Carbon Accounting for Food Scrap Composting in King County, WA

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The King County Solid Waste Division has been offering food scrap collection for several years. Residents are strongly encouraged to add food scraps to the yard waste bin. The co-mingled materials are composted at one of two facilities with the compost available for a range of end uses. The diversion of food scraps from landfill to compost is associated with a range of benefits, potentially the most significant being reduction in carbon emissions. Emissions reductions are associated with both avoided release of CH_4 from landfilling and sequestration associated with the use of the finished compost. This document will provide estimates of the carbon balance associated with the King County program including potential sequestration associated with different end uses of the compost. Yard waste diversion is also a critical component of this program. The co-mingled yard waste and food scraps provide an ideal blend for composting. Yard waste tends to have a low moisture content and a high C:N ratio while food scraps are much wetter with a low C:N ratio.

Introduction- Carbon balance

Both food scraps and yard waste come from what is referred to as the short-term carbon cycle. Here CO_2 is fixed by plants through photosynthesis and then that a portion of that fixed carbon is used by animals as an energy source and returned to the atmosphere as CO_2. Disruptions in the short- term carbon cycle are the source of carbon emissions and/or carbon sequestration. Excess emissions can occur when decomposition results in release of gases other than CO_2. The most critical example for food scraps is uncontrolled decay in an anaerobic environment that results in CH_4 production. Enhanced sequestration can occur when a significant portion of the fixed carbon is returned to soil. There can also be benefits associated with the use of compost. For example, when composts are used instead of synthetic fertilizers, there is a credit for avoided energy associated with producing the fertilizer.

There are two components to calculating a carbon balance for food/yard-based compost. The first component centers on the impact of diverting the feedstocks from landfill disposal. The second component relates to the use of compost. For both processes there are different levels of accounting that can be done. Site and material specific measures would provide the most accurate assessment. However, these are not possible for the King County food/yard program because there are no specific measures of CH_4 release from the Cedar Hills landfill and the finished compost is used by a wide range of individuals for a number of different purposes at different sites. These constraints contrast the work previously completed for the King County biosolids program. A majority of the biosolids are applied to dryland wheat fields in Douglas County. All applications require WA DOE approval and are done at permitted rates. The biosolids program worked with Washington State University to establish replicated long-term field plots in the area. Biosolids have been applied to these plots for over 20 years. Samples were collected from the plots to measure changes in carbon content and bulk density. It is also known that the materials are used in lieu of synthetic fertilizers. These measures were then used to calculate a carbon balance. Debits associated with the transport of the material were also easy to calculate as all transport is done in the same type of vehicle for approximately the same distance.

Unlike with biosolids, there are no replicated studies for the food/yard composts. The wide variety of end users will also result in a wide range of methods of use. A carbon balance of the urban use of composted biosolids for the biosolids program was estimated (Brown and Beecher, 2019). Here the range of end users would also be highly varied. For this estimate, peer review studies were used to develop carbon balances associated with different types of end uses on different types of soils. Also considered was the transportation by personal vehicles and larger capacity vehicles.

For this food/yard waste estimate, results for landfill diversion will be presented based on default values provided by the US EPA WARM model. Climate and type of landfill closest to the Cedar Hills landfill will be used. Estimates for compost use will be made both using default values and by using values from the peer review literature.

Quantities of materials

Determining the quantity of materials generated is critical to conducting a carbon balance. Here a range of data from King County was used to estimate quantities of materials. There are several components to this. Per capita generation of total food scraps and yard wastes is a critical component. Portion diverted to compost bins is the second factor. Based on data from 2018, the total food scraps and yard waste generated and collected is shown below (Table 1).

2018	Percentage	Total weight	Capture %	Capture
858,000 tons total		Wet tons		Wet tons
Food scraps	44	377,520	31%	90,433
Yard Debris	34	291,720	85%	247,962

Table 1. Quantities of food scraps and yard debris generated and collected in King County/ Seattle in 2018.

Methane avoidance

The most significant impact that food scrap diversion has on climate is associated with reduced methane (CH_4) emissions from landfills. Methane is a short-lived gas that has 23 times the warming impact of CO_2 based on a 100- year time frame. As CH_4 breaks down in the atmosphere over about 12 years, the reduction in CH_4 emissions has immediate and highly beneficial consequences. Methane is typically formed under anaerobic conditions where microbes are forced to use alternative electron acceptors for the mineralization of carbon. It is critical to realize that under controlled conditions, production and use of CH_4 as a source of energy can have beneficial carbon impacts. A pertinent example of anaerobic decomposition under controlled conditions are the digesters that are commonly used at wastewater treatment plants to reach pathogen kill and volatile solids reduction requirements for land application of the biosolids. The gas that is generated here is typically combusted for electricity or directly used to heat the digesters. The controlled conditions mean that CH_4 generation is optimized and that uncontrolled release of the gas is minimized.

