LAYING THE GROUNDWORK FOR CARBON ACCOUNTING FOR LAND-APPLIED METRO VANCOUVER BIOSOLIDS

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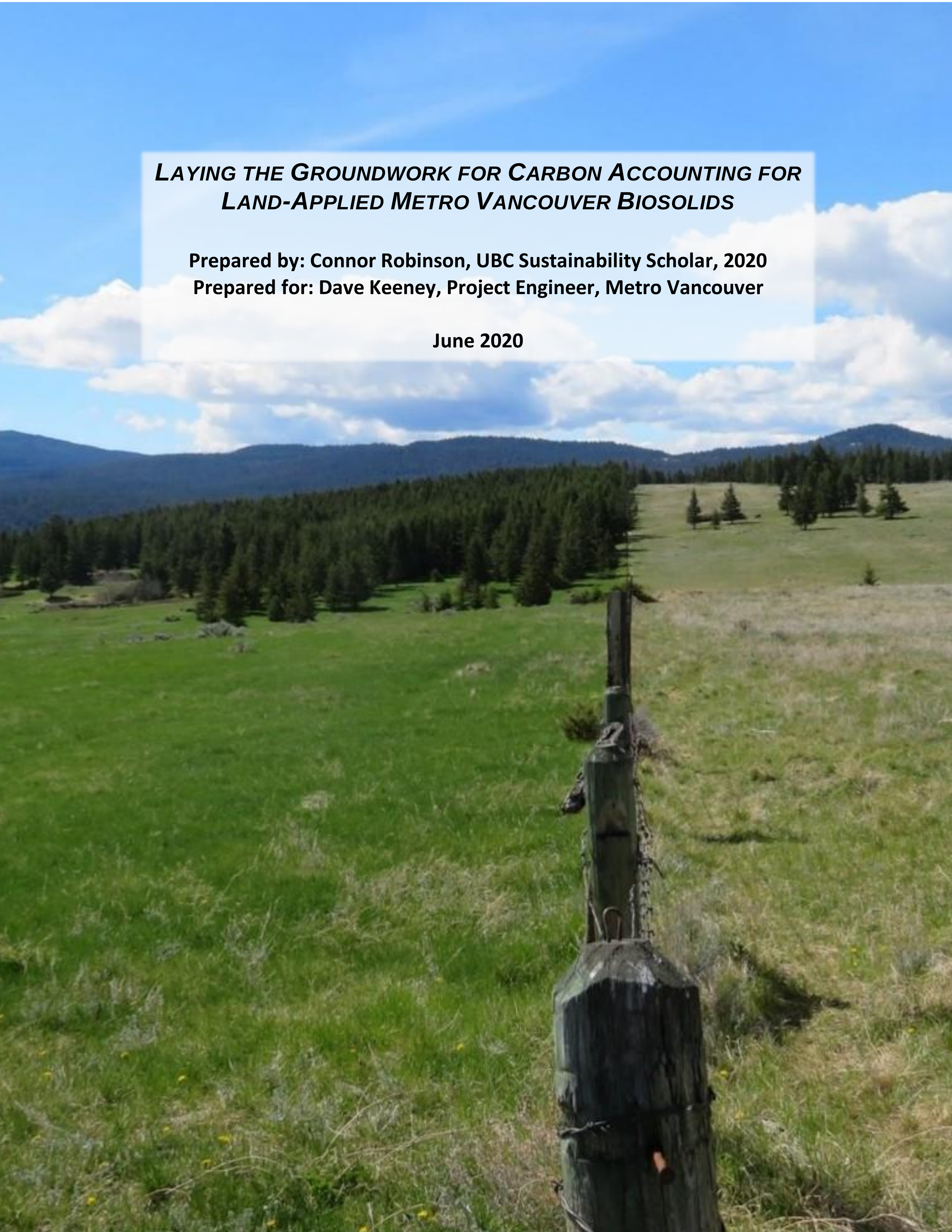

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Cover photo: A biosolids fertilized (left) versus non-fertilized (right) pasture

Courtesy of Northwest Biosolids: https://nwbiosolids.org/sites/default/files/inline-images/Picture1.jpg

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List of Acronyms

BEAM	Biosolids Emissions Assessment Model
C-seq	carbon sequestration
CAT	carbon accounting tool
CH_4	methane
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalents
DSF	Default Sequestration Factor
GHG	greenhouse gas
GWP	Global Warming Potential
KC	King County
MV	Metro Vancouver
N_2O	nitrous oxide
OM	organic matter
OMRR	Organic Matter Recycling Regulation
PCT	Pacific Carbon Trust
S&E	sequestration and emissions
SOC	soil organic carbon
SOM	soil organic matter
SYLVIS	SYLVIS Environmental

EXECUTIVE SUMMARY

Metro Vancouver (MV) intends to hire a specialized consultant to create a customized carbon accounting tool (CAT) for its biosolids land application program. A good deal of work was done in this regard in the early 2010's, and because some time has passed since then it was suggested that a review of the historical work be completed, industry practices examined, and a Scope of Work created for a future Request for Proposals to include and for the consultant to reference as they proceed with their work.

The purposes of this study were to:

- Examine the historical work done for MV on greenhouse gas (GHG) sequestration and emissions (S&E) due to land-applied biosolids and comment on the technical defensibility of the work as well as identify any gaps that remain (Section 2);
- Interview and gather information from industry professionals on common practices for GHG S&E quantification due to biosolids land application (Section 3);
- Create a list of considerations for future work regarding the development of a customized CAT for MV's biosolids land application program (Section 4); and
- Create a draft Scope of Work for a Request for Proposals regarding this MV-specific CAT (Appendix A).

In 2012 and 2013, SYLVIS Environmental (SYLVIS) published three reports for MV which highlighted carbon sequestration (C-seq) potential of various biosolids applications, explored various carbon offset protocols, and provided guidance on carbon tracking in biosolids management.

In their May 2012 report, SYLVIS estimated the quantity of carbon sequestered from the atmosphere in the soil and in plant biomass for various biosolids application types. In that report, SYLVIS also identified some information gaps that could hinder accurate estimation of the GHG S&E benefits of a given project. To address these gaps, SYLVIS highlighted the need for implementing pre-application sampling and measurement, as well as maintaining regular long-term monitoring of these sites.

In their two March 2013 reports, SYLVIS examined the practical aspects of how carbon tracking could take place, investigated four carbon offset protocols used at the time, made recommendations for future monitoring at biosolids land application sites, and outlined what the development of an offset protocol specific to biosolids management might look like.

In the 2013 report on carbon tracking, SYLVIS aimed to fill some of the gaps identified in their 2012 study by:

- Identifying land-based carbon pools influenced by biosolids application;
- Reviewing techniques for measuring carbon storage in ecosystems representative of those land uses;
- Surveying carbon offset protocols involving the studied land use types (or similar ones); and
- Recommending site monitoring strategies that would identify key carbon pools and measurement techniques, maximize useful data return while minimizing costs, and streamline data interpretation.

In the 2013 report on offset protocols, SYLVIS aimed to fill gaps regarding carbon credit/offset trading protocols, as MV was then seeking new ways to reduce its operational carbon footprint, and biosolids application was identified as a good candidate for such efforts. The focus of this 2013 study by SYLVIS was:

- Examining carbon offset or trading schemes that could be applicable (in terms of their structure and design) to MV's biosolids program;
- Discussing how readily these schemes might develop offset or trading schemes that are relevant to MV's biosolids program; and

- Looking into the process and costs that would be associated with creating a new offset protocol specific to MV's biosolids program.

The first interview performed as part of the present report was with representatives from King County's (KC) biosolids group. King County is a leader in biosolids management in the Pacific Northwest, with its biosolids program having been run for nearly 50 years and biosolids carbon credits accounting for over one-fifth of the Department of Natural Resources and Parks's total annual carbon credits. This interview shed light on:

- Considerations for KC's carbon accounting in agricultural and forestry applications, as well as compost use;
- Factors that influence KC's confidence in their carbon accounting, and issues in defining carbon accounting boundaries;
- The importance to KC of public perception and messaging for specific stakeholder groups; and
- Reasoning for KC excluding N_2O emissions from carbon accounting considerations.

The second interview performed as part of the present report was with Dr. Sally Brown, a renowned academic who has been working with biosolids for decades and has collaborated with many municipalities in the Pacific Northwest and other areas of North America on biosolids carbon accounting projects. This interview highlighted:

- Key adjustments that would need to be made to the Biosolids Emissions Assessment Model in order to create a CAT specific to a jurisdiction's biosolids land application program, related to:
    - Default sequestration factors (DSFs);
    - Emissions from transport and application; and
    - N_2O emissions from the soil;
- Difficulties in accounting for other less influential, but tangible benefits of biosolids application on carbon accounting, such as improved tillage or water holding capacity of the soil; and
- Other considerations that can potentially be useful in accounting for overall benefits of biosolids land application, such as ecosystem services.

The information presented in the historical work and the insights gained from the interviews were then synthesized to create a scope of work for building a customized CAT for MV's biosolids land application projects.

Overall, this report highlighted the importance of:

- Estimating specific DSFs for each application site;
- Adopting N_2O emissions factors from similar contexts due to the impracticality of monitoring N_2O fluxes;
- Estimating GHG emissions from biosolids stockpiles, ideally based on field study but likely based on assuming values from the literature;
- Gathering and using accurate data regarding diesel fuel usage for transportation and application;
- Estimating carbon stored in the biomass (where appropriate);
- Gathering and using accurate data on biosolids characteristics, including % carbon, %OM, and bulk density;
- Adopting fertilizer replacement values that are specific to the fertilizer that is replaced in a specific context (where appropriate); and
- Conducting pre-project and periodical post-application site monitoring (for soil and, in some cases, biomass) in order to estimate the project-associated C-seq benefits.

1 INTRODUCTION

In the late 2000's and early 2010's, Metro Vancouver (MV) became interested in generating carbon offsets by mitigating greenhouse gas (GHG) emissions or improving GHG sequestration. In an effort to better understand the opportunities and barriers and potential contributions of its biosolids management activities on carbon sequestration and emissions (S&E), MV put out a handful of Request for Proposals to consultants. SYLVIS Environmental (SYLVIS) was retained for three projects which involved web research, literature studies, and interviews, while Environnement Illimité was retained for a field study of GHG emissions from one of MV's wastewater treatment plants (Iona Island). These four projects were completed from 2011 to 2013.

Metro Vancouver intends to retain a specialized consultant to create a custom carbon accounting tool (CAT) that is specific to MV's biosolids land application program. With this objective in mind, it is useful to look back at and summarize the historical work and comment on its technical defensibility (section 2). Several jurisdictions and professionals are working on carbon S&E with respect to biosolids land application, so it is also useful to perform interviews to gain insight on how carbon accounting could be done in MV's context (section 3). After summarizing the historical work and interviewing industry professionals, a list of key considerations for future work can be developed (section 4). These considerations can then be used to draft a potential Scope of Work that can be used when engaging specialized consultants in a future Request for Proposals for a MV-specific CAT (Appendix A).

