Assessing soil carbon storage and climate change mitigation in biosolids mine reclamation projects

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Abstract

Carbon release due to land-use change and clearance of natural cover contributes significantly to anthropogenic climate change. Biosolids, the treated and stabilised solids from municipal wastewater treatment, have been applied to mines for decades to facilitate reclamation success. Using biosolids as a soil amendment in mine reclamation may help mitigate climate change by reversing carbon losses in land degraded by surface mining. However, the magnitude of long-term soil carbon storage increases with biosolids use in reclamation is largely unknown.

This study compared carbon storage in biosolids-amended and conventionally reclaimed mine soils several years after closure. Soil samples from 0–15 cm and 15–30 cm depths were taken from five surface mined areas, each containing sites reclaimed either with biosolids or with conventional reclamation approaches e.g. topsoil + synthetic fertiliser. A focus of the sampling was to acquire information on sites with greater age since final reclamation (up to 27 years). Mines reclaimed with biosolids stored an average of 32.47 ± 3.16 tonnes of carbon per ha more in the top 15 cm of soil than conventionally reclaimed sites; in the 15-30 cm soil layer differences in carbon storage were generally not significant.

Using estimates of carbon storage from one of the mine areas and other published studies, a life cycle assessment was conducted to estimate the net greenhouse gas (GHG) emissions from the use of biosolids in reclamation in the Pacific Northwest region of the United States. The assessment compared using biosolids to reclaim and reforest degraded land versus using biosolids in agriculture combined with conventional reclamation to forest. Accounting for GHG flows such as biomass and soil carbon increases and project-related fuel use, the assessment showed that using biosolids for reclamation had a greater GHG sink potential than conventional reclamation combined with agricultural biosolids applications. The results of the life cycle assessment show that coupling land reclamation with biosolids reuse carried a large potential for increases in on-site carbon storage.

Incorporating biosolids into a mine reclamation program can reduce reclamation costs as well as promote climate change mitigation through increased organic carbon storage on-site.

1   Introduction

Historic and ongoing processes of disturbance of natural land cover, such as deforestation, soil tillage, and land degradation have contributed substantially to the levels of CO_2 in the atmosphere through release of the carbon stored in plant biomass and healthy soils (Canadell et al., 2007). Taking steps to reduce or reverse the net losses of carbon from its land storage pools, such as global efforts to encourage forest regrowth and reduce cropland plowing intensity, could provide economically viable strategies for slowing the rate of atmosphere CO_2 increase, helping to mitigate climate change (Pacala and Socolow, 2004). Land disturbance during the course of surface mining activities leads to net CO_2 emissions from the loss of carbon stored in biomass and in soils. In the reverse of this process, soil carbon stocks slowly rebuild during recovery after disturbance as, for example, in reclaimed coal mine soils in Ohio which accumulated carbon in the soil at a rate from 0.5–3.1 t C ha^{-1} yr^{-1} over several decades after closure (Akala and Lal, 2001). Enhancing the speed and efficacy of mine reclamation efforts could therefore lead to greater greenhouse gas (GHG) reductions by more quickly removing carbon from the atmosphere and storing it in the recovering soil.

Conventional approaches to reclamation of disturbed lands such as mechanical loosening of compacted soils, applying stockpiled topsoil and synthetic fertilisers, seeding with grass-legume seed mixtures, and mulching

with straw or hydroseeding generally aid in vegetation recovery (Bowen et al., 2005; Jacinthe and Lal, 2007). However, soil conditions on reclaimed sites often remain poor due to low fertility, low organic matter content, compaction, inefficient nutrient cycling, diminished drainage, lack of stable soil aggregates or an active soil microbial community, and high bulk density limiting root penetration (Indorante et al., 1981; Sencindiver and Ammons, 2000). Soils reclaimed after mining often show altered physical and chemical properties that are inhibitive to plant growth (Haering et al., 2004), and have reduced capability for soil- and standing biomass-carbon recovery due to poor plant productivity (Amichev et al., 2004).

Applying organic materials such as biosolids, the stabilised solids removed during municipal wastewater treatment, as a soil amendment for mine reclamation can help to alleviate many of the deficiencies of reclaimed soil to produce a healthier matrix capable of supporting more stable and productive vegetation. Biosolids have been used for decades as an organic matter and nutrient source to reclaim soils disturbed by surface mining (Sopper, 1993), and have in many instances led to superior reclamation outcomes compared to traditional topsoil and fertiliser application alone (Haering et al., 2000; Roberts et al., 1988). Biosolids and other organic residuals are often more effective than conventional approaches to reclamation in restoring vegetation cover at sites with severe barriers to plant establishment, such as high soil acidity and contamination with heavy metals (Brown et al., 2003; Orndorff and Daniels, 2008).

