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Greenhouse Gas Emissions and the Interrelation of Urban and Forest Sectors in Reclaiming One Hectare of Land in the Pacific Northwest

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Ⓢ *Supporting Information*

ABSTRACT: The interrelation between urban areas and land use options for greenhouse gas mitigation was evaluated by assessing the utility of urban residuals for soil reclamation. Long-term impacts on soil C storage for mine lands restored with urban organic residuals were quantified by sampling historic sites reclaimed both conventionally and with residuals-based amendments. Use of amendments resulted in greater C storage compared to conventional practices for all sites sampled, with increases ranging from 14.2 Mg C ha^{-1} in a coalmine in WA to 38.4 Mg C ha^{-1} for a copper mine in British Columbia. Expressed as Mg C per Mg amendment, effective C increases ranged from 0.03 to 0.31 Mg C per Mg amendment. Results were applied to three alternative land-use scenarios to model the net GHG balance for a site restored to forest or low-density development. The model included construction of 3.9 243 m^2-homes, typical of urban sprawl. Emissions for home and road construction and use over a 30-year period resulted in net emissions of 1269 Mg CO_2. In contrast, conventional reclamation to forestland or reclamation with 100 Mg of residuals resulted in net GHG reductions of −293 and −475 Mg CO_2. Construction of an equivalent number of smaller homes in an urban core coupled with restoration of 1 ha with amendments was close to carbon neutral. These results indicate that targeted use of urban residuals for forest reclamation, coupled with high-density development, can increase GHG mitigation across both sectors.

■ INTRODUCTION

Traditional models of greenhouse gas emissions and mitigation options have considered urban areas and their associated waste streams separately from forestry and land use with limited exceptions.[1,2] A direct consideration of the overlap and interrelations between these two sectors can provide a more complete perspective. Urban areas currently occupy up to 2.4% of the terrestrial land surface and house approximately 50% of the total population.[3] Urban areas are increasingly less compact, with urban-associated land use expanding more rapidly than urban populations.[4−7] Increased density, with resulting decreases in transportation emissions, has been suggested as a means to reduce emissions due to urban residence and activity patterns.[8,9] However, increased density will likely increase concerns over end-use or disposal of urban residuals. Management of residuals, including food and yard waste and biosolids (the residuals from wastewater treatment), is a major source of emissions related to urban areas.[10]

The forestry sector is seen as an area of significant climate mitigation potential.[11] Currently deforestation and land-use change of forested land for agricultural production is the largest source of emissions in this sector.[12] Reversing these processes by afforestation of nonforest land and enhancement of existing forests has the potential to reverse this trend while simultaneously providing buffering capacity for anticipated changes in climate.[13] Forests also provide a range of ecosystem services including climate regulation, water retention and purification, and providing recreation opportunities.[14−16]

Reclamation and final end-use of disturbed lands offer an opportunity to evaluate potential linkages between urban areas, forested land, and management of urban wastes. Land is disturbed through a wide range of activities including surface mining operations. In the U.S. 3.2 million hectares have been permitted for mining since the passage of the Surface Mining Control and Reclamation Act of 1977 (SMRCA, Public Law 95-87). Near urban areas, sites are commonly disturbed during mining for sand, gravel, fill material, and topsoil. Surface mining disturbance results in significant losses of soil carbon and reduction in ecosystem services.[17−21] Disturbed sites can be reclaimed using conventional methods including application of replacement topsoil and chemical fertilizer. Reclamation under conventional approaches has resulted in accumulation of soil organic carbon (SOC) in a number of sites at rates of 0.01−3.1 Mg C ha^{-1} yr^{-1} for several decades post reclamation.[22,23] Research has also documented the efficacy of using urban

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Table 1. Soil Total Carbon, Soil Bulk Density, and Total Carbon and Nitrogen Storage for Two Sampled Depths for All Sites Included in the Study[b]

site	n	total carbon (g kg^{-1})	bulk density (Mg m^3)	carbon storage (Mg ha^{-1})	nitrogen storage (Mg ha^{-1})
Highland Valley					
Biosolids					
0−15 cm	14	25.3 ± 2.5[a]	1.15 ± 0.05	43.0 ± 4.0[a]	3.78 ± 0.44[a]
15−30 cm	14	6.2 ± 2.1[a]		11.3 ± 4.1	0.85 ± 0.48
Control (fertilizer)					
0−15 cm	6	2.4 ± 0.4	1.29 ± 0.05	4.6 ± 0.6	0.15 ± 0.07
15−30 cm	6	1.3 ± 0.2		2.6 ± 0.4	0.02 ± 0.02
Sechelt					
Biosolids, 50 Mg ha^{-1}					
0−15 cm	9	19.1 ± 3.3	1.27 ± 0.10	35.3 ± 6.2	3.00 ± 0.55
15−30 cm	9	6.2 ± 1.1		11.3 ± 1.9	0.84 ± 0.12
Biosolids, 102 Mg ha^{-1}					
0−15 cm	10	23.2 ± 2.1	1.13 ± 0.06	39.7 ± 4.8	3.29 ± 0.45
15−30 cm	9	17.0 ± 2.5		28.4 ± 4.2	2.24 ± 0.41
Biosolids, 80 Mg ha^{-1} + Pulp and Paper sludge, 406 Mg ha^{-1}					
0−15 cm	6	40.0 ± 9.8	0.80 ± 0.10	47.4 ± 4.6	3.15 ± 0.26
15−30 cm	6	26.0 ± 1.1		30.9 ± 3.2	1.68 ± 0.17
Control (benchmark)					
0−15 cm	N/A	6.6	1.1	11	0.94
15−30 cm	N/A	6.6		11	0.94
Centralia					
Biosolids					
0−15 cm	12	38.2 ± 3.7[a]	0.98 ± 0.05[a]	54.1 ± 4.0[a]	4.84 ± 0.48[a]
15−30 cm	12	17.7 ± 1.4		25.6 ± 1.8	1.83 ± 0.17[a]
Control (topsoil)					
0−15 cm	10	20.0 ± 1.5	1.34 ± 0.05	39.9 ± 2.7	1.96 ± 0.12
15−30 cm	10	14.0 ± 1.4		27.8 ± 2.2	1.36 ± 0.09
Pennsylvania					
Biosolids compost					
0−15 cm	17	41.4 ± 3.6[a]	1.18 ± 0.05[a]	71.2 ± 5.3[a]	3.58 ± 0.23
15−30 cm	16	25.7 ± 2.1		46.7 ± 4.6	1.96 ± 0.13
Control (topsoil)					
0−15 cm	7	25.3 ± 2.0	1.34 ± 0.00	50.6 ± 3.9	3.32 ± 0.28
15−30 cm	7	23.7 ± 2.3		47.5 ± 4.5	2.44 ± 0.18