2 SUMMARY OF HISTORICAL WORK AND GAP IDENTIFICATION

This section presents a summary of the historical work done for MV regarding carbon accounting for biosolids land application, and identifies gaps that remain with respect to the development of a complete understanding of carbon accounting for MV's current and potential future biosolids land application options.

2.1 HISTORICAL WORK

2.1.1 CARBON SEQUESTRATION FOR DIFFERENT LAND USE TYPES (SYLVIS, 2012)

In this 2012 study by SYLVIS, the approach taken was to review the scientific literature and best available data on soil and biomass changes with biosolids application, and review MV data and reports to identify sites for follow-up sampling. Default sequestration factors[1] (DSF) were determined based on the available data in the academic literature from similar land use contexts to those in which MV applied its biosolids. Then, follow-up sampling at the selected sites was performed to measure soil and biomass carbon storage. Last, the review and field sampling were reconciled to corroborate the measurement-based carbon storage estimates and DSFs from the literature and adjust the DSFs based on the field data.

2.1.1.1 LITERATURE REVIEW

For the literature review component of this study, SYLVIS surveyed dozens of references, in some cases spanning 25 years, for each land use type. SYLVIS was selective in terms of which specific references they used to gather C-seq values to determine DSFs, and in general provided a justification for why they chose to incorporate data from its references. In determining DSFs based on the literature, SYLVIS adopted a conservative approach, often opting for an estimate on the lower end of what the literature suggested. This was a 'safe' approach, but also led to the DSFs being drastically different than what was found based on the field measurements later in the study.

Based on field measurements taken at five different sites including mine reclamation, hayfield fertilization, landfill cap reclamation, and forest fertilization, SYLVIS estimated the difference in carbon storage in the soil and biomass relative to control areas which had no biosolids application. Landscape-scale carbon storage is dependent on a variety of local use and land quality factors and varies both between and within different land-use types. Thus, defining precise and context-specific C-seq factors is somewhat speculative and prone to inaccuracy.

[1] DSFs are quantities of CO_2-eq sequestered for each unit (usually a dry tonne) of biosolids applied to a given land use type. They are based on academic literature or field trials of biosolids application for that land use.

After combining the DSFs and field measurements, SYLVIS identified forestry as the most promising candidate for C-seq as it showed greatest carbon storage increases in the litter layer, soil in the 0-15 cm depth range, and biomass. However, mine closure also showed substantial C-seq in the surface (0-15 cm) soil layer, with a potential minor contribution from herbaceous cover and deeper (15-30 cm) soil. Overall, this study demonstrates positive C-seq for most biosolids application contexts.

To address the information gaps identified in this study, SYLVIS discussed some key next steps. These include:

- Implementing pre-application sampling and measurement (measuring % carbon, % organic matter (OM), and apparent bulk density); and
- Maintaining regular, long-term post-application monitoring for these projects.

Field-based measurement and monitoring is critical for accurately estimating the C-seq potential of any biosolids application project type.

2.1.1.2 SURVEYING CARBON POOLS: COMMONLY USED METHODS

In this study of C-seq due to biosolids land application, SYLVIS surveyed some of the most often used measurement techniques in the context of forestry, rangelands, mine sites, and silviculture. The methods relevant to MV's current biosolids program are summarized below, and the reader is referred to the SYLVIS report for additional details for the other end-use categories.

The most common methods in rangelands include:

- Direct estimation of soil organic matter (SOM) by soil sampling; and
- Computer modeling to assess the effect of biosolids application on C-seq.

At reclaimed mine sites, in general the measurement techniques include:

- Comparing between treatments within the study area or comparing to a nearby 'control' area;
- Soil monitoring in the upper 0-15 cm;
- Taking soil cores and grab samples at various depths to determine bulk density and % carbon; and
- Dry combustion to determine % carbon. It is often necessary to carefully examine and quantify or eliminate extant soil organic carbon (SOC) contaminants prior to dry combustion analysis.

2.1.2 GUIDANCE FOR CARBON TRACKING (SYLVIS, 2013A)

In this 2013 report by SYLVIS, the approach was to review the literature on carbon tracking, with respect to surveying carbon pools and relevant offset protocols, and providing recommendations for monitoring.

2.1.2.1 SURVEYING CARBON POOLS

In the literature review component of this report, for each of the land use types SYLVIS identifies relevant carbon pools, explains why certain pools may or may not be included for a given land use type, and describes the most widely practiced and best available direct and indirect measurement methods. In most cases, SYLVIS also outlines some of the strengths and weaknesses of the presented measurement techniques.

Taking an inventory of land-based carbon stocks generally involves measuring carbon storage in the soil and biomass, especially where long-lasting biomass such as trees are present. Most measurement methods rely on dry combustion analysis to estimate % carbon, and soil % carbon is usually measured based on multiple samples at various depth intervals. With regard to forestry, several carbon measurement methods use field measurements of biomass (e.g., height, diameter at breast height) and use those values to estimate carbon in biomass over the whole study area, by way of computer modeling or the use of commonly accepted allometric[2] equations. Soil carbon stocks tend to change at a slower rate than aboveground carbon stocks, so at long-lived timber stands the focus of measurement tends to be on aboveground parameters.

2.1.2.2 OFFSET PROTOCOLS

Four offset protocols are discussed: the Pacific Carbon Trust (PCT), Kyoto Protocol's Clean Development Mechanism, Alberta's Emissions Offset Registry, and California Air Resources Board. These protocols describe procedures for estimating the baseline and project C-seq that can be used to claim carbon offset credits. The baseline is often projected into the future and estimated based on computer models or by using certain equations; in some cases, control plots need to be established. Project C-seq is usually estimated based on limited field sampling across several years and approximated using mathematical assumptions or predictive models; some protocols exclude soil sampling due to the relatively slow rate of change in C-seq in some land uses.

2.1.2.3 RECOMMENDATIONS FOR MONITORING

The report is concluded with a synthesis of the above findings into a series of recommendations for future site monitoring for: establishing pre- and post-project inventories and projections; and for monitoring the biosolids, soil, biomass, and other carbon pools. SYLVIS recommends several methods and standards for monitoring carbon in the context of biosolids land application, and these are described below. For silviculture applications, SYLVIS provides carbon measurement recommendations, but as this is not a current focus for MV's biosolids land application program, the reader is referred to the SYLVIS report for those details.

- Carbon pools should be inventoried before application and the site should be periodically monitored after application, so that the baseline estimation is more accurate and can be periodically re-calibrated.
- As much as possible, all collected soil, biomass, and biosolids samples should be submitted for dry combustion to determine % carbon. If dry combustion is not an option, basic assumptions about carbon content (ideally, based on the literature) can be used to estimate % carbon.
- Carbon storage in aboveground biomass can rely on allometric equations, while belowground biomass can be approximated using an assumed ratio of aboveground to belowground biomass. In any case, tree stocking density is needed.

Periodic monitoring can allow for a more accurate comparison of project-related impacts relative to the baseline. The most important element of a strong biosolids carbon tracking program is the utilization of a standardized monitoring and analysis paradigm, which should be established for all biosolids application activities and include pre- and post-application measurement and monitoring.

2.1.2.4 MONITORING CARBON IN THE BIOSOLIDS, SOIL, AND BIOMASS

2.1.2.4.1 BIOSOLIDS CARBON

Having a good understanding of the organic carbon content of the biosolids initially applied is important. Because this carbon is not 'newly' fixed, the alternative fate of that carbon must be known as it should be included in baseline determination. The longevity of the biosolids carbon should be known so that the gains in SOC due to biosolids application can be distinguished from gains due to increased plant productivity (i.e. photosynthesis). Once biosolids are applied, they are subject to cycling and potential release from the soil as CO_2. Increases in carbon due to biosolids application must be distinguished from carbon that was already fixed in the soil prior to application. In some cases, the fertilizer value of biosolids, in terms of nitrogen and/or phosphorous content, can be counted as emissions reductions due to the avoided fossil fuel that would have been used to make alternate nitrogen and/or phosphorous

[2] Allometry is the relation between the size of an organism and aspects of its physiology, morphology, and life history. Allometric equations are used to approximate the size of an organism based on those traits.

fertilizers; this can be approximated by analyzing the biosolids for nitrogen and phosphorous content and using conversion factors, for example 4 kg CO_2e per kg nitrogen and 2 kg CO_2e per kg phosphorous.

2.1.2.4.2 SOIL CARBON

Soil carbon should be measured at 15 cm depth intervals, up to a maximum of 60 cm depth. At minimum, the first (0-15 cm) depth interval should be measured, and in mine reclamation contexts only the first 30 cm is advised due to the shallow soil at these sites. For each composite soil grab sample, at least eight samples should be combined forming at least half a litre in total, and one composite sample should be collected per treated area (but preferably at least one sample per 13 hectares). Bulk density should be measured at three different locations per treatment area, and preferably measured in each soil horizon. Where topography is significantly variable, more intensive soil sampling should be undertaken. Soil grab samples should be analyzed for % carbon and pH after being sieved to < 2 mm (if significant rock/gravel is present, samples should be analyzed as whole rock samples), and samples from arid regions or where the pH is above 7 should be analyzed for inorganic carbonates and/or treated with dilute acid prior to analysis).

2.1.2.4.3 BIOMASS CARBON

Biomass monitoring is only recommended if the site will be planted with trees, is already dominated by trees or will likely become quickly colonized by trees, or is likely to gain at least sporadic tree presence over time. The final case might apply to mine or gravel pit reclamation sites, but for example in silviculture the carbon in the biomass is generally not counted as it is periodically harvested.

In the case of sporadic and/or low-density patchy tree cover, the predominant tree species for each treated area should be recorded and, if possible, all trees larger than saplings should be counted to determine the stocking density (if not possible, the total area with tree cover should be recorded and photos or a foot survey should be used to estimate stocking density).

2.1.3 SCOPE FOR EMISSIONS OFFSET PROTOCOL DEVELOPMENT (SYLVIS, 2013B)

For this study, SYLVIS reviewed four different offset trading schemes (the PCT, the Clean Development Mechanism, the Emissions Offset Registry, and the California Air Resources Board) and conducted interviews with industry contacts from the PCT, Pembina Institute, Climate Action Reserve and Alberta Innovates Technology Futures. A thorough review of these offset protocols and trading schemes is, however, beyond the scope of this study, so they are only briefly summarized herein. For more details, the reader is referred to the report by SYLVIS.