As a result of biosolids amendment, reclaimed soils may also store more carbon than soils reclaimed conventionally with replacement topsoil and/or synthetic fertiliser alone (Tian et al., 2009). However, the long-term carbon storage effect of one-time biosolids applications during mine reclamation (a common practice with biosolids used in reclamation) is not extensively studied, and the quantity of carbon capable of being stored in this way is poorly defined. The current study addresses this information gap by comparing long-term (>5 years) differences in carbon storage in degraded mine soils reclaimed with biosolids amendment and those reclaimed conventionally.

Research has also indicated that different end-uses of biosolids can carry with them different GHG emissions outcomes as a result of the emissions and offsets incurred over the life-cycle of their use, due mainly to differences in energy and fuel requirements in transport and processing (Murray et al., 2008). Soil carbon storage increases with biosolids amendment will also affect the life-cycle GHG emissions of any particular biosolids end-use option, and should be accounted for as well. After field quantification of the soil carbon changes with biosolids use in reclamation, this study continues with a life-cycle assessment of GHG emissions due to managing land with biosolids, incorporating onsite carbon storage as well as transport- and manufactured input-related emissions. The assessment compares two hypothetical reclamation scenarios constructed based on biosolids application experience in the Puget Sound region of Washington state: Biosolids used to reclaimed degraded land to forest, versus conventional reclamation of forest land, with diversion of biosolids to fertilise dryland agricultural fields. The life-cycle assessment allows for a more complete comparison of the GHG benefits of using biosolids in reclamation, as it includes the related and ancillary emissions associated with each utilisation pathway and identifies potential environmental tradeoffs.

2 Methodology

Five closed mine areas in different geographical settings were sampled, each containing zones representing reclamation with biosolids and zones representing conventional reclamation (topsoil replacement and/or NPK fertiliser only). Sites were chosen for sampling to favour areas that had been reclaimed for longer periods of time (up to 31 years). The mine areas included a deactivated coal mine in central Washington, a former tailings impoundment lake at a hard rock copper-molybdenum mine in interior British Columbia; former settling ponds and a retired haul road at a sand and gravel mine in coastal British Columbia; reclaimed surface coal mines in eastern and central Pennsylvania; and closed sand and gravel mines located in New England (Massachusetts and New Hampshire). Site reclamation histories, including biosolids and other residuals application rates, were obtained from internal documents maintained by the mine operators and reclamation specialists, as well as from direct interviews with individuals involved in site reclamation. At the British Columbia sand and gravel mine, where conventional reclamation sites were unavailable for sampling, carbon storage was estimated based on the properties of the mine spoil and stored topsoil material. More detailed information on sampling methodology, site locations, soil treatments, prominent soil types and regional land use and climate at the individual mine sites is available in Trlica (2010).

At each mine area composited soil samples were collected from conventionally and biosolids-amended reclamation sites. The soil samples were collected from depths of 0–15 cm and 15–30 cm and segregated by depth. Sampling of soil up to 30 cm depth is a common technique in studies of mine soils (Akala and Lal, 2001; Shukla et al., 2005) and was selected for this study to capture the bulk of the mass of soil organic carbon assumed to be present in the sites, as well as the major differences in carbon storage that might have occurred as a result of reclamation approach. In undisturbed soils, the majority of soil organic carbon is typically found in the top 1m of soil (Brady and Weil, 2004), while in agricultural soils most of the short- to medium-term management-related changes in organic carbon content occur in the upper 10–20 cm (Dick et al., 1986). For sites disturbed by mining activities, it is likely that changes in soil organic carbon concentrations are also concentrated in the surface soil horizons (Malik and Scullion, 1998; Shrestha and Lal, 2007; Ussiri et al., 2006).