[a]Indicates a statistically significant difference between amended and conventionally reclaimed areas within a site. [b]Mean ± standard error presented for all measured variables. The number of sites included (n) in the sampling is also shown.

generated organic residuals to reclaim mine lands.[24,25] Use of residuals as a soil amendment has been shown to increase net primary productivity and enhance soil carbon levels in comparison to conventional practices.[25−33] More rapid soil C accumulation has also been shown on a limited number of residuals-applied sites. For example, repeated biosolids applications to reclaimed cropland over 34 years resulted in gains in soil carbon storage of 3.15−4.88 Mg C ha^{-1} yr^{-1}.[31]

The end-use of reclaimed lands, including those in close proximity to urban areas, will also impact carbon storage and greenhouse gas (GHG) emissions. Demand for living space in low-density areas and economic considerations often result in lands being developed rather than left as open or natural space. Home construction with associated infrastructure will result in GHG emissions for both construction materials and energy use during occupation.[34−39]

The overall objective of this study was to model GHG emissions and storage in disturbed land postreclamation, considering the interrelation between land-use and urban residuals utilization options. While previous studies have considered GHG implications of land-use or residuals management, the two have not been considered simultaneously. Here, both sectors were considered together to quantify potential overlap and synergies between the two sectors. Targeted field sampling of historic mine sites was used to quantify long-term changes in soil C storage. These results were applied to estimate the 30-year C emissions/storage associated with reclaiming one ha of degraded land on an urban periphery in the Pacific Northwest to forest, using either conventional approaches or with urban residuals. As an alternative for comparison, development of the land to low-density residences, with either landfilling or agronomic land application of residuals, was also modeled. As a final modeling scenario, home construction within the urban core, coupled with restoration of the peripheral degraded land to forest with the use of residuals, was considered.

■ SOIL CARBON STORAGE IN RECLAIMED MINE LAND

Materials and Methods. Soils from reclaimed mine areas from four sites in North America were sampled. Each area contained zones reclaimed with soil amendments (composts,

Table 2. Site Locations, Type and Rate of Amendment, Conventional Treatment, Excess Carbon Storage Efficiency (In Comparison to Conventional Treatment) and Excess Carbon Storage Expressed as Mg C ha^{-1} yr^{-1} for All Sites Included in the Sampling[a]

site	amendment	control	rate (Mg ha^{-1})	excess C storage efficiency (Mg C per Mg amendment)	added C remaining as excess C (%)	excess C accumulation (Mg C ha^{-1} yr^{-1})
Centralia	biosolids	topsoil	560	0.03 (0.01)	8−12	0.84 (0.23)
Pennsylvania	biosolids compost or lime-stabilized biosolids	topsoil	128−337	0.15 (0.04)	27−48	0.86 (0.30)
Sechelt	biosolids/pulp + paper sludge	topsoil	50−486	0.31 (0.06)	47−82	3.51 (0.38)
Highland Valley	biosolids	topsoil/over burden	135	0.28 (0.03)	81−142	7.04 (0.95)

[a]Means and standard errors (in parentheses) are shown.

pulp and paper sludges and municipal biosolids) and zones reclaimed conventionally (topsoil replacement and/or NPK fertilizer only). The mine areas targeted included a large former coal mine in Washington State (Centralia); a tailings impoundment area at a Cu mine in British Columbia (Highland Valley); settling ponds and a retired haul road at a sand and gravel mine in British Columbia (Sechelt); and surface coal mines in central and eastern Pennsylvania (Pennsylvania) (Table S1). Conventionally reclaimed sites ranged in age from 7 to 31 years, with a mean age of 21 years. Residuals-amended sites ranged in age from 4 to 27 years, with a mean of 12 years. Residuals application rates ranged from 50 to 560 dry Mg ha^{-1} with a mean rate across all sites of 247 Mg ha^{-1}.