2.1.3.1 SYNTHESIS OF FINDINGS

One of the key features of any biosolids land application GHG offset protocol is clear, accurate, long-term data on the GHG benefits associated with the processes related to the project activities. The primary driver for biosolids programs is likely carbon storage in long-term pools in both the soil and biomass. Because the SOC aspect is associated with such a high degree of uncertainty it is most critical to have an understanding of long-term SOC dynamics as influenced by biosolids application. In light of this requirement, SYLVIS recommended a program of data collection for at least one of MV’s then-upcoming biosolids land application projects.

The technical review component of protocol development can take several months. This is in addition to the several years of field-based background research that needs to first be completed.

One of the critical elements of an offset protocol is from whose perspective the protocol is written (i.e. to whom the offset credits will be credited) and their specific circumstances. Biosolids land application activities can conceptually fit under either the purview of a business or facility operator engaged in waste management, or the purview of a land manager. Both of these perspectives have their own set of pros and cons in terms of the potential to generate offsets, and desirability to the offset generators.

At the time of writing the SYLVIS (2013b) report, there was no single approved protocol or methodology that would have applied directly to biosolids land application. In order for protocols to be successfully developed, clear and extensive real-world data on the processes at play in the offset mechanism are often a pre-requisite, and such data usually takes several years to gather. The viability of a proposed offset activity or development of a related protocol can be significantly influenced by additionality requirements, offset calculation methodologies, and the definition of project activity eligibility and boundaries.

2.1.4 IONA ISLAND TREATMENT PLANT GHG EMISSIONS (ENVIRONNEMENT ILLIMITÉ, 2013)

From 2011 to 2013, Environnement Illimité studied the GHG emissions associated with the Iona Island Wastewater Treatment Plant digested sludge lagoons and biosolids stockpiles. Estimates of annual methane, nitrous oxide, and carbon dioxide emitted from the site were calculated, based on field measurements. While the lagoon component of this study is not relevant to the GHG implications of MV's biosolids land application activities, the portion covering emissions from the biosolids stockpile is potentially relevant because in 2019 over 107,000 tonnes of MV's biosolids were stockpiled at five different land application sites in the province (Metro Vancouver (MV), 2019). It may be worth considering GHGs from stored biosolids as other biosolids GHG estimation tools such as the Biosolids Emissions Assessment Model (BEAM) have taken into account GHGs emitted from biosolids storage, albeit in aerated lagoons (Canadian Council of Ministers of the Environment (CCME), 2009; Brown, Beecher, & Carpenter, 2010).

Estimation of GHGs was done by: (1) taking field measurements of mean diffusive and bubbling emissions per square meter per day for each stockpile (using a static chamber technique and infrared gas analyzers) and interpolating those fluxes to estimate daily fluxes year-round; (2) summing the daily calculated fluxes over the entire year; and (3) calculating CO_2e GHG emissions based on global warming potential (GWP) values from the Intergovernmental Panel on Climate Change.

2.2 TECHNICAL DEFENSIBILITY OF THE HISTORIC WORK AND GAP IDENTIFICATION

The historic work done for MV was comprehensive within the bounds of the study objectives, though several gaps remain that should be addressed in order to gain a more complete understanding of the GHG S&E related to biosolids application across various land uses.

The key gaps that remain are related to:

- Generating accurate default C-seq values;
- Measuring certain parameters in the field and considering certain factors in S&E estimations;
- Selecting end uses to be examined;
- Estimating the baseline and establishing additionality;
- Implementing standardized, comprehensive monitoring programs; and
- Addressing developments that have occurred since 2013 when the historical work was completed.

2.2.1 DEFAULT SEQUESTRATION FACTORS

In SYLVIS (2012), the estimated DSFs were within an order-of-magnitude of the estimates based on field sampling results. However, SYLVIS did not adjust its DSFs due to there being only one field site for verification for each land use category, and it is not clear why the stated objective regarding adjusting DSFs was kept in the report. In at least one case, the difference was greater than an order-of-magnitude; e.g., for silviculture, the DSF was 10 tonnes carbon/hectare, while the field measurements indicated 180 tonnes carbon/hectare – 18 times greater than the DSF. Moreover, for three of the evaluated project types (hybrid poplar plantation, cropland fertilization, and landfill closure – biocover for methane mitigation), no field measurements were performed with which field-based sequestration could have been estimated. Given the large discrepancy between the literature-based and field-based sequestration factors, I would suggest that neither the DSFs nor the field-based sequestration factors be adopted; instead, future work on biosolids GHG quantification for different land use types may focus on accounting for data gathered from several field sites so they can be more accurately estimated.

Most of the DSFs in SYLVIS (2012) were estimated despite there being a moderate to high degree of inaccuracy, though the inaccuracy was simply due to a lack of available or data. SYLVIS appears to agree with hesitancy to adopt these DSFs, noting that the effect of biosolids application on landscape-scale C-seq depends on several local factors and varies both within and between land use categories. As a result, SYLVIS notes that defining precise, context-specific DSFs is tentative and using the sequestration factors presented in this 2012 study today for different land application sites would be subject to inaccuracy.

2.2.2 FIELD MEASUREMENTS AND CONSIDERED PARAMETERS

The field measurement portion of the work done by SYLVIS (2012) involved gathering samples of soil in two different depth intervals (0-15 cm and 15-30 cm), biomass, and in one case forest floor litter, from biosolids-amended and control plots, then performing analyses to determine % carbon of the samples, and calculating the carbon stored in these materials in the biosolids-amended and control plots.

The study by SYLVIS (2012) is limited with respect to the parameters it considered in the carbon accounting and measured in the field. The study did not account for transportation- and application-related GHG emissions due to fuel/diesel consumption, fluxes of GHGs from the soil-atmosphere interface, or GHG reductions due to the displacement of synthetic fertilizers. However, all of the above have been considered noteworthy sources of GHGs associated with biosolids land application (Brown et al., 2010; Yan, 2014; Pilli, Bhunia, Yan, Tyagi, & Surampalli, 2015; Alvarez-Gaitan, Short, Lundie, & Stuetz, 2016). In contrast, the BEAM considers the GHG implications of transportation- and application- related emissions, fugitive emissions from stockpiles, and fertilizer offset credits (SYLVIS, 2009); however, most of these were not included in SYLVIS (2012).

In SYLVIS (2012), CH_4 emissions were only considered in the scenarios involving landfill closure, which did not incorporate any corroborating field measurements and instead relied on values from the literature. However, CH_4 is believed to be a source of GHGs at land application sites, at least due to release from stockpiles prior to land application; in some cases, the amount can be negligible, but it depends on the age of the stockpile as younger stockpiles tend to emit more (Environnement Illimité, 2013; Majumder, Livesley, Gregory, & Arndt, 2014, 2015).

In SYLVIS (2012), fugitive N_2O emissions after land application were not considered. However, N_2O can comprise a significant portion of GHG emissions from biosolids land application. For example, Alvarez-Gaitan et al. (2016) modelled five different biosolids treatment trains, some of which exemplify MV's treatment processes, and found N_2O emissions in the range of 83 to 101 kg CO_2e per tonne of dry biosolids applied. This is equal to 7-12% of the biomass and soil C-seq and 415-424% of the carbon offset for urea fertilizer replacement in that study, so it suffices to say that N_2O emissions can be substantial (Alvarez-Gaitan et al., 2016).

The parameters omitted from consideration by SYLVIS (2012) are in line with the BEAM (SYLVIS, 2009), which assumes negligible fluxes of GHGs following land application because it is assumed that biosolids are usually applied to aerobic soils that are not prone to eutrophication and that N_2O emissions from biosolids are the same that would occur from synthetic fertilizer of equal fertilizer value. However, several studies have demonstrated that these CO_2, N_2O, and CH_4 fluxes are present and can be significant sources of GHGs. The work by Environnement Illimité utilized gas capture chambers to measure GHG fluxes at the soil-atmosphere interface, and this provided a relatively accurate estimation of those fluxes. In the future, the consultant tasked with helping to improve the understanding of the GHG implications of MV's biosolids land application may wish to consider this approach or a similar one.

The fertilizer replacement value may represent a significant carbon offset at some of MV's land application sites. For example, SYLVIS (2017) found that the monetary nitrogen replacement value of biosolids can be approximately the same as that of the OM applied. Brown et al. (2010) found that the carbon credits from fertilizer offsets were only 8% less than those for soil C-seq, and based on the application of biosolids for their nitrogen content, biosolids tend to provide more phosphorous, calcium, and magnesium than plants need to grow (SYLVIS, 2017).

2.2.3 END USES

The most common current use for MV biosolids is in growing crops (hay or alfalfa) for cattle feed, followed by grassland fertilization, then mine reclamation, landscaping soil, and gravel pit reclamation. In 2019, MV biosolids were beneficially used to make soil products that were used in agricultural production and landscaping, and utilized for ranch fertilization, gravel pit reclamation, and mine reclamation (Metro Vancouver (MV), 2019). Of the 71,216 metric tonnes of biosolids beneficially used (Metro Vancouver (MV), 2019; Metro Vancouver, 2020):

- 34% was used on a dairy farm (Blackwell) where biosolids were mixed with sand and wood at a NutriGrow-operated facility to reclaim degraded land for growing feed, i.e. hay or alfalfa;
- 26% was used on a cattle ranch (OK Ranch) where biosolids were applied directly to grassland;
- 19% was used on a mine ('Mine A') where biosolids were mixed with overburden and wood at a NutriGrow-operated facility to be used for mine reclamation;
- 10% was used at a soil mixing facility (NutriGrow Richmond) where biosolids were converted into a manufactured soil that is sold to and used by the public and municipalities; and
- 10% was used at a gravel pit (FVA Pit) where biosolids were mixed with sand and wood for pit reclamation.

The historical work done for MV has provided a significant amount of information on the methods and approved offset protocols for carbon storage estimation in forestry applications, but comparatively little information on some applications such as manufactured soil which are currently prevalent options for MV biosolids. Future work should therefore focus on examining some lesser-investigated end uses which are now common or are likely to be explored by MV in the near future.

For example, MV is interested in knowing the GHG implications of the use of the manufactured soil products produced by NutriGrow at its three facilities; this soil is used for fertilizing fields of hay and alfalfa, for mine reclamation, and by the public and municipalities in various applications (Metro Vancouver (MV), 2019). NutriGrow creates custom soil products for different applications (NutriGrow, 2020), and their manufactured soils are created for different land application contexts, have different compositions and thus different GHG implications. Several simplifying assumptions would need to be made in order to estimate the GHG implications of land applying these manufactured soils, but if carefully chosen the assumptions could have a small or negligible impact on the results.