Bulk density samples were also collected from the top 4 cm of soil at each site sampled for soil carbon content. Analysis for all soil parameters was segregated by the soil sample depth of collection. Dry composite samples were sifted to <2 mm and analysed for %C and %N by weight using a automated dry combustion analyser (Model 2400 Series II Analyser, Perkin Elmer Inc., Waltham, MA). Soil pH was determined after Thomas (1996). Soils from zones and depths with pH readings >7.0 were acidified prior to dry combustion analysis following Ryba and Burgess (2002). Soils were screened from coal contamination by excluding high outliers in %C or C:N (Insam and Domsch, 1988). The per-layer soil carbon storage at each site was calculated using the site-specific measurements of %C and soil bulk density in the following formula (Ellert et al., 2001):

$$SCS = C_a \times t_a \times D_b \times 10^2 \qquad (1)$$

where:

SCS	=	soil carbon storage (t C ha^{-1})
C_a	=	organic carbon concentration in soil from layer 'a' (% dry weight)
t_a	=	thickness of layer 'a' between top and bottom depth of sampling window (m)
D_b	=	bulk density (t m^{-3})
10^2	=	scale correction factor

This method for estimating per-ha carbon storage approximates the mass of carbon that exists in each soil slab of thickness 't' according to the within-layer mean %C. Site-specific surface bulk density measurements were used to approximate the whole-slab bulk density in both soil layers in order to complete the calculation.

Changes in carbon storage between biosolids-amended and conventionally reclaimed mine soils were assumed to be zero unless statistically significant differences could be demonstrated from the collected field data. SPSS (version 16.0) was used to compare means in carbon storage in conventionally reclaimed and biosolids-amended sites using independent samples T-test to a level of significance of $p < 0.05$ (p values corrected for unequal variances when necessary).

3   Results

3.1   Field study

In the upper 15 cm soil layer, biosolids-amended sites stored significantly more carbon than conventionally reclaimed sites at every mine area sampled. Mean carbon storage in soils after biosolids amendment was elevated by varying degrees at each mine area over the means for conventionally reclaimed soils (Table 1). The concentration of carbon (%C) was also significantly higher in all the biosolids-amended mine sites (data not shown). Averaged across all mine areas sampled, sites reclaimed with biosolids stored an average of 32.47 ± 3.16 t C ha^{-1} more in the top 15 cm of soil than sites reclaimed conventionally. Mean carbon storage in the top 15 cm layer and mean differences in top-layer carbon storage between conventional and biosolids-amended sites varied significantly between the different mining areas (Figure 1).

Table 1   Summary of site reclamation treatments and increase in soil C storage in top 15 cm layer with biosolids amendment

Mine Area	Reclamation Soil Treatment	Years Since Reclamation	Mean Soil C Increase With Biosolids (t C ha^{-1})
Coal, central Washington	Topsoil only; or topsoil + 560 dry t ha^{-1} biosolids	17–31	15.5
Copper, interior BC	NPK fertiliser; or 133–138 dry t ha^{-1} biosolids	4–8	38.4
Sand/gravel, coastal BC	Estimated topsoil/spoil benchmark; or 50–102 dry t ha^{-1} biosolids	4–8	29.0
Coal, eastern and central Pennsylvania	Topsoil + NPK fertiliser; or topsoil + 128–337 dry t ha^{-1} mine mix (biosolids/sawdust)	5–27	23.3
Sand/gravel, New England	Topsoil + NPK fertiliser; or manufactured topsoil w/ 617 t ha^{-1} added organic matter (81 dry t ha^{-1} biosolids)	2–7	87.5
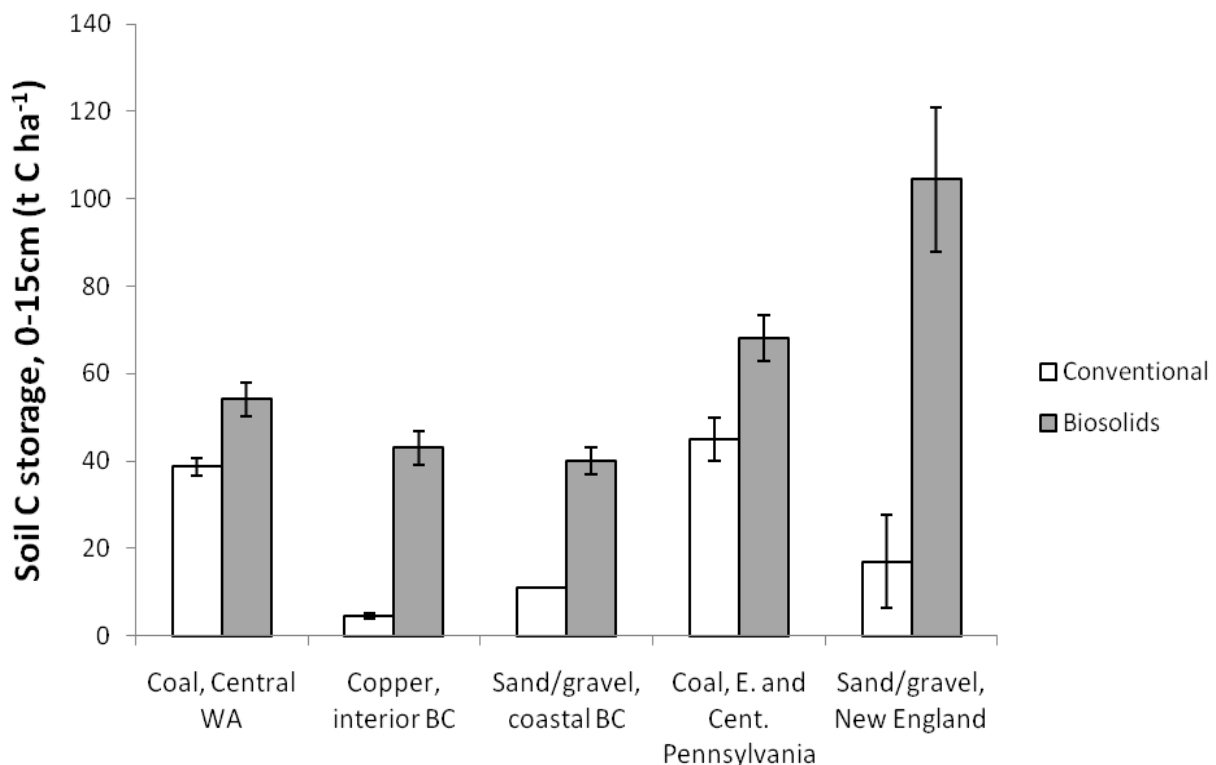
Figure 1   Mean organic carbon storage in the top 15 cm soil layer of reclaimed mine areas (error bars show standard error of the mean)