Multiple sites were sampled within each mining area (Table S1). Within each reclamation site, composite samples composed of between 4 and 5 individual samples for both the 0−15- and 15−30 cm depths were collected. A bulk density (BD) sample was collected from the top 0−4 cm of soil at each sampling site using a coring device. Soil was analyzed for total C and N by dry combustion (Model 2400 Series II Analyzer, Perkin-Elmer Inc., Waltham, MA) using the <2 mm size fraction. Measures taken to ensure that carbonates or coal were excluded from the C measures are detailed in the Supporting Information. Surface BD values were used in C storage calculations for both depths.

Soil C storage per ha was calculated for each measured depth using the measured total C and soil BD as follows:[31]

$$\begin{aligned} &\text{Soil C Storage (Mg ha}^{-1}) \\ &= \%\text{SOC}/100 \\ &\quad \times \text{layer thickness (m)} \times \text{bulk density (Mg m}^{-3}) \\ &\quad \times \text{surface area per ha (10000 m}^{2}\text{ ha}^{-1}) \end{aligned}$$

Soil C storage differences were evaluated as Mg C ha^{-1}, Mg soil C per Mg amendment, and Mg C ha^{-1} yr^{-1}. The second two variables were included to enable comparisons across sites and amendment loading rates. SPSS was used for statistical analysis.[40] Means for C storage were compared using independent samples *t* test (corrected for unequal variances when significant using Levene's test of Equality of Variance). Simultaneous means comparison within and between mine areas was performed using univariate ANOVA with Tukey's Honestly Significant Differences, with a homogeneous subsets grouping criterion of $p < 0.05$.

Results: Soil Carbon Storage. At every mine area studied, soils reclaimed with residuals stored more C than similar conventionally reclaimed sites. This increase was significant across sites, site ages, and residual application rates for the surface (0−15 cm) horizon (Table 1). Although there was a trend for increased C storage at the 15−30 cm depth for all cites except Centralia, there were no statistically significant differences. Mean C storage in the 0−15 cm layer in conventional sites ranged from 4.6 at Highland Valley (fertilizer alone) to 50.6 Mg C ha^{-1} in the Pennsylvania sites (topsoil and fertilizer). The mean C storage for conventional sites in this layer was 33.9 ± 4.2 Mg C ha^{-1}. Mean C storage in the 0−15 cm layer in residuals-amended sites ranged from 40.0 at Highland Valley to 71.2 Mg C ha^{-1} in the Pennsylvania sites with a mean across all sites of 50.9 ± 2.5 Mg C ha^{-1} (Table 1). These results fall within the range reported in the literature.[22,31,41,42]

The effect of amendment application rate, expressed as Mg C per Mg amendment, can be used to compare the efficacy of amendment addition on increasing C storage across sites (Table 2). Tonnage of additional C stored per ton of amendment (in comparison to C storage for conventional sites) was lowest in Centralia (0.03 ± 0.01) but similar for the three other sites, where it ranged from 0.16 to 0.31 Mg C per Mg amendment.

The effective increase in excess C storage with use of amendments over time (increase in C storage in amended versus conventional sites, normalized over site lifetime) ranged from 0.84 ± 0.23 Mg C ha^{-1} yr^{-1} at Centralia to 7.04 ± 0.95 Mg C ha^{-1}yr^{-1} at Highland Valley.

Data on the C concentration of the original amendments were not available, but organic C concentration in biosolids and composts is typically between 0.20−0.35 Mg C per Mg amendment.[26,43] Using this C concentration range, the fraction of C possibly remaining from the initial amendment and generating the additional soil C was estimated (Table 2). This fraction ranged from 8−12% at Centralia to 81−142% at Highland Valley. It is not obvious which measures are appropriate for C accounting in the case where carbonaceous amendments are added to soils. Some studies attempt to differentiate between the fraction of total soil C derived from the external source and the C input from increased net productivity, whereas others combine both input fractions.[26,44] We did not attempt to differentiate the origin of the increased C as the comparative soil C benefits associated with amendment use were taken into account by including land-use and alternate residuals management GHG effects in the subsequent land- and residual-use modeling (below). Additional benefits including decreased soil bulk density and increased soil N were observed (Table 1).

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LAND USE GHG MODELING SCENARIOS

Methods. Data from the previous soil sampling and published studies were used to estimate the GHG balance of three different postreclamation land use end-points. The GHG balance for reclamation of 1 ha of degraded land forest, with or without organic soil amendments, or developed to low-density residences was modeled. The land unit was set to be 60 km SE from Seattle, WA. Each end-use was evaluated for a 30-year period postconversion. A biosolids end-use/disposal pathway was included in each scenario, accounting for the fate of an equivalent amount of biosolids (100 dry Mg). A scenario-building approach, as is common for life cycle assessment (LCA), was used to develop the assessment.[45] The land use/residuals utilization scenarios modeled included 1) conventional reclamation and reforestation; 2) reclamation and reforestation with municipal biosolids as a soil amendment; and 3) partial conventional reclamation and reforestation with construction of a low-density residential development. For scenarios where biosolids were not utilized in restoration, the impact of biosolids use as fertilizer for dry land wheat or landfilling were considered. These three scenarios represent common land use and residuals utilization end-points in the Puget Sound. They also reflect the growing expansion of urban areas and highlight the impact of different land use and residuals management options for urban areas.