The potential for CH_4 release from landfills has been recognized in the scientific literature, the revised version of the US EPA WARM (Waste Reduction Model), a methane avoidance protocol for the Climate Action Reserve, Project Drawdown, and by multiple cities and states that are enacting bans on landfilling food scraps. The quantity of CH_4 associated with landfilling food scraps and yard waste will vary based on the CH_4 generation potential of the feedstocks, the level of management at the landfill, and the local climate (Brown, US EPA). The revised WARM model divided landfill capture efficiencies into three categories: landfills without gas recovery systems, those with gas recovery and flaring, and those with recovery and power generation. A critical component of the model that was changed in the revised version was the recognition that before gas collection has started in a particular cell, gas collection efficiency is nil. During the years prior to final cover of the landfill, collection efficiency is also reduced. As food waste has a rapid decay rate, CH_4 generation will likely start within weeks after placement in a landfill cell.

The local climate for this input was defined based on annual precipitation with higher decay rates for wetter areas. The Maple Valley area of Washington, with over 50" of annual rainfall, falls into the highest rate ($k = 0.06\ yr^{-1}$) of unmanaged (non-bioreactor) landfills. EPA also updated the expected CH_4 generation potential and carbon storage potential of different types of organic wastes. Combining the landfill capture efficiency, local climate and decay rates of specific waste streams allows for an approximation of CH_4 generation potential and release of food scraps at the Cedar Hills Regional Landfill.

WARM also considers transportation of material to the landfill and energy use associated with landfill equipment. This amounts to 0.04 $MTCO_2e$ short ton. There is also a credit provided for energy recovery and use. The range of default values leading up to total emissions/ sequestration for food scraps and yard waste is shown in Table 2. Here the values for a landfill that is aggressive in gas collection is presented and that uses the gas for energy generation.

Material	Initial biogenic carbon content	CH4 yield as a proportion of initial C	Carbon storage as a proportion of initial C	CH_4 generation per dry Mg	CH_4 generation per wet short ton	Decay rate (k)	Landfill specific collection efficiency	Estimated % solids	Carbon storage	Landfill CH_4	Net emissions
	% dry weight			Mg CO_2e		based on wet conditions	%		% of dry weight	short ton wet	Aggressive gas collection
Corrugated containers	47	22	55	3.48	2.62	0.06	56	83	26	1.19	-0.08
Coated paper	34	13	74								
Food scraps	51	42	16	7.13	1.75	0.43	55	27	8	0.79	0.43
Grass	45	23	53	3.48	0.57	0.39	45	18	24	0.29	0.1
Leaves	46	8	85	1.17	0.65	0.22	52	62	39	0.3	-0.57
Branches	49	7	77	1.12	0.85	0.02	53	84	38	0.4	-0.82

Table 2. Values from the EPA WARM model on methane generation by food scraps, paper, and yard waste in landfills.

As the model indicates, landfills are not designed for optimal CH_4 generation or to limit uncontrolled release of the gas. A recent study confirmed this with direct measures of CH_4 release from different types of facilities in California (Duren et al., 2019). The authors did fly over measures of methane from 270,000 potential sources over three years. This was done by connecting a remote sensing spectrometer to aircraft. The authors identified 574 point sources that accounted for between 34-46% of the total methane produced in the state. Landfills accounted for 41% of the observed emissions.

There are concerns with the WARM model even with the most current revisions. The CH_4 generation potential and decay rates for feedstocks that are used in the model for food scraps and yard waste are from single lab incubations. Controlled anaerobic digestion of food scraps has yielded significantly higher quantities of CH4. It is also not clear that the dried leaves and branches would produce anywhere near the quantities of CH_4 that is modeled by WARM. It seems that this model underestimates emissions associated with food scraps and overestimates the benefits associated with landfilling yard waste (Brown, 2014).

However, as no measures of CH_4 release for the King County landfill are available, the WARM model provides a good option for estimating methane release. An updated version of the BEAM spreadsheet was used to calculate emissions associated with landfilling. The BEAM was developed for the Canadian Council of Ministers on the Environment (CCME) to estimate carbon emissions associated with biosolids end use/ disposal (Brown et al., 2010). The model was recently updated to include the revised emissions factors from WARM and applied to the New York City biosolids program (Northern Tilth). The default factors for both landfill emissions and soil carbon sequestration presented here are derived from that model. The model is based heavily on the WARM model. It also includes a small factor for N_2O emissions.