In the 15–30 cm layer of soil there were generally small increases in the calculated carbon storage (t C ha^{-1}) and in measured carbon concentration (%C) between biosolids-amended and conventionally reclaimed sites, but these increases were not significant ($p > 0.05$).

3.2   Life-cycle assessment of biosolids in land reclamation

The life-cycle assessment incorporated the findings of the field research as well as other published studies on biosolids effects in soil e.g. increases in plant growth and soil emissions of GHG. The assessment also took into account estimates of industrial, ecological and practical parameters appropriate to biosolids management, for instance expected hauling distance, material inputs required, equipment fuel efficiency and biosolids application rate. An attempt was made to take into account each activity that resulted in significant output or capture of GHG. A summary of the life-cycle assessment methodology and description of model construction and parameter estimation are available in Trlica (2010).

The assessment compared GHG emissions outcomes from utilising a set amount of biosolids (100 dry t) generated in the Seattle area in two different land management contexts, evaluated for their effects over a period of 30 years (Table 2). In the Biosolids Reclamation scenario, biosolids were assumed to be applied to replacement topsoil at 100 dry t ha^{-1} to a parcel of degraded land in the western Cascade mountains, which was then replanted to native conifer forest. In the alternate Conventional Reclamation scenario, the reclamation parcel was assumed to be reclaimed with topsoil replacement only followed by reforestation, while the parcel of biosolids were assumed to be trucked to dryland wheat fields on the Columbia Plateau and applied at an agronomic rate for crop production (approximately 7.8 dry t ha^{-1}), a common present-day practice for biosolids utilisation in the region.

Table 2   Summary of assumptions for life cycle assessment scenarios

Assumption	Biosolids Reclamation	Conventional Reclamation
Biosolids trucking distance	100 km	300 km
Amendment applied to reclamation site	Biosolids (100 dry t ha^{-1})	None
Source of nitrogen supplement in wheat fields	Ammonia fertiliser	Biosolids (7.8 dry t ha^{-1})
Tree biomass growth rate at reclamation site (30 years)	150 t ha^{-1}	100 t ha^{-1}
Net C accumulation in reclaimed soil (30 years)	50 t C ha^{-1}	40 t C ha^{-1}
Net C accumulation in cropland soil (30 years)	0 t ha^{-1}	0.25 t C ha^{-1} per dry t biosolids applied

The life-cycle analysis scenarios were chosen because of their relevance to biosolids management in King County, Washington (which includes the Seattle metropolitan area) where biosolids have been land applied in the contexts of both mine reclamation and dryland wheat field fertilisation, though the life-cycle GHG consequences of either use option had not previously been estimated. For both scenarios, important parameters and assumptions were determined based on real-world management experience (e.g. haul distances to application sites), or on the best available reported information (e.g. GHG intensity of manufactured inputs; soil and plant response to biosolids).

