soil organic C ranged from 0.4 to 1.5 Mg CO₂ per dry Mg biosolids when the surface 30 cm of soil is taken into account (Sally Brown, unpublished data). These data are from mine sites ranging in age of post restoration from 2 to 28 years as well as agricultural sites with a history of biosolids application ranging from 2 to 16 years.

The soil C increase with biosolids application includes both the residual biosolids C and the soil C sequestration (Tian et al., 2009). The remaining biosolids C in soil depends on the amount and type of biosolids. Tian et al. (2009) developed an equation that can estimate the C remaining from the land application of anaerobically digested liquid, dewatered, and lagooned/air-dried biosolids for Fulton County, a land-reclamation site in Illinois.

$$y = [0.339 - (55 - V_S)/55]C_{BS}e^{-0.0205t} + \{1 - [0.339 - (55 - V_S)/55]\}C_{BS}e^{-0.000301t}$$

In which, y = remaining biosolids C, V_S = VS in biosolids, C_{BS} = C input from biosolids application, t = time (day). The V_S in biosolids can vary from 36.4 percent (lagooned/air-dried, most stable) to 55 percent (digester draw-off, least stable).

Subsequently, Tian et al. (unpublished) extended the model from a double to a triple exponential decay equation as follows:

$$y = [0.35 - (55 - V_S)/55]C_{BS}e^{-0.0222t} + [0.52 + 0.8(55 - V_S)/55]C_{BS}e^{-0.000381t} + [0.13 + 0.2(55 - V_S)/55]C_{BS}e^{-0.0000448t}$$

In developing the equation, it is assumed that the decomposition of slow and recalcitrant fractions begins only after the labile fraction is completely decomposed. Thus, with decomposition, there is a relative increase in slow and recalcitrant fractions due to the loss of labile fractions, which can be measured as $(55 - V_S)/55$. Since the liquid biosolids from which dewatered and air-dried product are derived have a ratio of 0.52/0.13 or 4/1 for slow/recalcitrant fraction, the increase of $(55 - V_S)/55$ can be partitioned into a slow and recalcitrant fraction by 80 and 20 percent, respectively.

The predictions of biosolids C remaining in Fulton County soils showed a negligible difference between the two models within ten years of biosolids application. However, for the time frame of decades, the triple-decay model tends to predict more biosolids C remaining than the double-decay model. The triple exponential decay model yields a recalcitrant fraction of biosolids C in soil with $t_{1/2}$ of 61 years, which can be considered as the ultimate remaining (stable) C. For the District's anaerobically digested biosolids with V_S that are 55 percent in liquid, 52.5 percent in dewatered cake and 35.75 percent for air-dried, the stable fraction is, therefore, 0.13, 0.14, and 0.20 for liquid, cake, and air-dried, respectively.

Using the long-term study data generated from the District's Fulton County land-reclamation site in western Illinois, Tian et al. (unpublished) established the rate of soil C sequestration by biosolids application for the GHG accounting. The rates for dewatered biosolids are as

follows: 0.310 Mg CO₂ per Mg dry biosolids in mineland reclamation, 0.198 Mg CO₂ per Mg dry biosolids in unmined land; for air-dried biosolids: 0.187 Mg CO₂ per Mg dry biosolids in mineland reclamation, and 0.175 Mg CO₂ per Mg dry biosolids in unmined land.

The data show a credit of 126 Mg CO₂ per day in 2001 and 94.4 Mg CO₂ per day in 2008 from soil C sequestration (Table 5). This amount is in excess of the total credit for fertilizer offsets (77.9 Mg CO₂ per day in 2001 and 54.8 Mg CO₂ per day in 2008) and also far exceeds the debit associated with transportation and application of the biosolids (13.7 Mg CO₂ per day in 2001 and 10.6 Mg CO₂ per day in 2008).

Based on the results from soil sampling across Washington State, it is likely that this credit can be increased with a better understanding of the types of soils and application rates that maximize soil C gains in relation to biosolids loading rates. It is also likely that the C storage reported in Tian et al. (2009) underestimates actual storage as only the surface soils were considered.

Mineland Reclamation

In 2001, the District used a significant portion of its biosolids for mineland reclamation (Table 6). There is a potential for mineland reclamation to result in a somewhat different C balance than agricultural end uses. However, at this point, the level of sophistication in knowledge on fugitive emissions, carbon storage, and fertilizer use efficiency in mineland projects in comparison to agricultural end uses is such that default values for agricultural applications were applied to calculate values for mineland application. Historically, the District applied very high rates of biosolids annually for restoration. These high application rates may have resulted in fugitive emissions of N₂O and potentially CH₄. In a laboratory study in which biosolids were added to soils to mimic high rates used for mineland application, Stuczynski and McCarty (2007) observed N₂O release equivalent to 0.2 percent of total N. This rate is below the IPCC one percent default emissions rate, and therefore, no debits are used in this estimate.