One end use that MV is currently considering is compost – using biosolids to create 'Class A' or 'Class B' biosolids compost, as defined by the OMRR. Composting results in increased volume of the end product (often, doubling; Brown and Beecher (2020)), which is rich in OM, and the conversion of some plant-available nitrogen to forms that are less readily available to plants and are more slowly released into the soil (Alba, Buzuk, & Thompson, 2019). Since compost could be used for many of the current applications of MV biosolids (and likely, others not currently practiced), composted biosolids would compete with the other end uses and would be associated with an entirely new set of GHG implications with respect to all of its potential end uses.

2.2.4 UPSTREAM FACTORS

The historical work focused primarily on downstream GHG implications of biosolids land application, such as post-application C-seq and GHG emissions. However, as identified by the PCT and accounted for in the BEAM, upstream factors can also be significant; for example, emissions resulting from extraction and production of materials and fuels used, transport-related emissions from vehicles not under the direct control of MV, and activities that were outsourced are all important to consider to ensure carbon accounting is comprehensive.

In order to develop a complete picture of the GHG implications of a given biosolids management option, it would be important to consider the GHG implications of processes such as thickening, stabilization, dewatering, drying, and additional treatment. This would mean considering all of these factors for each of the unit processes at MV's residuals treatment facilities, considering how much of the biosolids used for a given land application purpose originate from which of MV's facilities, and assigning the appropriate amount of GHG S&E to those biosolids which would be carried forward in estimations of the GHG S&E due to land application.

However, upstream factors such as these are outside the scope of carbon accounting for MV's biosolids land application because such accounting is only intended to consider the carbon and GHG implications of biosolids management after the biosolids have been produced. As a result, these factors do not need to be included in MV's biosolids GHG S&E tool, so long as those S&E sources and sinks are considered elsewhere by MV.

2.2.5 MONITORING PROGRAMS

One of the main findings of the work done by SYLVIS is the importance of a carbon monitoring program being implemented at any biosolids application site, both pre- and post-application. This is needed in order to support estimation (and if necessary, occasional adjustment) of the baseline and quantification of the project-related GHG profile as it develops over time. This monitoring should involve measuring the carbon in biosolids, the soil, biomass, and other carbon pools.

Biosolids are tested at MV operational sites and the soil products made using those biosolids are tested for most of the application sites, however there is a lack of consistency across the sites in terms of the parameters measured and the frequency of sampling (Total Carbon can, however, be calculated based on Total Nitrogen and the C/N ratio. This means that, currently, Total Carbon could be calculated for the soils produced at Blackwell, Ecowaste, and FVA Pit 15, but not for the biosolids cake or the soil manufactured at 'Mine A'.

Table 1) (Metro Vancouver, 2020). Also, the monitoring does not include measuring some soil parameters such as carbon, OM, or bulk density at any of the application sites. Total Carbon can, however, be calculated based on Total Nitrogen and the C/N ratio. This means that, currently, Total Carbon could be calculated for the soils produced at Blackwell, Ecowaste, and FVA Pit 15, but not for the biosolids cake or the soil manufactured at 'Mine A'.

Table 1. Parameters tested for in the biosolids and amendments used at MV application sites.

	Biosolids Cake	NutriGrow Soils			Soil Blend
Parameter	Metro Vancouver	Blackwell	Ecowaste	'Mine A'	FVA Pit 15
total solids	x				
volatile solids	x				
TKN	x	x	x	x	x
total nitrogen		x	x		x
Ammonia	x	x	x	x	x
Nitrate	x	x	x	x	x
Nitrite	x				
total carbon					
C/N ratio		x	x	x	x
organic matter		x	x		x
moisture				x	
pH				x	

At OK Ranch (grassland fertilization), SYLVIS conducts testing and monitoring of the soil, and all samples are tested using the Loss on Ignition method. The parameters measured are OM, Total Organic Carbon, and Total Nitrogen. This sampling is performed around one year after application and includes four samples. Sampling is performed to a depth of 15 cm, with each sample representative of approximately 60 hectares of land fertilized with biosolids.

Metro Vancouver has not yet implemented regular monitoring for carbon in the biomass and other carbon pools across its land application sites (Metro Vancouver, 2020). Such monitoring would be helpful to estimate C-seq in these pools due to biosolids application, and the data aquired from regular monitoring could be used to increase accuracy of C-seq estimates generated by the CAT over time.

2.2.6 DEVELOPMENTS SINCE THE HISTORICAL WORK

The protocols discussed in SYLVIS (2013a, 2013b) are not specifically relevant to mine or gravel pit reclamation or grassland fertilization. Because a substantial portion of MV's biosolids are used in mine reclamation and rangeland fertilization (Metro Vancouver (MV), 2019), it would be important to gather information on protocols specifically applicable to mine or gravel pit reclamation and grassland fertilization. Awareness of the details of such protocols would help guide MV's focus as it proceeds with biosolids land application GHG quantification.

Moreover, since 2013, some of the offset protocols examined by SYLVIS (2013b, 2013a) have changed or have been dissolved. In particular, the offset system with jurisdiction in B.C. in 2013 has been dismantled and replaced by a new system.

The PCT, a B.C. crown corporation, was dissolved in 2013 and its operations were shifted to be entirely conducted by the B.C. Ministry of Environment (Bennett, 2013). In its place, the Greenhouse Gas Emission Control Regulation was created by the B.C. government in 2015 and came into effect in January 2016 (British Columbia, 2015). The Greenhouse Gas Emission Control Regulation established the B.C. Carbon Registry which is used to monitor compliance unit transactions and facilitate the issuance, transfer, and retirement of compliance units. The Greenhouse Gas Emission Control Regulation also allows operators of regulated entities whose emissions exceed the pre-determined limits to purchase offsets from the market or funded units from the government, in order to comply with the regulation. Offset units can also be allocated based on the removal or reduction of GHG emissions via approved emission offset projects which have been verified by a third-party. In B.C., there is currently only one approved offset protocol: the Fuel Switch protocol, which was first published in August 2018 and last amended in August 2019. Two protocols are in the development stage: Vented Emissions Reductions and Organic Waste Diversion, both of which were open for public consultation for two months in late summer/early fall 2018. Of these three, only the last one could be relevant for MV biosolids management, but it is not applicable to land application as it is intended to simply quantify emissions reductions as a result of diverting organic wastes from the landfill and would therefore only provide offset credits to the residuals treatment facility.

There are many third-party verification bodies that operate according to international standards and are well-suited to assist with the development of standards, provide independent assessment and accounting services, and registering projects (ANSI National Accreditation Board (ANAB), 2020); however, the B.C. Ministry of Environment is the only entity in this province that provides payments for verified offset credits and only does so for projects that meet the guidelines in its protocols. As a result, there is currently limited or no opportunity to gain carbon offset credits for biosolids land application activities in B.C. Until applicable protocols are established locally, the main reason to seek carbon offsets would be to reduce GHG emissions or reach carbon neutrality within an organization.

Another consideration relevant to future work would be using updated GWP values. The GWP values used in previous work were adjusted in the Intergovernmental Panel on Climate Change's 5th Assessment Report, published in 2014. Assuming no climate-carbon feedback, the 5th Assessment Report places 100-year GWP values for CH_4 and N_2O at 28 and 265 (or 34 and 298 with climate-carbon feedback), respectively (Myhre et al., 2013). However, Etminan, Myhre, Highwood, and Shine (2016) presented revised GWP values for CH_4 and CO_2, and found that the newly calculated value for CH_4 was 25% higher than earlier estimates while the value for high CO_2 concentrations was up to 9% higher. Future work using updated GWP values could choose from these values or select other ones, but in any case, new GWP values should be selected as the values used in the historical work are now outdated.

2.2.7 BASELINE ESTIMATION AND ESTABLISHING ADDITIONALITY

A finding that repeatedly surfaces in the work by SYLVIS is the importance of the baseline condition being properly understood and accurately estimated (SYLVIS, 2012, 2013b, 2013a). It is said that once the baseline scenario is defined, it is then possible to differentiate the project-related GHGs from those that would have otherwise occurred had the baseline continued. The baseline is then often used to determine whether a project is 'additional'.

However, the concept of 'additionality' has proven to be one of most challenging aspect of emissions offset protocols, but it is necessary in order to assess the GHG benefits of a project under a given protocol. As noted in the historic work done for MV (SYLVIS, 2013a, 2013b) and emphasized in the academic literature both before (Schneider, 2009; Gillenwater, 2012) and since then (Thamo & Pannell, 2015; Campbell, Herremans, & Kleffner, 2018), it is critical but challenging to establish whether or not an activity is specifically enacted for its climate change mitigation benefits, and whether or not that activity achieves GHG reductions beyond the standard baseline scenario.

In the case of MV, it is unlikely that its projects will ever achieve additionality, as biosolids application has been commonplace for so long that it is essentially part of the baseline scenario. Metro Vancouver's interest in S&E quantification comes from the internal incentive to account for it, and not due to an external incentive that would be provided by an offset trading scheme. As such, additionality is not a key consideration for MV's biosolids land application projects.

2.2.8 SUMMARY OF IDENTIFIED GAPS

The historical work done for MV included an analysis of GHG sequestration associated with various land use options, guidance on how to track carbon in biosolids land application, and recommendations on how to develop a carbon offset protocol. However, some technical deficiencies in the work are apparent and should be addressed in future GHG quantification work. These include:

- In one study, C-seq factors for different land-uses were estimated based on the literature despite significant inaccuracies, resulting in sequestration values that were significantly different from those determined based on field measurements in the same study, and therefore could not be taken at face value.
- The parameters omitted from consideration by SYLVIS (2012) are in line with the BEAM (SYLVIS, 2009), which assumes negligible fluxes of GHGs following land application; however, several studies have demonstrated that these fluxes are present and can be significant sources of GHGs. The fertilizer replacement value of biosolids can also contribute a significant portion of the overall C-seq.
- Certain biosolids land application contexts were examined that are less relevant to MV's biosolids program today than they were at the time of the historical work. It would be important to re-consider which land-uses are included in any future biosolids GHG analysis, and the considered options should include both currently prevalent options, as well as those that may be practiced in the near future.
- Comprehensive, consistent monitoring programs are not yet in place for all of MV's biosolids application sites, for example in terms of the materials examined, parameters tested for, and frequency of testing. Metro Vancouver's biosolids cake is not tested for carbon content, which makes accounting for C-seq due to biosolids application challenging. A standardized monitoring program across all sites would result in consistent data for all land use types that could be used as input for a GHG S&E estimation tool.
- There have been several changes to the offset credit schemes examined in the historical work. Because such protocols are both central to the financial incentive aspect of GHG offsets and provide guidance on GHG monitoring, reporting and verification, it would be useful to take another look at the current and potential future policies and programs for GHG quantification.
- Relatively little research has been done on MV's biosolids-amended sites with which the GHG implications of the baseline or project-related GHG S&E could be accurately quantified. Therefore, if the intention was to base GHG estimations specifically on real-world conditions, it would be worthwhile to focus on improving the accuracy of baseline estimations; this could be done through pre-project measurements and/or comparison with nearby or control plots. Such research could occur on sites where MV biosolids are applied but could also be based on specific examples from other jurisdictions where similar biosolids are applied in similar contexts (i.e. same land use type, similar site conditions, etc.). In addition to pre-application inventories of the biosolids/manufactured soil, the soil, biomass, and other carbon stocks, regular post-application site monitoring is recommended in order to determine with relative certainty the amount of GHG S&E associated with the project as compared to the baseline.