The boundaries of these systems included only those processes that occur on the hectare of land or inputs directly used in producing the required reclamation/development end-states (Figure S1). It was assumed that each scenario starts with 100 dry Mg of biosolids requiring management and with 1 ha of land in a degraded state with no vegetative cover but with basic initial regrading and replacement topsoil placement complete. The impacts for tree seedling production/planting were excluded. The model included GHG emissions and sinks due to soil C gains, growth of long-lived tree biomass, and construction and maintenance/occupancy of necessary land cover elements (roads and houses). For soil amendments, fuel consumption for transportation, energy use related to synthetic fertilizer production, and fugitive GHG emissions associated with use or disposal were considered. The model did not include emissions associated with infrastructure construction for supplying electricity and water or managing waste materials generated by residents on the modeled hectare.

Conventional Reclamation and Reforestation. In the "Conventional forest" (CF) scenario, the land area is replanted to early successional forest dominated by Douglas Fir (*Pseudotsuga menziesii*). Tree seedlings are planted directly into the regraded/topsoiled soil surface with no fertilizer application.[46−48] Soils are reclaimed with a mixture of topsoil and overburden stockpiled on site prior to land disturbance. Tree growth and soil C accumulation over the course of 30 years were considered in terms of their atmospheric CO_2 sink/source potential.

Reclamation and Reforestation with Biosolids Amendment. In the "Biosolids forest" (BF) scenario, a single biosolids application (100 dry Mg ha^{-1}) is incorporated with stockpiled topsoil, followed by replanting similar to the CF scenario. This rate of biosolids amendment is within the range reported for degraded land reclamation.[30] Higher rates would limit competitiveness of tree seedlings in comparison to grasses.[49] The biosolids are assumed to originate in King County, WA, with properties similar to the reported averages over the past several years. This agency currently land applies biosolids at fertilizer-based rates primarily to dryland wheat, with a smaller component used as fertilizer in commercial forest plantations in the region.[50] The impact of biosolids application on increasing soil C and tree biomass growth was considered.

Partial Reforestation and Suburb Construction. In the "Suburb" scenario the site was reclaimed to a combination of forest (as described for the CF scenario) and developed with low-density single-family housing and asphalt roadways. Home and road construction, maintenance, and use were included. The modal value for suburban population density and the 2007 average home size and household membership in the U.S. were used for reference, requiring the construction of 3.9 243 m^2 homes covering 0.09 ha.[51,52] Road area was set at 0.44 ha, resulting in a total nonvegetated area of 0.53 ha. This distribution of different land cover types falls within the parameters in the National Land Cover Database for low-intensity developed areas, with vegetation cover ranging from 20 to 70%, and "constructed" cover at 30−80% of total cover.[53] This fraction of impervious cover (53%) is within the range observed for partially vegetated urbanized areas of the lowland Puget Sound (39−74%).[54]

MODELING ASSUMPTIONS FOR LAND BASE

Soil C Accumulation. Soil C storage existing prior to reclamation was excluded from consideration. Estimates for C storage were based on results of the sampling reported in the first section of the study. Conventional reclamation with topsoil replacement was taken to result in soil accrual of C at a rate of 1 Mg ha^{-1} yr^{-1}.[22,23,31] Use of biosolids in combination with topsoil was taken to result in an additional 1 Mg ha^{-1} yr^{-1}, near the observed rate for the two oldest sites in the sampling portion of this study. These rates of C accrual result in C storage of 30 Mg ha^{-1} (110 Mg CO_2 ha^{-1}) in the conventionally reclaimed and 60 Mg ha^{-1} (220 Mg CO_2 ha^{-1}) in the biosolids amended soils after 30 years (Table 4). These soil C end-points are similar to what sampling showed for the Centralia and Pennsylvania sites over a similar time frame. Total C storage in undisturbed soils in the region have been estimated or measured to be similar or higher than the values used for this modeling.[26,55,56]

Biomass. Biomass C accumulation was included as a GHG credit for the reforestation scenarios due to the assumed longevity of the forest stand (Table 4). Previous studies have measured biomass accumulation ranging from 77 Mg ha^{-1} to 150 Mg ha^{-1} 30 years postlogging in conventionally managed forests in the region.[57,58] Lower productivity would be expected on poorer quality postdisturbance soils.[59] Using a midrange value of 100 Mg ha^{-1} of biomass accrual for conventional reclamation with an associated C content of 50 Mg per Mg biomass, total biomass C storage of 183 Mg ha^{-1} of CO_2 would be realized in the conventionally reforested site. For comparison, an old growth forest in this region has been estimated to store 500 Mg C ha^{-1} in biomass and soil.[55]

For the BF scenario, biosolids amendment was assumed to result in increased tree biomass growth rate. Previous studies conducted in the Pacific NW have shown significant growth increases following biosolids fertilization.[49,60,61] Young Douglas Fir stands growing on a low quality site showed a 72% height increase 10 years after a biosolids application of 47 Mg ha^{-1}.[49] An increase in tree biomass of 9.4 Mg ha^{-1} in similar regional forest four years after a single biosolids application of 18 Mg ha^{-1} was reported.[60] Similar responses have been observed for

Table 3. Estimated Greenhouse Gas Emissions Associated with Different Reclamation End-Use Options for 1 Hectare of Land in the Pacific Northwest (Assuming Dryland Wheat Field Fertilization As Default Biosolids End-Use)[b]

	conventional suburb	conventional reclamation	reclamation with biosolids	biosolids reclamation + urban development
road			Mg CO_2 for 1 ha	
construction	93	--	--	--
maintenance	42	--	--	--
home				
construction	283	--	--	212
use and maintenance	989	--	--	258−404[a]
reclamation				
soil carbon accumulation, reclaimed mine	−52	−110	−220	−220
biomass carbon	−86	−183	−275	−275
biosolids transport to reclamation site	--	--	2.1	2.1
biosolids fugitive emissions	--	--	18	18
total	1 269	−293	−475	−4.9−141