Current emissions

Total wet tons of food scraps generated in King County/ Seattle in 2018 was 377,520. That is approximately 1,000 tons per day. A 20% solids concentration, total N of 3%, and total volatile solids of 67.4% was assumed. These characteristics of food scraps are approximate and assume a relatively low soiled paper content and high content of actual food scraps. Using the BEAM model, emissions for that material, if all of it had been landfilled at Cedar Hills, would have totaled **125,898** Mg CO_2e annually (Figure 1). By diverting 31% of that, an emissions credit of approximately **-39,030** Mg CO_2e was achieved. That also points to the critical impact of increasing diversion rates.

Increasing diversion rates for food scraps is the single most effective tool for reducing greenhouse gas emissions associated with landfilling food scraps. Each wet ton of food scraps landfilled results in emissions of **0.35** Mg CO_2e. This is the case with an aggressive landfill that follows all regulations and best management practices.

For purposes of comparison, the BEAM model was also run for emissions at a worst-case landfill. Here emissions for food scraps assuming total generated had been landfilled were **272 337** Mg CO_2e annually, or more than double the predicted emissions at the Cedar Hills facility (125, 898 Mg CO_2e).

Unit Processes & Inputs	Inputs & Daily Emissions
Food Characteristics Input	
Quantity going to landfill (Mg/day-wet)	1000
Density (kg/m^3)	950
Solids content (%)	20.0%
Quantity going to landfill (Mg/day-dry)	200
Has the sludge been digested prior to disposal?	no
Total nitrogen (%-dry weight)	3.0%
TVS (%-dry weight)	67.4%
Organic carbon (%-dry weight)	50.0%
Organic carbon (Mg/day-dry weight)	100.0
Methane correction factor for landfill (DOC_1 that will decompose in landfill)	1.0
Quality of soil cover at landfill (high = good organic matter content, supports vegetation well)	high
Oxidation of methane by soil cover - applies three years after placement of wastewater solids in landfill	25%
Methane captured at landfill and flared, combusted or otherwise used - after capping	90%
Percent of captured methane used to generate electricity	100%
Level of Digestion/Processing	Undigested/Raw
DOC1- fraction of degradable organic carbon that can decompose	80%
Landfill climate zone (see Reference sheet cells A141 - A 147 for climate criteria)	cool wet
K -decay rate	0.185
Methane Emissions	
CH_4 released from first half year after landfilling (Mg/day)	3.70
CH_4 released from years 0.5-2 after landfilling (Mg/day)	7.32
CH_4 released from years 3-14 after landfilling (Mg/day)	4.95
CH_4 released after capping (Mg/day)	0.01
Fugitive CH_4 from combusted CH4 (Mg/day)	0.07
CO_2 Emissions equivalents from released CH4 (Mg/day)	**401.41**
Nitrous Oxide Emissions	
N_20 emitted from landfilled sludge (Mg/day)	0.141
CO2 emissions equivalents from released N2O (Mg/day)	42.15
Carbon Sequestration	
From undecomposed carbon from landfilled sludge (Mg CO2'day)	**-73.33**
Electricity Generation Credit	
Electricity generated (kWh/day)	87,425
CO_2 emissions avoided from electricity generated (Mg/day)	**-25.29**
CO_2 emissions from biomass (biogas) combustion (Mg/day)	**0**
Co., equivalents (Ma/vear1	**125.898**
Scope 1	**135,130**
Scope 2	**-9,232**
Scopes 1 & 2	**125,898**
Scope 3	**0**
Biomass combustion*	**0**

Figure 1. Output from the revised BEAM model showing estimates for emissions associated with landfilling all of the food scraps generated in Seattle/ King County in 2018.

Carbon accounting for use of compost

Use of Default Values

The WARM model provides a default value for soil carbon sequestration associated with composting of food scraps. The model gives a sequestration credit of -0.2 Mg CO_2 per wet ton of food scraps diverted to compost facilities. The model also mentions the value of the nutrients in the compost and the potential for additional credits but does not quantify them. This is a very high estimate of sequestration potential. The model reports a moisture content of 73% for food scraps. Food scraps decay rapidly in an anerobic environment (evidenced by the high CH_4 release from landfills) and are highly compostable in the aerobic environments that characterize composting operations. One estimate of volatile solids destruction during composting suggested that between 25 and 50% of the volatile solids would mineralize (Geoff Hill, personal communication). Taking both factors into account, the credit that would amount to expressed can be calculated as a dry ton of compost.