3 INTERVIEWS WITH PROFESSIONALS

This section summarizes the findings of two interviews with biosoldis industry professionals who are knowledgeable in the area of carbon accounting. This includes an interview with staff at King County's Resource Recovery section (Wastewater Treatment Division), and an interview with a renowned expert in the field who collaborates with academics, government, and private firms on biosolids projects.

3.1 KING COUNTY

3.1.1 BACKGROUND

King County (KC), Washington, produces a Class B biosolids product that is branded as Loop™. King County has been running its biosolids program for nearly 50 years, and currently the majority of their biosolids goes to agriculture, some goes to forestry, and a small amount of has gone to compost production (though its compost producer recently ceased operation). In the past, KC has done some forest road remediation and mine reclamation, and in the future, KC may perform some remediation of Superfund sites. King County is exploring alternative options for creating a Class A product – possibly, a compost – which was identified as the most desirable alternative as noted in their biosolids management plan (King County, 2018). I interviewed two employees of King County's Resource Recovery Section in the Wastewater Treatment Division, in order to gain an understanding of how another jurisdiction is doing carbon accounting for its biosolids land application program; the interviewees were Erika Kinno, Research and Policy Project Manager, and Ashley Mihle, Project Manager.

Unlike MV, KC's biosolids are not utilized in making blended soil products and are only directly applied in agriculture and forestry (aside from the compost, which has historically been locally marketed, but the producer of which has gone out of business). The KC Environmental Lab performs testing on soil samples gathered from KC's research plots, and KC's biosolids are routinely analyzed for the full spectrum of physicochemical properties.

The carbon credits gained by KC's Resource Recovery Section comprise a substantial portion (approximately 22%) of the overall carbon credits gained by the Department of Natural Resources and Parks (in which the Wastewater Treatment Division is situated), though Resource Recovery only uses 3% of the Wastewater Treatment Division's annual budget (King County, 2016a, 2020).

King County's biosolids CAT is based on the BEAM (SYLVIS, 2009; Brown et al., 2010), though the soil C-seq factors have been adjusted from the BEAM based on published research on soil C-seq in agricultural settings (Brown, Kurtz, Bary, & Cogger, 2011). That research determined rates of carbon storage (in terms of metric tonnes of CO_2e) per dry tonne of biosolids applied at nine sites across four counties in Washington, spanning a variety of site types and crops grown (e.g., orchard, turf, dryland wheat). Those C-seq factors are used in KC's CAT: for agriculture, forestry, and compost they are 1.25, 1.0, and 0.35 metric tonnes of CO_2e/dry tonne of biosolids applied (King County, 2016b).

King County, like many other local governments and corporations, has a mandate to be carbon neutral (or positive) in each department. This has created an internal financial incentive for KC to accurately account for carbon credits, because if they cannot achieve carbon neutrality internally then KC must purchase carbon credits to offset their activities. However, the utility is currently (and for the next 3-4 years is projected to remain) carbon neutral.

King County performs pre-application soil testing to determine the agronomic application rate for its biosolids, and this testing includes Total Organic Carbon and nitrogen. However, post-application testing is not performed.

3.1.2 CARBON ACCOUNTING CONSIDERATIONS

At present, embedded emissions are largely unaccounted for in KC's biosolids carbon accounting. King County's accounting is based on its guidelines for carbon accounting, and this includes the definition of which Scope 1 (direct emissions), Scope 2 (purchased electricity, heat or steam), Scope 1 and 2 combined, or Scope 3 (indirect or embedded emissions from production of purchased materials and uses of end products) emissions are to be counted and which are not.

Currently, there is little focus on Scope 3 emissions; for example, KC accounts for emissions from running equipment, but does not count the emissions associated with creating or delivering that piece of equipment. However, there is a push from KC's Executive branch to consider embedded emissions in carbon accounting. This would result in a more accurate overall carbon footprint estimation.

King County does not include biomass carbon in its biosolids carbon accounting, as its current applications are not suitable for such inclusion: in agriculture and commercial forestry, the crops and timber are harvested at too short of an interval for carbon accounting, which usually considers a 100-year timescale, to be appropriate.

3.1.3 CONFIDENCE IN ACCOUNTING

King County is most confident in its carbon accounting for its agricultural applications, largely due to the fact that the C-seq factors are based on replicated field trials and decades of data. However, the research performed by Kate Kurtz and colleagues was done nearly 10 years ago (Brown et al., 2011), and in the meantime agricultural practices have been changing – for example, farmers in the region are starting to switch to no-till agriculture, which has not been common in the past.

No-till agriculture has been shown to influence the level of C-seq and GHG fluxes. Therefore, since the historical data on which KC's CAT is based essentially assumes the farming practices at the time continued until present, if more and more farmers adopt no-till practices it would be pertinent to update the C-seq factors based on more modern data which would more accurately reflect the current scenario.

King County is somewhat lacking confidence in its carbon accounting for its forestry applications, so KC is currently attempting to determine updated C-seq factors for those applications. KC's forestry carbon accounting has not been based on studies performed specifically for their program, their climate, and their uses, so a research project is underway to determine site-specific C-seq factors and increase confidence in KC's carbon accounting for forestry.

King County has the least amount of confidence in its carbon accounting for its compost, largely due to a lack of available data specifically applicable to their program. King County uses a generic number for its compost C-seq factor, and while this is likely inaccurate it does not have a large impact on their overall carbon accounting due to the fact that only very small amount (<1%) of its biosolids are used for this purpose. However, if compost was to become a larger end use in KC's biosolids program, KC would want to perform a more rigorous research project to generate more specific C-seq factors for compost. Such a research project would be particularly challenging, as compost is sold to retail customers who represent a wide variety of end uses, application methods, and transport methods and distances. Generating accurate data in terms of where the product is going, how it is being applied, how it is being picked up and transported, et cetera, would be logistically challenging. Several assumptions would need to be made (e.g., proportions that go to each customer, how each type of customer uses the compost, distance travelled, fuel used, and type of car), but those assumptions could be based on specific local data which could be gathered with a survey.

Drawing the boundaries of carbon accounting for compost use is another challenge which needs to be addressed. For both agricultural and forestry applications, KC has well-defined boundaries of its carbon accounting as it either owns or closely manages transportation and application equipment and manages and monitors its biosolids application. In contrast, KC does not have well-defined boundaries for its compost applications, and for the reasons described in the previous paragraph it would be necessary to determine what those boundaries are.

3.1.4 PUBLIC PERCEPTION AND MESSAGING

Public perception and community support have proven to be cornerstones of KC's highly successful Loop™ biosolids program. Several years ago, KC embarked on a journey to re-brand its biosolids, and since then education, outreach, and communication have been at the center of its approach. King County relies heavily on public-private partnerships, local advocates, and champions of their product to create trust within the community in which the biosolids are applied, and that model has worked well. The science-based, approachable, and positive messaging that centers around the benefits that biosolids create for the soil, the climate, the public, and plants in general has allowed KC to increase public awareness and acceptance of its biosolids and overall approach. Awareness of KC's biosolids program has increased 75% since they began measuring it, which is substantial given the short time period in which they have been measuring awareness.

Rather than transporting their biosolids to application sites in unmarked trucks so as to 'hide' what is being done (which has historically been common practice for biosolids management), KC has clear branding on its trucks and visually attractive imagery to accompany the branding. Moreover, the slogan for Loop™ is catchy and easy to understand: 'Turn Your Dirt Around'.

In order to increase awareness and acceptance, messaging considerations for KC are driven by the target audience and their priorities. Depending on the audience, KC emphasizes certain aspects of the 'story', such as the climate, resource recovery, or economic aspect(s). Internally, there is a substantial focus on the climate aspect, due to the internal financial incentive for carbon neutrality; in this case, the economics are far less important than the climate aspect. For the public, the most relatable aspect of the story has been the resource recovery aspect, as people can relatively easily understand that biosolids are is something they helped create and instead of being wasted are being used to do something good; the climate story is more complicated and science-based and can be harder to grasp for some members of the public. For farmers, the most important aspect of the story is the economics and their bottom line; the climate benefits and resource recovery benefits are less important than growing healthy plants and adopting practices that save money.

In addition to the individual stakeholders and end users, it is important for KC to consider other factors such as social norms and political inclinations in a given area, as these can play a role in determining which messaging story will resonate more with that community. For instance, on average, farmers of small-scale agriculture in western Washington may be more inclined to value soil C-seq and the associated climate benefits than farmers in eastern Washington, and this might be due to a confluence of several factors, such as those created by the east-west divide at the Cascades, differences in political ideologies, or a difference in the age (generation) of the farmers themselves. Given the potentially large variances in priorities of stakeholders, communication, outreach, and messaging must be targeted to specific audiences in order to make sure the information being communicated resonates.

3.1.5 N_2O EMISSIONS

One notable difference in King County's methodology and the methodology used in the BEAM is that KC does not include N_2O emissions as part of its accounting. Their previous research has shown that N_2O emissions are negligible, so while the N_2O column in its CAT has been 'zeroed out' for many years, KC recently removed the column from its spreadsheet.

3.2 DR. SALLY BROWN

Dr. Sally Brown is a renowned expert in the biosolids field in the Pacific Northwest and North America, and she has been studying or working with biosolids for over two decades. Dr. Brown did a lot of the work on the BEAM and was the lead author on the related publication. She has done biosolids carbon accounting for KC, Chicago, and Washington, D.C., and has published papers on the carbon balance for biosolids compost use in urban areas and the carbon balance for using biosolids to grow corn for ethanol. I interviewed Dr. Brown to get her perspective on biosolids carbon accounting and gain some insights regarding the development of a customized CAT for MV.

Dr. Brown suggested that creating a customized CAT might not look that different than the BEAM, even though the BEAM was created around a decade ago. She noted that the most important aspects of the BEAM that should be adjusted to create a program-specific tool are C-seq factors, transport, fertilizer replacement, and N_2O emissions.