[a]Lower figure is for 3.9 units of a 12-unit dwelling and higher figure is for 3.9 small homes. [b]Land-use scenarios modeled include low-density residences, conventional reclamation to forest, and reclamation to forest with municipal biosolids as a soil amendment.

other tree species in other regions.[61,62] Growth increases of 40−46% were seen following low rates of biosolids addition in pine grown in New Zealand.[62] Growth was tripled over controls for western hemlock (*Tsuga heterophylla (Raf.) Sarg.*) and amabilis fir (*Abies amabilis [Dougl.] Forbes*) 11 years following fertilization with biosolids in British Columbia.[61] We assumed a 50% increase in above ground C for trees in biosolids amended soil in comparison to conventional reclamation, equivalent to 75 Mg ha^{-1} of biomass C, or 275 Mg CO_2 ha^{-1}.

Biosolids End-Use. Alternative end-use/disposal options for biosolids will have an impact on the net GHG emissions of any land-use scenario that includes biosolids as a soil amendment. Since organic residuals are generated independent of any demand for their use, the net GHG balance for a particular end-use is relative to alternative end-uses and their corresponding GHG emissions or C storage potential. Two additional biosolids end-uses were considered: an agricultural end-use (dryland wheat fertilizer) and landfill disposal (Table 4). Approximately 50% of the biosolids generated in the U.S. is currently landfilled, and landfilling remains an option for biosolids disposal in King County.[63] Factors considered in alternative end-uses included relative soil C storage benefits, avoided fertilizer use, and fugitive GHG emissions for land application and landfilling. King County, the source of the biosolids assumed in the model, applies the majority of its biosolids to dryland wheat as a substitute for synthetic fertilizer. For the scenarios that did not include use of biosolids in reclamation (CF and Suburb), the 100 Mg of biosolids revert to their default end-use as dryland wheat fertilizer in fields approximately 300 km east of the Puget Sound. Data from this and previous studies were used for this estimate.[26,50,64]

Biosolids are typically not landfilled in the Puget Sound region, but this end-use remains an option depending on the feasibility and cost of land application in the region. The landfill alternative was considered as an additional alternative within each scenario not otherwise using biosolids (CF and Suburb). Fugitive emissions for the biosolids landfill end-use were based on gas collection information provided by a regional landfill, which was then applied to a landfill gas evolution model to generate specific estimates.[64] Soil gas flux measures from the dryland wheat fields following biosolids application showed no detectable CH_4 or N_2O emissions over repeated sampling events, so similar debits were not taken (data not shown). Soil N_2O emissions for restoration were estimated as 1% of applied N (18 Mg CO_2).[65] No fertilizer was assumed to be used in the conventionally forest site, resulting in no debits for N_2O emissions and no credits for fertilizer avoidance for the biosolids reforestation scenario. Fertilizer avoidance related credits were derived from reported values.[64] Transport-related emissions for all three end-use/disposal options for biosolids were also accounted for.[64]

■ MODELING ASSUMPTIONS FOR DEVELOPMENT TO LOW-DENSITY RESIDENTIAL AREA

Road Construction and Maintenance. Previous studies have estimated GHG emissions associated with road construction and maintenance.[38,39,66−70] Estimates vary depending on material used for construction and level of maintenance required.[38,39,66,68] Energy associated with maintenance is significantly higher if roadways include lighting and traffic control.[38,69] Construction and maintenance emissions estimates generally include embodied energy in road materials and fuel and electricity use.[38,68,69] Emissions were reported either as tons of CO_2 per km or GJ of energy per km. We converted reported emissions for construction and maintenance to units of Mg CO_2 m^{-2} of road coverage for all studies. Reported emissions associated with maintenance were scaled linearly to reflect the particular time frame and road area of this study (0.44 ha). Emissions factors across previous studies generally ranged from 0.02−0.27 Mg CO_2 m^{-2}.[38,39,67−69] We used a study based on roads built in Canada using California-based standards for a two-lane road 13 m wide built with hot asphalt over concrete with 20% recycled asphalt materials for this estimate, along with reported maintenance-related materials and energy use.[68] This resulted in emissions of 0.03 Mg CO_2 m^{-2} for construction and maintenance for total emissions of 135 Mg CO_2 for all paving within the Suburb (Table 3). The estimate does not include vehicle use-related emissions.

Home Construction and Occupation. LCA for homes often include consideration of multiple life-cycle phases including production of materials, construction, and maintenance, with materials and energy use associated with occupation and demolition.[71] Previous LCAs of the GHG emissions associated with construction of single-family units have reported emissions ranging from 0.21 to 0.61 Mg CO_2 per

m^2 of floor space for homes in Oregon, Michigan, Scotland, and England.[34,35,72−74] Emissions varied based on the relative amounts of wood, concrete, and steel used in the structure.[34,71,72,74] Increases in construction emissions for more energy-efficient homes were offset by reduced emissions during the use phase. For all studies, the occupancy phase accounted for the majority of emissions.