Urban Use

The District's Class A air-dried material has been successfully distributed to a range of uses, including golf course establishment and fertilization, sports fields, and landscaping (Table 7). The Class A material offers a wide range of benefits both for the end users as well as for the District. These benefits include reduced transportation costs, reduced landscaping costs, and the opportunity to develop a diverse market base. The benefits associated with urban uses of the air-dried biosolids are most likely similar to the benefits associated with agricultural applications. Transportation debits will be lower due to both a shorter hauling distance (16 miles) and the higher solids content of the air-dried product. The GHG balance analysis also shows this practice clearly contributed to the reduction of GHG emissions (Table 7).

TABLE 6: BALANCE SHEET ESTIMATES OF GREENHOUSE GAS EMISSIONS FOR THE METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO'S UTILIZATION OF AIR-DRIED BIOSOLIDS FOR MINELAND RECLAMATION IN 2001¹

	2001
Biosolids Characteristics	
Quantity going to land application (Mg/day-wet)	86
Solids content (%)	70.2
Quantity going to land application (Mg/day-dry)	60.4
Density (kg/m ³)	690
Type of biosolids to be land applied	Digested
Total nitrogen (%-dry weight)	1.87
Total phosphorus (%-dry weight)	2.20
Volatile solids (%-dry weight)	35.4
Organic carbon (%-dry weight)	20.5
Biosolids CaCO ₃ equivalence (%-dry weight)	0
Average number of days biosolids is stored prior to land application	0
Will biosolids replace commercial fertilizer where it is applied?	Yes
Is lime in biosolids derived from a waste product (e.g. cement kiln dust)	NR ²
Will the lime in biosolids replace purchased lime where it is applied?	NR
Fine-textured (% of land application area)	50
Coarse-textured (% of land application area)	50
Fuel Use	
Hauling and applying biosolids to land (L-diesel fuel/day) ³	68
CO ₂ emissions from diesel used (Mg/day)	0.190
Methane Emissions	
CH ₄ emitted from storage of biosolids prior to land application (Mg/day)	0
CO ₂ emissions equivalents from released CH ₄ (Mg/day)	0
Nitrous Oxide Emissions	
N ₂ O emitted from storage of biosolids prior to land application (Mg/day)	0
CO ₂ emissions equivalents from released N ₂ O (Mg/day)	0
Carbon Sequestration	
From biosolids residual C (Mg CO ₂ /day)	-9.10
From soil C sequestration (Mg CO ₂ /day)	-10.6
Fertilizer Off-Set Credits	
From nitrogen applied to soil (Mg CO ₂ /day)	-4.52
From phosphorus applied to soil (Mg CO ₂ /day)	-2.66
Calcium Carbonate Debit	
From CaCO ₃ applied to soil (Mg CO ₂ /day)	0
CO₂-Equivalent Emissions (Mg/year)	-9,733

¹No biosolids were utilized in mineland reclamation in 2008.

²NR = not relevant.

³Transport to Fulton County mineland reclamation site is not included.

TABLE 7: BALANCE SHEET ESTIMATES OF GREENHOUSE GAS EMISSIONS FOR THE METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO'S UTILIZATION OF AIR-DRIED BIOSOLIDS AS URBAN TURF FERTILIZER

	2001	2008
Biosolids Characteristics		
Quantity going to land application (Mg/day-wet)	12	77
Solids content (%)	70.2	71.3
Quantity going to land application (Mg/day-dry)	8.42	54.9
Density (kg/m ³)	690	690
Type of biosolids to be land applied	Digested	Digested
Total nitrogen (%-dry weight)	1.87	2.22
Total phosphorus (%-dry weight)	2.20	2.13
Volatile solids (%-dry weight)	35.4	38.1
Organic carbon (%-dry weight)	20.5	22.1
Biosolids CaCO ₃ equivalence (%-dry weight)	0	0
Average number of days biosolids is stored prior to land application	0	0
Will biosolids replace commercial fertilizer where it is applied?	Yes	Yes
Is lime in biosolids derived from a waste product (e.g. cement kiln dust)	NR ¹	NR
Will the lime in biosolids replace purchased lime where it is applied?	NR	NR
Fine-textured (% of land application area)	50	50
Coarse-textured (% of land application area)	50	50
Fuel Use		
Hauling and applying biosolids to land (L-diesel fuel/day)	21.8	140
CO ₂ emissions from diesel used (Mg/day)	0.060	0.388
Methane Emissions		
CH ₄ emitted from storage of biosolids prior to land application (Mg/day)	0	0
CO ₂ emissions equivalents from released CH ₄ (Mg/day)	0	0
Nitrous Oxide Emissions		
N ₂ O emitted from storage of biosolids prior to land application (Mg/day)	0	0
CO ₂ emissions equivalents from released N ₂ O (Mg/day)	0	0
Carbon Sequestration		
From biosolids residual C (Mg CO ₂ /day)	-1.27	-8.91
From soil C sequestration (Mg CO ₂ /day)	-1.48	-9.62
Fertilizer Off-Set Credits		
From nitrogen applied to soil (Mg CO ₂ /day)	-0.63	-4.88
From phosphorus applied to soil (Mg CO ₂ /day)	-0.37	-2.34
Calcium Carbonate Debit		
From CaCO ₃ applied to soil (Mg CO ₂ /day)	0	0
CO₂-Equivalent Emissions (Mg/year)	-1,346	-9,255