- In terms of C-seq factors, it is critical to perform field work and gather site-specific C-seq values. The amount of carbon sequestered can be calculated based on soil bulk density and total carbon content, in combination with historical biosolids application records.
- In terms of transport, the factors to be adjusted are truck capacity, transport distance, fuel economy, and fuel used. These factors can be used to determine the CO_2e emissions resulting from transport. A similar calculation can be carried out for estimating emissions from the application activity itself, based on the type and amount of fuel used for applying the biosolids.
- In terms of fertilizer replacement, the BEAM includes generic factors from the published literature of 4 kg CO_2e per kg nitrogen and 2 kg CO_2e per kg phosphorous. These default values can be used if more specific values are unavailable; however, a more specific value based on the fertilizer that would have been applied in that particular context would produce more accurate carbon accounting. This means considering where the fertilizer would have come from and the energy (source and intensity) used to manufacture that fertilizer.

- For example, fertilizer made using hydro power would have a far lower carbon footprint than manufacturing with coal as the fuel source. Considering such details regarding the manufacturing of the replaced fertilizer would provide a more context-specific value for MV's biosolids program. It might also be worthwhile to consider other nutrients, such as sulphur, which can constitute a significant portion of biosolids nutrient content.

Soil N_2O emissions are the only potentially substantial GHG emissions in biosolids land application contexts, and a customized CAT should ideally involve local and/or site-specific N_2O emissions factors. The soil N_2O emissions factor should be adjusted, but because measuring GHG fluxes is so costly Dr. Brown recommended the use of standardized values such as those presented by Rochette et al. (2018). The work by Rochette and colleagues indicates that factors like soil texture, region, and cropping system can provide pertinent information regarding expected N_2O emissions from the soil, and present N_2O emissions factors as related to these aspects.

Wastewater agencies are usually monitoring (effluent and biosolids/sewage sludge) to ensure they 'do no harm' and not to see if they 'do benefit'. As a result, monitoring programs may not account for beneficial aspects like C-seq; beneficial components are usually only consistently monitored when the agency has a mandate or incentive to measure the amount of 'benefit' they are gaining from their activities. It likely takes time for institutional inertia to dissipate and for novel paradigms such as 'do benefit' to become embodied at all operational levels of the agency.

Biosolids can increase a soil's water holding capacity, improve ease of tillage and workability of the soil, increase photosynthetic activity and absorption of CO_2, relative to traditional NPK fertilizers; however, Dr. Brown said that putting those factors into a model and seeing if they have any impact can be an issue. This is because not enough data is available on these factors for specific contexts. Even if one could measure such factors and estimate the benefits, whether it would have a real impact on the carbon accounting is unclear. Moreover, it is difficult to know the actual benefit of these sorts of factors, as there are several other influences at play; for example, biosolids application may reduce the demand for irrigation, and the farmer might irrigate her field less because of this but she might not adjust her irrigation schedule whatsoever – accurately accounting for this type of factor is dodgy at best.

Mine reclamation is likely the only currently or recently practiced land application context in which changes in aboveground biomass can be significant and included in carbon accounting. Commercial crops and trees grown for harvest cannot be counted towards a carbon budget, especially since most carbon accounting is done on a 100-year timeframe. In general, herbaceous biomass is not considered – only trees are usually included in biomass carbon considerations. The key is whether or not the biomass is to be removed on a short timescale or is to be allowed to grow and accumulate over a long timescale.

Carbon accounting is an important practice, but according to Dr. Brown, comparing between specific end uses can become challenging, and it may be worthwhile to bring in other considerations such as ecosystem services. For example, the difference in C-seq between landfilling and biosolids compost is substantial, but the difference between biosolids compost and biosolids land application is likely much smaller. One way to distinguish between the benefits of beneficial use options would be to consider ecosystem services; for example, what are the effects on biodiversity, food security, environmental awareness, *et cetera*? This is one potential way to make the benefits of biosolids compost clearer, as there are so many potential end uses for compost that it becomes difficult to 'see past' the many simplifying assumptions that must be made in estimation.

4 CONSIDERATIONS FOR FUTURE WORK

In order to develop a customized CAT for MV's land-applied biosolids, the most straightforward and appropriate approach would be to create a set of customized BEAM modules based on each land application site. The main adjustments that could be made to the BEAM are to parameters regarding (1) DSFs, (2) GHG emissions from the soil and biosolids stockpiles, transport, and application, and (3) biosolids characteristics. Other considerations that could be relevant to some current MV sites and potential future sites are related to (4) biomass carbon, (5) fertilizer offset, and (6) composting. These adjustments would be in line with research on biosolids land application GHG inventorying which has identified the pertinent inputs and outputs related to transport are diesel use and emissions to air, and outputs related to land application are diesel use and fertilizer offset, soil C-seq, and emissions to the air (Alvarez-Gaitan et al., 2016).

A customized MV-specific CAT might incorporate a spreadsheet for each application site, so all of the below adjustments may be performed several times (though some values would be the same for all application sites). Gathering the data used to make these adjustments may involve reviewing the literature, reviewing MV files/data, consulting with MV Project Coordinators, or performing a field study, depending on the parameter or the amendment (i.e. biosolids or manufactured soil).

The BEAM accounts for many unit processes potentially applicable to biosolids management: storage, solids conditioning/thickening, aerobic digestion, anaerobic digestion, dewatering, thermal drying, alkaline stabilization, composting, landfill disposal, combustion, land application, and transportation (SYLVIS, 2009); however, in the case of land application, only the final two unit processes would be applicable (though some aspects of composting may be applicable in the future). All upstream processes are out of scope of the current study and are to be accounted for by Plant Operations in their modelling.

4.1 DEFAULT SEQUESTRATION FACTORS

Default sequestration factors are measures of how much CO_2e is sequestered per unit of dry biosolids applied, and they are integral to carbon accounting for biosolids management. The scientific literature has many references to DSF values that could be assumed for MV. For instance, the BEAM DSF is 0.25 tonnes CO_2e/dry tonne biosolids, values in the literature have been found to range from 0.23 to 1.74 tonnes CO_2e/dry tonne biosolids (Tian et al., 2009; Trlica, 2010; Brown et al., 2011), and SYLVIS (2012) found values at MV's biosolids application sites ranging from -10 (i.e. a carbon source) to 301 tonnes CO_2e/dry tonnes biosolids. There is a large range of reported DSFs, so site-specific DSFs would be more accurate and useful for a customized CAT. Therefore, the focus of future research should be on gathering site-specific data to generate accurate DSFs for each application site.

SYLVIS (2012) calculated DSFs for MV's then-active biosolids application sites, which included Vancouver Island University woodlot plots (silviculture fertilization), Loon Lake sand and gravel mine and 'Mine A' waste rock dump (mine reclamation), Jura Stock Ranch (rangeland fertilization), and Jackman Landfill (landfill closure – cap improvement, and biosolids fabricated topsoil).

Today, MV's biosolids land applications are different: MV's biosolids are currently made into a soil product that is applied to land growing crops (hay and alfalfa) for fodder, made into a landscaping soil product that is sold to municipalities and the public, made into a soil product that is applied in gravel pit reclamation, and directly land-applied in rangeland fertilization and mine reclamation.

In order to determine updated DSFs for MV's current applications, another research effort would need to be undertaken, and could be similar to the study by SYLVIS (2012). As per SYLVIS' methodology, carbon storage can be calculated based on soil % carbon, sampling layer depth, and apparent bulk density. In cases where no pre-project measurements were performed at the application sites, a nearby representative control plot must be carefully selected for comparison with the test plots. Chapter 13 of Ravindranath and Ostwald (2008) outlines in detail methods for estimating soil organic carbon. The soil sampling procedure should follow the recommended methods outlined in sections 2.1.2.3 and 2.1.2.4 of this report, and described in greater detail in SYLVIS (2013a).

4.2 GREENHOUSE GAS EMISSIONS

One development since the historical work done for MV that will have an influence on carbon accounting is the GWP of the GHGs included. In developing a customized CAT, the consultant should utilize the most current GWP values of 28 and 265 for CH_4 and N_2O, respectively, which come from the latest Intergovernmental Panel on Climate Change Assessment Report. The GWP for CH_4 is higher than previously reported, while the GWP for N_2O is lower. In addition, adjustemnts with respect to GHG emissions from the soil and stockpiles, and due to transport and application would need to be performed.

4.2.1 SOIL

SYLVIS (2009) noted that at the time of creating the BEAM, the most was known about CO_2, followed by CH_4, and then N_2O, and that the contribution of these GHGs to climate change is inverse to that order, with N_2O and CH_4 being 310 and 21 times more potent GHGs than CO_2, respectively. Therefore, as more research was performed after the BEAM was developed, especially with regard to N_2O and CH_4, SYLVIS suggested that the default values and emissions factors should be adjusted to make the model more accurate.

Nitrous oxide emissions have been recognized as one of the most significant sources of uncertainty for biosolids life cycle assessments (Brown et al., 2010), so it is important that accurate data are used for estimating N_2O emissions. Nitrous oxide emissions are understood to be primarily influenced by soil drainage and texture, with coarse and drier soils usually emitting less (SYLVIS, 2009). Nitrogen volatilization (and the resulting N_2O emissions) have been shown to increase after periods of rainfall, when the soil becomes anaerobic (Scott, Ball, Crichton, & Aitken, 2000). Rochette et al. (2018) compiled soil N_2O flux data collected since 1990 on agricultural soils in Canada and found the primary factors influencing N_2O fluxes are growing season precipitation, soil texture (fine, medium, or coarse), type of nitrogen applied (synthetic or organic), and crop type (annual or perennial).

Because of the many factors influencing these emissions, N_2O emissions factors to be used in carbon accounting should be updated at least on an annual basis, taking into consideration the precipitation patterns as they develop over time. Different amounts of precipitation fall at the various MV biosolids application sites, so it wold be worthwhile to determine local precipitation, and thus N_2O emission factors, for each site individually.

Table 2 provides the relevant values that should be adjusted, and their references, as presented the BEAM v1.1 (Canadian Council of Ministers of the Environment, 2011), as well as suggestions for amending these values in creating an MV-specific CAT. Adjusting these values will require reviewing the literature.

Table 2. Soil emission parameters in the BEAM and their references, and recommended sources and the relevant work needed to generate adjusted values for an MV-specific CAT.

Parameter	BEAM		MV-specific CAT	
	Value	Reference in BEAM worksheet	Reference	Work needed
N_2O emissions from land application - coarse soils (% of initial nitrogen content)	0.50%	BEAM default based on an interpretation of the Rochette 2006 paper	Rochette (2018)	Review literature
N_2O emissions from land application - fine soils (% of initial nitrogen content)	2.30%	average of 1.3% and 3.3% from Rochette 2006 for incorporated and topdressed, respectively, on fine-textured soils	Rochette (2018)	Review literature

4.2.2 STOCKPILES

While fugitive post-application CH_4 and CO_2 emissions are usually negligible and the only significant GHG from land application is likely to be N_2O (Alvarez-Gaitan et al., 2016), one potentially influential source of GHGs (CH_4 and N_2O) biosolids stockpiles (Environnement Illimité, 2013; Majumder et al., 2014, 2015). Methane generation could occur under anaerobic conditions, and more tends to be generated from younger, wetter biosolids in the summer months.