Energy use during the occupancy phase is generally a combination of heating and cooling requirements and energy for lighting and electrical appliances.[34,35,37,73,74] Studies modeling residential energy use in OR and MI estimated 60% of total energy consumption went to heating.[35,73] In MI approximately 8000 GJ of natural gas was used for home and water heating over a 50-year life for a conventionally built home but was reduced to less than 2000 GJ for an energy efficient home. Electrical use for the home was 6000 GJ and 2200 GJ for the standard and energy efficient structures, equivalent to 0.024 Mg CO_2 m^{-2} yr^{-1} for an energy efficient structure and 0.08 Mg CO_2 m^{-2} yr^{-1} for a conventional home.[35] Other studies have reported occupation-associated emissions within a similar range.[34,37,73,74] Emissions associated with occupying a standard size home (243 m^2) in OR over a 70-year time frame included 280 Mg CO_2 for heating and cooling (using a combination of natural gas and electricity), 185 Mg CO_2 for lighting and appliances, and 133 Mg CO_2 for water use and associated water treatment.[73] These values assumed the average national U.S. grid value for GHG intensity of electricity production (0.23 kg CO_2 MJ^{-1}). Substituting the Northwest States grid value (0.126) or the Oregon Production Mix (0.072) resulted in 21% and 33% reductions in estimated energy use GHG emissions. The Oregon study noted the uncertainty of GHG intensity for energy consumption over future time frames.

The GHG emissions for construction and occupation of a standard home in Oregon were used to estimate emissions in the modeled scenario.[73] Energy use for occupation and maintenance were scaled linearly to fit to a 30-year time frame. Construction-related GHG emissions remained fixed. Emissions due to demolition were excluded. These adjustments resulted in emissions of 283 Mg CO_2 for construction of 3.86 conventional 243 m^2 homes (Table 3). Occupying and maintaining 3.86 homes for 30 years resulted in additional emissions of 989 Mg CO_2. Credits for reclamation and reforestation of the undeveloped portion of the land were included in this scenario under the soil and biomass assumptions used for the CF scenario (Table 3).

Model Sensitivity. The range of reported values for soil C storage, above ground biomass, road construction and maintenance, home construction, and energy use were applied to the model boundaries for this exercise to evaluate the sensitivity of our results to reported variation (Figure 1). We generally used conservative values for our analysis. For example, total sequestration potential for restoration with biosolids (BF) ranged from 356−1 323 Mg CO_2 ha^{-1} over the 30 year time frame. We used 384 Mg CO_2 ha^{-1} for this analysis. For home construction and use and road construction reported values ranged from 960−4 011 Mg CO_2 ha^{-1} for the 30 year time frame. We used 1402 Mg CO_2 ha^{-1} for this analysis.

Housing Alternatives. As a basis for comparison, a GHG emissions balance for construction of an equivalent number of small homes in an urban area was estimated for comparison to the Suburb conditions of low-density development on reclaimed lands in the urban periphery (Table 3). Data for this modeling aspect were taken from the same study that was used

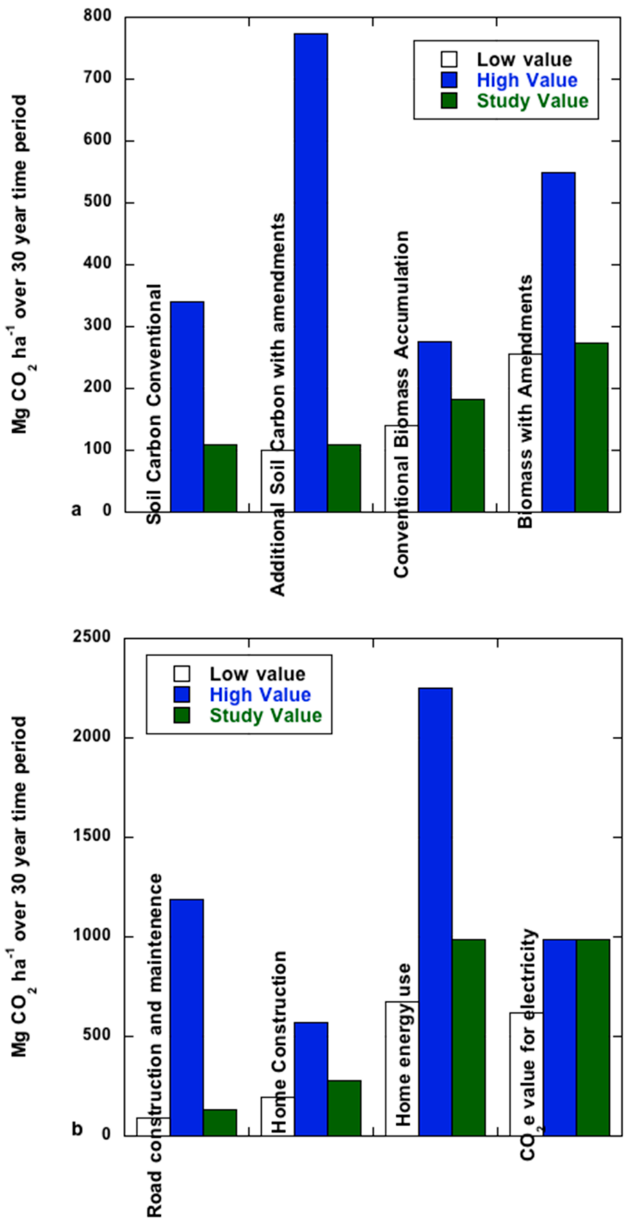

Figure 1. Sensitivity analysis for the different components of the end-use options for the 1 ha parcel of land. High and low values for different parameters were taken from the literature and scaled to fit the defined boundaries of the study. Values used for the study are also shown. Values for potential sequestration are shown in part a, and emissions for home construction and use and road construction are shown in part b.