Each wet ton of food scraps @ 20-25% solids contains 200-250 kg of dry material
Assuming a 25% loss by VS destruction that 200-250 kg of dry material becomes 175-188 kg of material.

For purposes of simplicity, **one wet ton of food scraps can be estimated as 0.2 dry tons of compost.**

That means that the **WARM model** provides a credit of about **1 ton of CO2 for each dry ton of food scraps** that is composted. According to the supporting information provided in WARM, this was done via modeling using a wide range of studies. The focus of these studies was almost certainly on agricultural land. As precise rates of sequestration for different end uses of compost within King County are not known, the Division could use this default value.

The value for carbon sequestration associated with the use of compost calculated by the **BEAM model** is lower than the EPA WARM model. Using the model with the same parameters for feedstocks as was used for the landfill section, the model gives a credit of **0.66 Mg CO_2 per dry Mg food scraps**. This is equivalent to **0.17 Mg CO_2 per wet ton food scraps assuming a solids content of 25%**. As with the WARM model, this value includes a cost for energy use during composting as well as fugitive emissions during composting. The energy includes both fuel use and electricity use and comes to 0.017 Mg CO_2 per wet Mg. Fugitive emissions during composting are minimal in a well -managed facility that meets time and temperature requirements for pathogen kill. The pile has to be generally aerobic to generate sufficient heat to reach temperature, minimizing the potential for CH_4 release. As with the WARM model, this value is based on mean values gleaned from the peer review literature rather than specific values for compost use in King County. The BEAM model (shown below) also includes credits for fertilizer avoidance. Again, it would be acceptable to use this value as a more conservative value than the WARM, in lieu of attempting to estimate King County specific values due to the absence of a robust data set and with the varied end uses that characterize the King County program.

Unit Processes & Inputs	Inputs & Daily Emissions
Feedstock Input	
Type of composting operation	ASP
Quantity of sludge going to composting (Mg/day-wet)	1000
Solids content (%)	25.2%
Quantity of sludge going to composting (Mg/day-dry)	251.7
Sludge density (kg/m³)	no
Total nitrogen (%-dry weight)	3.0%
Total phoshorus (%-dry weight)	1.3%
Organic carbon (%-dry weight)	50.0%
Volume ratio of amendment to sludge (m³ amendment: m³ sludge, as is)*	3
Amendment grinding on -site?	yes
Volume of sludge in compost (%)	25%
Volume of amendment in compost (%)	75%
Density of amendment (kg/m³)**	250
Quantity of amendment going to composting (Mg/day-wet	789
Blended Feedstock Characteristics	
C:N	43
Solids content(%)	41%
Are active composting piles covered or is the air from them treated through a biofilter?	yes
Fuel Use	
Grinding (L-diesel fuel/day)	
Setting up and breaking down piles (L-diesel fuel/day)	
Total fuel use for composting eQuipment (L-diesel fuel/day)	7,079
ApplyinQ compost to land (L-diesel fuel/day)	675
CO_2 Emissions from Diesel used (Mg/day)	**20.91**
Electricity Use	
Electricity requirements of composting system (kWh/day)	45,309
From undecomposed carbon from landfilled sludge (Mg CO_2'day)	**13.11**
Methane Emissions	
Electricity generated (kWh/day)	87,425
CO_2 emissions avoided from electricity generated (Mg/day)	**-25.29**
Nitrous Oxide Emissions	
N_2O emitted from compost pile (Mg/day)	0.000
CO_2 Emissions equivalents from released N20 (Mg/day)	**0.00**
Carbon Sequestration	
From compost applied to soil (Mg C02'day)	**-166.13**
Fertilizer Off-set Credits	
From nitrogen applied to soil (Mg $C0_2$/day)	**-30.21**
From phosphorus acolied to soil (Mg CO_2/day)	**-6.35**
CO_2 equivalents (Mg/year)	**-61,564**
Scope 1	**-53,005**
Scope 2	**4,785**
Scopes 1 & 2	**-48,221**
Scope 3	**-13,344**
Biomass combustion*	**-**

Figure 2. Output on carbon balance for compost production and use from the BEAM model.