Parameters were intentionally selected from the range of results from above field study and reported in the scientific literature to conservatively underestimate the effect of biosolids on soil and plant carbon storage. For instance, the smallest increase in carbon storage in the top 15 cm with biosolids-amendment measured in this study was 15.5 t C ha^{-1} but for the purposes of the lifecycle analysis was assumed to be 10 t C ha^{-1}, and in the 15–30 cm layer sites was assumed to be zero given that no significant differences were detected in this soil layer.

Under either scenario the life-cycle assessment accounted for activities and emissions in both land parcels simultaneously, given the tradeoffs and substitutions necessary when biosolids were shifted from one use to the other. For instance, under the scenario of biosolids in reclamation it was assumed that manufacture of

nitrogen fertiliser was required for use in the wheat fields, while in the biosolids to wheat field scenario it was assumed that carbon storage in the cropland soils increased (Kurtz, 2010) and that tree growth rate and soil carbon storage was lower in the reclamation site in the absence of biosolids.

The outcome of the life-cycle assessment implies that the use of biosolids in land reclamation in the King County area with return to forest may produce greater net sequestration of GHG (62 t CO_2 eq.) than use in dryland wheat fertilisation (Table 3). The main GHG benefit of biosolids utilisation in mine reclamation was that sites reclaimed with biosolids stored more biogenic CO_2 in both on-site soil organic carbon pools and through enhanced rate of biomass accumulation in the growing trees. Emissions of GHG in other activity categories, for instance in transport-related emissions due to differences in biosolids haul distance, were not significant contributors to net GHG outcomes in comparison to the ecosystem-level carbon storage differences created by using biosolids in reclamation.

Table 3   Greenhouse gas emission (or reductions) in alternative biosolids utilisation scenarios, in tonnes CO_2 equivalents (negative numbers indicate net reduction in greenhouse gas emissions)

Activity/Process	Biosolids Reclamation	Conventional Reclamation
Net capture of CO_2 in trees and soil at reclamation site	-568	-422
Net capture of CO_2 in cropland soil	0	-91
Transport/handling of biosolids	5	16
Soil N_2O release	24	19
Fertiliser production emissions	0.2	0
Net GHG balance	-539	-477

4   Conclusions

Biosolids used as a soil amendment during reclamation of areas degraded by surface mining resulted in significant increases in soil carbon storage that were persistent on the scale of decades. The differences between mines in overall soil carbon storage were likely due to variations in initial mine spoil properties, reclamation history (including replacement topsoil quality), regional climate and vegetation cover. These findings indicate the need to evaluate soil carbon storage on a region-specific basis, given the potentially large influence of local site factors.

An important goal of this study was to ascertain the degree to which increases in soil carbon with biosolids amendment persist for long periods of time. The duration factor is relevant to the suitability of using biosolids soil amendment projects for generating tradable emissions offsets, as the permanence of emissions reductions or sequestration is very often a key consideration in evaluating the credibility of GHG offsets projects. While we would expect that over the very long term conventionally reclaimed and biosolids-amended sites should stabilise at a similar average C storage, all other soil formation factors being equal, the sites examined in this study had apparently not equilibrated even up to 31 years after reclamation. Soil carbon increases due to biosolids amendment may therefore prove to be persistent enough to satisfy the requirement of permanence in relation to GHG offset credit production.

Life-cycle assessment is a tool capable of taking into account the effect of biosolids in increasing long-term soil carbon storage, as well as other practical differences between realistic biosolids utilisation scenarios. Based on realistic assumptions for the life-cycle of land utilisation of biosolids in the Puget Sound region, using biosolids to promote soil and forest recovery on degraded sites resulted in the more favourable GHG outcome of either potential utilisation pathway considered. This outcome was primarily a product of greater soil carbon storage and increased plant growth rate resulting from biosolids use.

Biosolids management choices and the use of biosolids in mine closure both may play a part in reducing global GHG emissions (Brown and Leonard, 2004; Brown and Subler, 2007). Using biosolids in mine

reclamation is a utilisation pathway that can allow mine operators to participate in reducing climate change, meet their commitments to effective land stewardship, and capture the environmental benefits of utilising an inexpensive and widely available product. Biosolids utilisation in mine reclamation therefore represents an opportunity for partnership between biosolids generators and mine operators, with the potential for cost-effective and successful biosolids management and mine closure that comes with significant GHG benefits.

Acknowledgements

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