for emissions for single-family homes.[73] Dwellings in urban core areas can potentially reduce transport related emissions.[36,75,76] We assumed no new emissions for road construction as these residences can make use of existing infrastructure. Homes in urban areas are typically smaller than single-family residences in low-density developments.[36] There are also more multifamily dwellings in areas with greater density. These multifamily dwellings, with the exception of high-rise buildings, have been associated with reduced emissions for construction and use.[73,77,78] The number of occupants per household will also alter this balance: As density per housing unit decreases, emissions per capita will increase.[36,75,76] For this alternative housing case, we included construction and energy associated emissions for multifamily low-rise dwellings and for smaller homes.[73] Construction emissions were approximately 212 Mg CO_2 for both types of housing. Over the 30-year time frame, emissions due to occupation and maintenance of smaller homes (107 m^2 total floor space) or multifamily homes (12 units with 107 m^2 floor space per dwelling area) were 404 and 258 Mg CO_2, respectively, in comparison to 989 Mg CO_2 for the standard homes.

OUTCOME OF MODELING SCENARIOS

Results from the field portion of the study showed persistent increases in soil carbon storage with use of organic amendments in degraded land reclamation. These results were then incorporated into a model to estimate GHG emissions associated with different land use options for 1 ha of degraded land modeled in the Pacific Northwest over a 30-year period. Three primary scenarios were considered: Suburb, which considered construction of low density housing with biosolids applied to dryland wheat; Biosolids reclamation (BF), in which degraded land was entirely devoted to reclamation to forest, with bioslids used to enhance reclamation (BF); and Conventional Reclamation (CF), in which land is reclaimed to forest and the biosolids unit is used for dryland wheat fertilization. The Suburb scenario, most representative of current conditions in the Puget Sound, is compared two further scenarios: Worst Case, with construction of low density housing with biosolids landfilled; and Optimized, with biosolids used for degraded land reclamation and equivalent housing constructed in the urban core. The outcome of the Suburb scenario compared to these two land use and residual use options are shown in Figure 2.

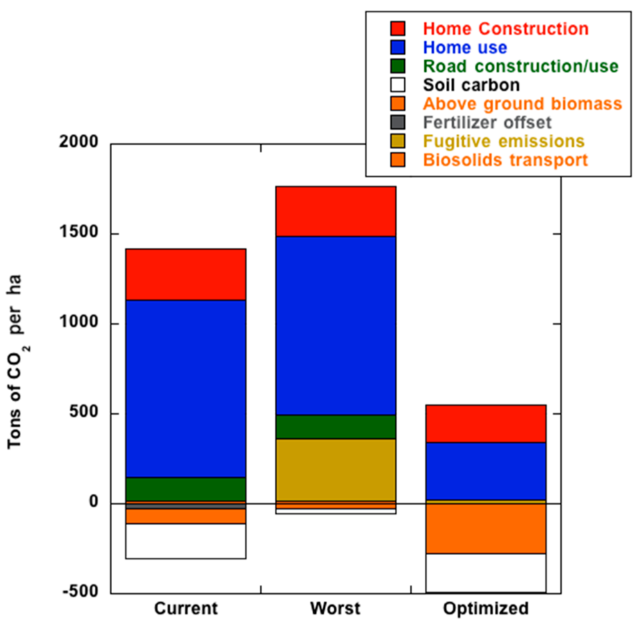

Figure 2. Greenhouse gas emissions/mitigation for three potential land/residuals end-use options as defined in the study. Current involves construction of 3.9 homes on the reclaimed ha of land with biosolids used for wheat fertilization. Worst includes home construction on the reclaimed ha with biosolids diverted to a landfill. Optimized has home construction of smaller homes in an urban core with biosolids used to enhance reclamation on the ha of land.

This modeling showed that reclamation to forest resulted in net GHG reductions due to C storage in soil and above ground biomass. This benefit increased by approximately 60% when residuals were used to enhance the reclamations process. GHG benefits due to dryland wheat application of residuals (the default residuals utilization option) were less than the benefits associated with using the residuals in land reclamation.

In the CF scenario, the total increase in C storage in both soil and biomass for 1 ha of land over the 30-year period was 293 Mg CO_2. Reclamation to forest with biosolids (BF scenario) resulted in greater net increases for soil C and aboveground biomass (total sink of 495 Mg CO_2 ha^{-1}). Both of these practices show significant C sequestration benefits. Adding organic soil amendment to reclamation increased both above and below ground C storage significantly.