In the BEAM, the only factor influencing GHG emissions due to biosolids storage is the length of time that the biosolids are stored, but this does not include stockpiling at the application site – only storage in lagoons prior to processing at the treatment facility. However, previous research has demonstrated that other factors such as biosolids moisture content, age, and the time of year can influence GHG emissions from stockpiles at a fine spatial and temporal resolution.

A significant amount of MV's biosolids were stockpiled at some application sites in 2019: at OK Ranch the stockpile increased by over 95% to around 12,900 bulk tonnes by the end of the year, at FVA Pit 15 the stockpile decreased by 31% to around 13,800 bulk tonnes, at 'Mine A' the stockpile increased by 50% to around 16,700 bulk tonnes, and at 'Mine B' and 'Mine C', the stockpiles remained constant at around 14,400 and 49,400 bulk tonnes, respectively (Metro Vancouver (MV), 2019). No biosolids were stockpiled at the Blackwell and Ecowaste soil manufacturing facilities in 2019.

It would be worthwhile to amend the BEAM by adding more detail around GHG emissions from biosolids stockpiles, given the lack of attention to that aspect in the BEAM and the fact that several factors are understood to influence GHG emissions from stockpiles. To add this detail, the most accurate method would be to gather location-specific data at the stockpiles, perhaps using a methodology similar to that of Environnement Illimité (2013) – or, one could use appropriate default values from published scientific literature.

Table 3 provides the relevant values that should be adjusted, and their references, as presented in the BEAM v1.1 (Canadian Council of Ministers of the Environment, 2011), as well as suggestions for amending these values in creating a MV-specific CAT. Adjusting these values will require performing a field study or reviewing the literature, depending on the desired level of accuracy.

Table 3. Stockpile emission parameters in the BEAM and their references, and recommended sources and the relevant work needed to generate adjusted values for an MV-specific CAT.

Parameter	BEAM		MV-specific CAT	
	Value	Reference in BEAM worksheet	Reference	Work needed
CH_4 emissions during storage of biosolids prior to land application (kg/m^3-day)	0.0091	average of uncovered raw and digested, winter and summer for cattle slurry from Clemens et al 2006 normalized to 1 day	MV site-specific value, or Majumder et al. (2014, 2015)	Field study, or review literature
N_2O emissions during storage of biosolids prior to land application (kg/m^3-day)	0.00043	average of uncovered raw and digested, winter and summer for cattle slurry from Clemens et al 2006 normalized to 1 day	MV site-specific value, or Majumder et al. (2014, 2015)	Field study, or review literature

4.2.3 TRANSPORT AND APPLICATION

As noted in the literature and reinforced by KC staff and Dr. Brown, CO_2 emissions due to transport are one potentially significant factor in the total GHG emissions of a biosolids land application project.

Diesel consumption due to transporting biosolids depends on fuel efficiency, distance to and from the application site, and the proportion of solids in the biosolids (the wetter the biosolids, the less efficient transport is, in terms of the final dry weight of the biosolids). Diesel consumption due to applying biosolids depends on tractor fuel usage rates, the number of tractor loads applied per hour, and the size of the loads. Table 4 provides the relevant values that should be adjusted, and their references, as presented in the BEAM v1.1 (Canadian Council of Ministers of the Environment, 2011), as well as suggestions for amending these values in creating an MV-specific CAT. Adjusting these values will require reviewing the literature, reviewing MV files, performing a field study, or reviewing published data, depending on the parameter and data availability.

While the BEAM indirectly calculates emissions from fuel used based on parameters such as fuel efficiency and distance travelled, an alternative method would be to perform a more direct calculation based solely on the amount of fuel used. This may be feasible in the case of MV's program, as its contractors report fuel usage as part of the regular invoicing process. An MV-specific CAT could therefore facilitate a more direct calculation of transport- and application-related emissions, however it would be worthwhile to include the option to calculate emissions indirectly in cases where potential future applications are being considered and no data is available for those sites yet.

Table 4. Transport and application parameters in the BEAM and their references, and recommended sources and the relevant work needed to generate adjusted values for an MV-specific CAT.

Parameter	BEAM		MV-specific CAT	
	Value	Reference in BEAM worksheet	Reference	Work needed
CO_2e diesel (g/L)	2772	Canadian default CO_2 emissions factors for transport fuels – Climate Registry General Reporting Protocol V. 1.1	Latest Climate Registry General Reporting Protocol	Review literature
Truck fuel efficiency (miles/gal diesel)	5	King County (Washington State, USA)	MV site-specific value, in metric system (km/L)	Review MV files, or field study
Tractor fuel use (L diesel/hr)	25	http://tractortestlab.unl.edu	Updated/current value from the same reference	Review published data
Time to apply (loads/hr)	3	estimate	MV site-specific value	Review MV files, or field study
Size of loads (m^3)	13	estimate	MV site-specific value	Review MV files, or field study

4.3 BIOMASS CARBON

In most instances of MV biosolids land application, carbon storage in biomass should not be considered as there are no trees – only herbaceous crop cover which is periodically removed by grazing, for example. However, in cases where sporadic tree cover is expected to develop over time, it would be worthwhile to include biomass in carbon accounting; this is the case at mine and gravel pit reclamation sites.

Approaches for quantifying carbon in biomass, as presented by SYLVIS, are described in sections 2.1.2.3 and 2.1.2.4, while the work of Trlica (2010) provides an example of how biomass C-seq can be estimated in a mine reclamation context. Chapter 10 of Ravindranath and Ostwald (2008) details methods for estimating carbon in the aboveground biomass.

4.4 BIOSOLIDS CHARACTERISTICS

In the 'Land Application' sheet within the BEAM worksheet (Canadian Council of Ministers of the Environment, 2011), several default values are suggested for biosolids characteristics. Table 5 provides the relevant default values that should be adjusted, as presented in the BEAM v1.1 (Canadian Council of Ministers of the Environment, 2011), as well as suggestions for amending these values in creating an MV-specific CAT. Adjusting these values to create an MV-specific CAT will require reviewing MV files, analyzing MV biosolids cake, consulting MV BPCs, or performing a field study, depending on the parameter, data availability, and level of accuracy desired.

Table 5. Biosolids characteristic and use parameters in the BEAM and their references, and recommended sources and the relevant work needed to generate adjusted values for an MV-specific CAT.

Parameter	BEAM	MV-specific CAT	
		Reference	Work needed
Quantity going to land application (tonnes/day-wet)	100	MV site-specific value	Review MV files, consult Project Coordinators/contractors, or analyze MV biosolids/soil product
Solids content (%)	25.0%	MV biosolids/soil product value	Review MV files, consult Project Coordinators/contractors, or analyze MV biosolids/soil product
Density (kg/m^3)	950	MV biosolids/soil product value	Review MV files, consult Project Coordinators/contractors, or analyze MV biosolids/soil product
Total nitrogen (% dry weight)	5.0%	MV biosolids/soil product value	Review MV files, consult Project Coordinators/contractors, or analyze MV biosolids/soil product
Total phosphorus (% dry weight)	1.9%	MV biosolids/soil product value	Review MV files, consult Project Coordinators/contractors, or analyze MV biosolids/soil product
TVS (% dry weight)	51.0%	MV biosolids/soil product value	Review MV files, consult Project Coordinators/contractors, or analyze MV biosolids/soil product
Organic carbon (% dry weight)	28.6%	MV biosolids/soil product value	Review MV files (soil product), or analyze MV biosolids
Average number of days biosolids is stored prior to land application	25	MV site-specific value	Consult Project Coordinators/contractors
Will biosolids replace commercial fertilizer where it is applied?	yes	MV site-specific value	Consult Project Coordinators/contractors
Is lime in biosolids derived from a waste product (e.g. cement kiln dust)	no	MV site-specific value	Consult Project Coordinators/contractors
Will the lime in biosolids replace purchased lime where it is applied?	yes	MV site-specific value	Consult Project Coordinators/contractors
Fine-textured (% of land application area)	50%	MV site-specific value	Field study, or consult Project Coordinators/contractors

4.5 FERTILIZER REPLACEMENT

The replacement of synthetic or chemical nitrogen and/or phosphorous fertilizer due to agronomic application of biosolids can provide a benefit (in addition to the universal benefit of C-seq in the soil), however this would only be applicable in instances where these fertilizers would have otherwise been applied if biosolids were not. The only MV biosolids application sites where this may be the case are Blackwell (rangeland fertilization for growing fodder) and OK Ranch (grassland fertilization).

The reported fertilizer replacement value of biosolids varies. For nitrogen, it may range from 1.5 to 4.7 kg CO_2e/kg nitrogen, while for phosphorous it may range from 2 to 4.9 kg CO_2e/kg phosphorous (Canadian Council of Ministers of the Environment, 2011). However, the BEAM utilizes default values of 4 and 2 kg CO_2e per kg nitrogen and phosphorous, respectively (SYLVIS, 2009).

For an MV-specific CAT, these values could be made more accurate by considering where and how the fertilizer would have been produced, i.e. the energy source and energy input required to manufacture the fertilizer, in addition to the emissions associated with transporting the fertilizer to the application site.

4.6 OTHER CONSIDERATIONS

One finding that is clear in much of the historical work done for MV as well as the academic literature is that it is very helpful for carbon accounting to have pre-project measurements from the site, so that the project-related GHG S&E can be differentiated from that which would have occurred naturally, without biosolids application. Because some C-seq is likely to occur naturally, there is a tendency for S&E to be over-estimated as the estimate would then include S&E that would have occurred naturally, in addition to the biosolids application-related S&E.

In the future, MV may explore composting as a biosolids management option to diversify its portfolio and expand its biosolids use options to reach new markets. As identified in the interviews, carbon accounting for biosolids compost land application would be difficult to undertake. The BEAM contains a worksheet dedicated to composting; however the parameters and calculations are primarily related to the production of the compost and not to its application.

The most uncertainty around carbon accounting for compost will be in calculating C-seq for the plethora of end uses, for which there is limited to no data. Therefore, if a compost program is initiated, it would be crucial to undertake a study or tracking program to determine where the compost is going and how it is being used. For example, a survey of compost users may be an appropriate way to gather adequate data on how and in what context the compost is used. Even though many assumptions will need to be made, carbon accounting for compost use would be an opportunity for MV to become an industry leader in something that few, if any, local jurisdictions are currently doing with much accuracy.