¹NR = not relevant.

SUMMARY

GHG emissions (Mg CO₂) for the biosolids program for 2001 and 2008 (positive values represent emissions and negative values represent potential credits) are shown in [Table 8](#). The data in [Table 8](#) clearly show that the use of biosolids for landfill daily cover or landfill disposal is the largest GHG emitter among all end use options. All other end use options provide potential GHG credits. These credits are provided through soil C sequestration and fertilizer offsets. There are no deductions taken for fugitive gas release for options other than landfill disposal. As discussed previously, there is a range of uncertainty in this estimate. For example, soil C sequestration estimation based on data from Tian et al. (2009) is fairly conservative. In addition, it is likely that the frequency and rate of application for maximum soil C sequestration has not been identified. Additional research in this area would potentially show a higher estimate for carbon credits.

The greatest uncertainties in this estimate are associated with the potential for fugitive emissions from the drying process for air-dried biosolids as well as for the use of these materials at a high loading rate for landfill final cover. Drying thick layers of biosolids has the potential to release both N₂O and CH₄. Monitoring the drying beds for release of these gases will improve the estimate of the contribution of those gas emissions to GHG accounting.

This evaluation shows that landfilling is the practice that results in the most significant debit, and among the other practices, the credits are relatively similar ([Table 9](#)). The aging of biosolids is the major factor that results in different credits for all beneficial use practices. Transportation is significantly lower for air-dried materials used in the urban areas. Despite the large quantity of fuel required for transportation to farmland, the credits associated with centrifuge-dewatered biosolids application are still higher than distribution of air-dried biosolids in urban areas. Transportation emissions, though commonly perceived as a major GHG debit, are of little significance compared to credits associated with the replacement of fertilizer and the soil C sequestration in the utilization of biosolids.

TABLE 8: GREENHOUSE GAS EMISSIONS FOR THE METROPOLITAN
WATER RECLAMATION DISTRICT OF GREATER CHICAGO'S
BIOSOLIDS USE PROGRAMS IN 2001 AND 2008

		2001	2008
		-----Mg CO ₂ equivalent/day-----	
Landfill Disposal	Transport/application	1.94	1.16
	Fugitive emissions	352	200
	Carbon credit	-19.9	-11.3
	Fertilizer offset	0	0
	Total emissions	334	190
Landfill Final Cover	Transport/application	0.023	0.677
	Fugitive emissions	0	0
	Carbon credit	-1.37	-43.1
	Fertilizer offset	-0.500	-16.7
	Total emissions	-1.85	-59.1
Farmland	Transport/application	13.7	10.6
	Fugitive emissions	9.49	7.20
	Carbon credit	-126	-94.4
	Fertilizer offset	-77.9	-54.8
	Total emissions	-181	-131
Mineland Reclamation	Transport/application ¹	0.19	0
	Fugitive emissions	0	0
	Carbon credit	-19.7	0
	Fertilizer offset	-7.18	0
	Total emissions	-26.7	0
Urban Turf Fertilizer	Transport/application	0.060	0.388
	Fugitive emissions	0	0
	Carbon credit	-2.75	-18.5
	Fertilizer offset	-1.00	-7.22
	Total emissions	-3.69	-25.3
Program Total		117	-29

¹Transport to Fulton County mineland reclamation site is not included.

TABLE 9: SUMMARY OF GREENHOUSE GAS EMISSION FOR EACH
 OF THE METROPOLITAN WATER RECLAMATION DISTRICT
 OF GREATER CHICAGO'S BIOSOLIDS END USES

Biosolids End Use	Emission Rate (Mg CO ₂ equivalent/Mg dry biosolids)		
	2001	2008	Mean
Landfill Disposal (dewatered biosolids)	2.52	2.44	2.48
Landfill Final Cover (air-dried biosolids)	-0.44	-0.46	-0.45
Farmland (dewatered biosolids)	-0.52	-0.49	-0.52
Mineland Reclamation (air-dried biosolids)	-0.44	NA	-0.44
Urban Turf (air-dried biosolids)	-0.44	-0.46	-0.45

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