This exercise showed a relatively modest benefit for diverting residuals from existing land application sites to restoration sites. Following current management trends in the Puget Sound, the model assumes that the majority of biosolids are applied land applied to wheat and are diverted from agricultural end-use only for another type of beneficial use (i.e., land reclamation). Diverting biosolids for reclamation of land to forest results in an increase of soil carbon storage benefits from 140 tons of CO_2 in the wheat fields to 220 tons of CO_2 (Table 4).[25] Credits

Table 4. Estimated Greenhouse Gas Emissions Associated with Different End-Use/Disposal Options for 100 Mg of Biosolids in the Pacific Northwest[b]

	Mg CO_2		
	landfill	wheat	reclamation
transport	13.9	11.2	2.1
application-related emissions			
fertilizer offset			
N		−24	(−24)[a]
P		−3.8	(−3.8)[a]
soil carbon sequestration	−29	−140	−220
biomass carbon			−275
fugitive gas emissions			
CH_4	298	0	0
N_2O	48	0	18
total emissions/sequestration	330.9	−156.6	−475

[a]Fertilizer offsets were not included for the reclamation estimate as the conventional scenario did not include fertilizer application. [b]Landfill estimates are based on default factors and landfill specific management information. Wheat estimates are based from locally collected data. Emissions associated with reclamation are based on results from the Centralia and PA coalmine sites.

for fertilizer replacement included for wheat fertilization (27 Mg CO_2 for N and P) were removed from the GHG balance for reclamation as the reclamation site did not include fertilizer use for the conventional treatment. Transport emissions for biosolids diverted to reclamation decreased from 11.2 tons CO_2 to 2.1 tons CO_2 due to a shorter haul distance. Finally, significant gains in aboveground biomass associated with enhanced tree growth increased on-site carbon storage for this end-use. Nitrous oxide emissions for the reclamation site added to overall GHG emissions relative to dryland wheat, due to the model assumption of some N_2O release in the forest soils and zero release in wheat fields.

In contrast, diverting biosolids from a landfill to reclamation of forest would result in a major reduction in GHG emissions.

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For this case, the haul distance to the landfill is comparable to the dryland wheat site. While there is a small credit for C storage in the landfill (29 Mg CO_2), fugitive emissions of both CH_4 (298 Mg CO_2) and N_2O (48 Mg CO_2) result in high net GHG emissions associated with this disposal option. Landfilling residuals instead of using them to enhance reclamation or in other land-based uses would also reduce GHG mitigation potential due to reduced soil C storage and aboveground biomass gains in conventional reclamation. Emissions associated with fugitive gas release from landfilling residuals (346 Mg CO_2) would negate any benefits from conventionally restoring the 1 ha of disturbed land to forest. This outcome clearly shows the potential benefits of incorporating use of residuals into forest and land use planning. The GHG reductions associated with reclamation to forest and beneficial use of residuals do not consider the broader range of ecosystem services that these practices may also enhance.[15] Both the restoration end-use and the agricultural end-use show the benefits associated with the use of urban organic residuals in the management of surrounding lands. These results illustrate the potential interrelationship between the urban sector and the forest and land-use sectors.

The interrelationship is more pronounced when considering different end-use options for reclaimed land. Our model estimated net emissions of 1269 Mg CO_2 for converting degraded land to a residential area with conventional homes, asphalt road surface, and recovering forest. In contrast, full reclamation to forest resulted in significant net GHG mitigation. Our estimate did not include emissions related to increased vehicle traffic or required infrastructure improvements, suggesting that our values are conservative.[35] King County estimated annual household emissions for transportation for different areas within King County.[76] Within the urban core transportation emissions per household ranged from 0.36−6 Mg CO_2 yr^{-1}, while in the vicinity of the modeled 1 ha of land per-household transport emissions were 8−20.25 Mg CO_2 yr^{-1}. Using the midpoint for each of these, transport emissions over the modeled time frame could result in an additional 1653 Mg CO_2 for the low-density development. This is in comparison with 372 Mg CO_2 transport related emissions for an equivalent number of households in the urban core.

Construction, occupation, and maintenance of equivalent housing in the urban core resulted in lower emissions than using the 1 ha land parcel for construction of low-density housing. There were minor reductions in construction-related emissions on a per-unit basis for both small homes (107 m^2) and a 12-unit (107 m^2 per unit) multifamily dwelling, in comparison to a standard home. Significant reductions in energy use for heating and cooling were predicted, with minor reductions in energy for lighting and appliances. Building in an urban core to fulfill housing demand would eliminate the need for new road construction and so eliminate these associated emissions. Our estimates suggest that emissions associated with building and occupying small homes in an urban core would be largely offset by increased carbon storage in the 1 ha site that was thereby left available to be reclaimed with biosolids (Figure 2). In contrast, constructing low-density development outside the urban core with biosolids diverted to rural agricultural uses had a higher GHG impact, and further opting for landfilling of biosolids rather than land use resulted in the highest GHG impact.

■ IMPLICATIONS

In this model construction of low-density residences results in significant net GHG emissions. These emissions are only minimally offset by reclaiming the remainder of the land to forest and by use of residuals. Net emissions are higher when residuals are landfilled rather than applied to land. Reclamation of degraded land to forest results in significant GHG reduction, which is increased with use of urban residuals. In contrast to low-density suburb development and nonreclamation biosolids use, constructing smaller homes within an urban core, paired with reclamation of disturbed lands to forest using urban residuals, was close to carbon-neutral. The intersection and potential overlap of the urban- and land-use sectors are clearly shown in this example. Analysis of this sort can allow for decision-making aimed at reduced emissions and enhanced sequestration across both sectors. This study shows the benefits of expanding the scope of mitigation/emissions-based decision making to optimize processes across multiple sectors.

■ ASSOCIATED CONTENT

Supporting Information

Additional information including results of different extractions to correct for potential coal contamination and carbonates in soils, C content of native soils, and a diagram showing system boundaries for the land use assessment. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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