5 SUMMARY

This report was produced because MV intends to hire a consultant to create a customized CAT that will allow MV to quantify carbon S&E with respect to the land application of their biosolids at current and potential future application sites. The stages involved in this study were to examine the historical work done for MV on carbon S&E with respect to their biosolids land application program, interview and gaining insights from knowledgeable professionals in the industry, create a list of considerations for future work, and draft a Scope of Work that may be incorporated into a future Request for Proposals for the development of the MV-specific CAT.

Synthesizing the information and data gathered from reviewing the historical work and interviewing the industry professionals facilitated the identification of gaps that remain, pertaining to developing a more accurate or complete understanding of carbon S&E in biosolids land application. The gaps identified were on the topics of C-seq values, considered parameters and field measurements thereof, end uses examined, baseline C-seq and additionality, monitoring programs, and developments that occurred since the time of the historical work.

This study has highlighted the importance of estimating specific C-seq factors for each application site, adopting N_2O emissions factors from similar contexts, estimating or assuming GHG emissions from biosolids stockpiles, utilizing accurate values for diesel fuel use, estimating biomass-stored carbon stored, gathering and using accurate data on biosolids characteristics, adopting fertilizer replacement values from the literature; and conducting pre- and post-application monitoring for the soil and, in some cases, biomass.

NOTES

The names of partner mines have been withheld for confidentiality.

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APPENDIX A – SCOPE OF WORK

PART 1 BACKGROUND INFORMATION

As one of its mandates, the Corporation protects public health and the environment, and supports the prosperity of the region through the delivery of liquid waste services and recovery of resources to communities within the greater Vancouver area. The regional liquid waste management infrastructure treats an approximate daily average of 1,300,000 cubic metres of wastewater with five wastewater treatment plants (two primary and three secondary). The Corporation is responsible for the secure, reliable and sustainable management of residuals generated at its wastewater treatment plants. The Corporation is mandated to extract the maximum economic and environmental value from the Corporation's utility residuals, and to meet or exceed the applicable regulatory standards.

The Corporation beneficially used 71,216 bulk tonnes of biosolids in 2019 in accordance with the BC Organic Matter Recycling Regulation. Biosolids were used to make soil products that were used in agricultural production, landscaping, ranch fertilization, gravel pit reclamation, and mine reclamation. Of the total amount of biosolids used:

- 64% was used for land reclamation projects where biosolids were first mixed with sand and wood to make a subsoil and/or topsoil and then used for onsite reclamation;
- 26% was used on a cattle ranch where biosolids were applied directly to grassland; and
- 10% was used at a soil mixing facility where biosolids were mixed with sand and wood to fabricate soils that were sold commercially.

The Corporation has undertaken several studies looking at GHG sequestration and emissions, and carbon tracking, related to biosolids land application. The final reports from these studies are available to all proponents as reference information for this project. A list of these studies with a brief overview of each is provided below:

- Guidance for Carbon Tracking in Biosolids Management, SYLVIS Environmental, March 2013 – This report includes a review of the most important carbon pools in terrestrial ecosystems under different land uses, and identification of the pools and methods for measuring the pools, in contexts relevant to the Corporation's biosolids management program (at that time: forestry, rangelands, mine reclamation, and poplar fertilization). The study also contains recommendations for future monitoring of biosolids land application sites, in terms of measuring carbon pools in the soil, biomass, and biosolids, and estimating the amount of carbon in these pools at control (baseline) and biosolids-amended plots.
- Greenhouse Gas Emissions Measurements at the Iona Island Wastewater Treatment Plant Lagoons and Stockpile, Environnement Illimité inc., Feb. 2013 – This study contains an assessment of GHG emissions associated with the Iona Island wastewater treatment plant biosolids stockpiles.
- Assessment and Evaluation of Carbon Sequestration of Biosolids Land Application Projects, SYLVIS Environmental, May 2012 – This study reviews the scientific literature and best available data on soil and biomass changes (carbon sequestration factors) as a result of biosolids application, and reviews Corporation data and reports to identify sites for follow-up sampling. The study also includes sampling at the selected sites to measure soil and biomass carbon storage, and a reconciliation of the literature review and field sampling results.

The Corporation does not guarantee the correctness, accuracy and completeness of any information, interpretation, deduction or conclusion shown and given in the reference material. It is the successful Proponent's responsibility to obtain all the necessary information required to satisfactorily complete the work.

PART 2 PROJECT OBJECTIVE

The objective of this project is to produce a carbon accounting tool specific to the Corporation's biosolids land application program. The tool should facilitate the quantification of carbon sequestration due to the Corporation's current and potential future biosolids land application activities. Where appropriate and operationally feasible, key components of the tool should be based on accurate site-specific data. Where inclusion of such data is determined to be not appropriate or operationally feasible, the underlying assumptions are to be clearly defined and discussed so that future work can address the assumptions, as appropriate, to make the carbon accounting tool more accurate.

PART 3 SCOPE OF WORK

In order to develop a customized carbon accounting tool for the Corporation's biosolids, one approach would be to create a set of customized modules, similar to those in the Biosolids Emissions Assessment Model (BEAM), a tool developed by Environment Canada and used to estimate GHG emissions from biosolids management programs. These modules could be based on each current and potential land application method.

The tool should allow for the incorporation of site-specific data that is known or can be gathered at current land application sites, as well as default values, consistant with the BC context, that can be used for reviewing potential new projects.

The Corporation assumes the following tasks may be one approach to achieve the objective; however, the Successful Proponent is to propose the methodology and steps they see as necessary to meet the objective. If additional components are included, they shall be clearly explained by the Successful Proponent in the proposal and may be accepted as part of the Scope of Work for the project at the discretion of the Corporation.

This study may include:

- Gathering information and data;
- Reviewing sources of carbon sequestration and emissions;
- Developing site-specific and generic input data; and
- Synthesizing the above to create the carbon accounting tool.

Task 1 – Gathering of Information and Data

Obtain information and data from Corporation staff and its contractors regarding its biosolids, biosolids-based manufactured soil, and biosolids compost including, but not limited to:

- Historical studies done for the Corporation;
- Past reports from the Corporation's relevant departments;
- Biosolids, manufactured soil, or compost property and application records; and
- Records of soil property measurements.

Obtain information and data available in the published academic literature for carbon sequestration and emissions from the soil and biosolids stockpiles. The topics of relevance may include, but are not limited to estimations of:

- Carbon sequestration in the soil due to biosolids, manufactured soil, or compost application;
- Carbon sequestration due to storage of carbon in the biomass;
- Carbon dioxide credits due to the replacement of synthetic or mineral fertilizer;
- Methane and nitrous oxide emissions from stockpiles; and
- Nitrous oxide emissions from the soil.

Task 2 – Review of Sequestration and Emissions

Identify factors that may influence GHG sequestration or emissions in each considered land application context. These factors may include, but are not limited to:

- Biosolids physicochemical properties (e.g., solids content, organic carbon content, bulk density, total nitrogen, total phosphorous, total volatile solids);
- Biosolids management parameters (e.g., quantity applied on land, length of time stored prior to land application, source of lime in the biosolids);
- Stockpile physical properties (e.g., surface area, volume, surface area to volume ratio, age of the stockpile material);
- Manufactured soil or compost physicochemical properties (e.g., carbon content, bulk density) and composition (e.g., % biosolids, % wood, % sand);
- Soil properties (e.g., texture, carbon content, bulk density, moisture);
- Crop type (e.g., annual, perennial);
- Biomass properties (e.g., carbon content of biomass, stocking density);
- Climatic parameters (e.g., growing season precipitation, ratio of growing season precipitation to potential evapotranspiration, mean annual air temperature);
- Fertilizer replacement (e.g., whether biosolids replaces synthetic nitrogen and/or phosphorous fertilizer, fuel source and amount of fuel used to make the replaced fertilizer);
- Transport (e.g., amount of biosolids transported, distance travelled, fuel type, percent of fuel that is biodiesel, truck fuel efficiency); and
- Application (e.g., emissions per litre diesel, tractor fuel use, time to apply, size of loads).

Where appropriate, identify the amount of carbon dioxide equivalents emitted with respect to each of the factors identified. This should include, but is not limited to: sequestration of carbon and emissons of methane, nitrous oxide, and carbon dioxide.

Task 3 – Identification of Input Data

The carbon accounting tool will have specific calcluations for current or potential future applications including:

- Biosolids-based manufactured soil, used to reclaim land;
- Biosolids directly applied to grasslands;
- Biosolids-based manufactured soil, marketed externally;
- Biosolids in long-term stockpiles;
- Biosolids-based compost, marketed externally;
- Biosolids direct application for forest fertilization; and
- Biosolids-based manufactured soils for methane attenuation during landfill closure.

Of the factors identified as potentially influential on carbon sequestration and emissions, identify which are critical to be adjusted for each application site and for which it would be acceptable to use generic values for all applications.

Justify each of the generic assumptions and discuss their accuracy or reliability. In addition, there should be a discussion of what additional work would be required to remove the assumptions by gathering the required information or data, as well as what information or data would need to be gathered. This discussion will be referenced when determining which, if any, assumptions are to be addressed to make the carbon accounting tool more accurate in the future.

Task 4 – Creation of the Tool

This Task will involve synthesizing the information gathered from the previous Tasks to create the carbon accounting tool. The objective of this tool will be to generate GHG balance (net sequestration and emissions) estimates for the Corporation's biosolids applications that are currently practiced and may be practiced in the future. One way to do this may be to create individual spreadsheets for each application considered.

The tool should have the ability to evaluate current projects for which there is data available, but also potential future projects about which there is limited information available. The tool should be amenable to the addition of site-specific data as they become available, with the goal to increase the accuracy of carbon balance estimations over time. However, the tool should also be able to produce carbon balance estimates for potential future (i.e. hypothetical) applications, such that comparisons among hypothetical projects can be performed.

The Successful Proponent may wish to create site-specific spreadsheets and also a generic spreadsheet for each land application category. The generic spreadsheets could be used to evaluate potential future projects without there being any site-specific data available, and at a later point the spreadsheets may be customized when site-specific data becomes available as a result of sampling or monitoring programs.

If using the BEAM as a model, the Successful Proponent shall determine which of the parameters are to remain the same default values as in the BEAM and which are to be adjusted so they are more specific to the Corporation's context. This determination may be performed for each spreadsheet that is based on a specific application site or general land application category.

The parameters calculated for each of the Corporation's land application sites will include:

- Carbon sequestration due to biosolids, manufactured soil, or compost application;
- Carbon sequestration due to storage in the biomass;
- Reduction of GHG due to fertilizer replacement;
- GHG emissions from stockpiles;
- GHG emissions from the soil; and
- GHG due to transport and application.

Carbon sequestration and emissions are to be calculated per unit of biosolids applied. This will be relatively straightforward when biosolids alone are applied, however when the other soil amendments (e.g., manufactured soil or compost) are applied it will be necessary to consider how much of the amendment is comprised of biosolids.