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Peer reviewed literature

There are also values in the literature that could be used in lieu of local data. A meta-analysis of data from England and Wales suggested a net soil organic carbon increase of 40-80 kg C $ha^{-1}yr^{-1}$ following application of yard waste compost (Powlson et al., 2012). The same study noted an increase of 130-230 kg C $ha^{-1}yr^{-1}$ following application of digested biosolids. The yard waste here had 13% organic C, while the biosolids had 35% organic C. The compost produced from the food scraps and yard waste would likely have higher nutrient content than the yard waste material in this British review and lower nutrient content than digested biosolids. Another study, conducted on wheat fields in the Pacific Northwest, suggested that nutrient content of the amendment was a critical factor in determining carbon sequestration rate per ton of amendment (Wuest and Reardon, 2016). This suggests that sequestration associated with the food/ yard waste compost would be in a mid- range between the two estimates- likely between 80- 130 kg C $^{-1}yr^{-1}$. Another review estimated a potential carbon sequestration rate associated with the use of compost at 0.4 t ha^{-1} yr^{-1} (Freibauer et al., 2004). This was based on use of compost on agricultural soils in Europe. No loading rate or characteristics of compost were presented. However, with a dry application rate of 4 tons per ha, this estimate is similar to the estimate derived from (Powlson et al., 2012). These estimates would result in a credit of:

100 kg (0.1 Mg) C per Mg of compost
'0.1 Mg C* (44/12) (conversion from C to CO_2) = 0.37 Mg CO_2 per Mg Compost
0.2 Mg food scraps per Mg compost
0.37 Mg CO_2 per Mg compost * 0.2 dry tons compost per wet Mg food scraps = **0.073 Mg CO_2 per Mg food waste**

This is significantly less than the credits provided by the EPA WARM Model and the BEAM model. It is derived primarily from agricultural use and does not take into account urban uses that are more common for the King County materials.

Local data specific estimates

Transport

All local end uses will require transport to get the compost to the use site. Using the research from King County's biosolids as a model, two types of transportation can be considered for the carbon accounting for urban use of compost: transport by 5-ton truck and transport by personal vehicle.

Personal vehicle

20 km round trip
50 kg compost
Mileage 10.6 km L-1 (25 mpg)

Total emissions: 0.09 Mg CO_2 per dry Mg Compost

Truck

20 km round trip haul
5 Mg capacity
4.25 km L^{-1}(10 mpg)

Total emissions: 0.005 Mg CO_2 per dry Mg Compost

For either of these, expressing transport on a per wet ton of food scraps results in de minimus emissions.

Nutrients

Previous studies have given a small credit for the fertilizer value of the amendment (Brown et al., 2010; Brown and Beecher, 2019; Brown et al., 2019; Trlica and Brown, 2013). While the compost will contain a full suite of plant-required nutrients, these studies have focused on the macro nutrients of nitrogen and phosphorus. These are present in sufficient quantities to merit inclusion. The energy intensity of nitrogen fertilizer will vary based on the source of energy used in the industrial process. Nitrogen fertilizer is synthesized from atmospheric nitrogen using an industrial process developed in the early 20th century. A value of 4 kg CO_2 per 1 kg N has been used and will be applied here. Phosphorus is produced by mining phosphate rock and converting it from $CaPO_4$ to phosphoric acid. The energy used for this process is approximately 2 kg CO_2 per kg P. For accounting purposes, total nutrient concentration has been used. The nutrient content of the Cedar Grove compost was reported as 2.2% total N and 1% total P. For each dry ton of compost that means:

0.022 * 1000 kg/Mg = 22 kg N
22 kg N * 4 kg CO_2/kg N = 88 kg CO_2 per ton of compost

0.1* 1000 kg/Mg = 10 kg P
10 kg P *2 kg CO_2/kg P = 20 kg CO_2 per ton of compost

Total nutrient value = 88+ 20 = 108 kg CO_2 per ton of compos
108 kg/ton * 0.2 tons of food scraps per ton of compost = 22 kg CO_2 per wet ton food scraps for nutrient value of finished compost

End use options

Restoration

For estimating carbon storage associated with local use of compost for restoration, data from a local project was used, in which several divisions within King County participated in a study/demonstration at Vashon Island. The project was started in 2009. A borrow pit next to the Vashon transfer station was amended with different composts including GroCo biosolids compost and Cedar Grove compost. Material was surface applied. Incorporation wasn't possible due to the slopes at the site. Compost was also added as a 50:50 mixture with clean fill from the Roads division. Soils were sampled for several years after amendment addition. Data from this site can be used to estimate a carbon balance for use of compost for restoration.

Here 104 yards of compost was applied both as a surface application and as a mixture with the fill. Soil samples were collected 3 years post application. Total CO_2 stored was calculated as follows:

I assumed a dry weight equivalent to a yard of compost at 500 pounds or 0.25 tons. This is based on a wet weight per yard of 0.5 tons and a moisture content of 50%. This results in a compost application rate of 26 tons per acre or 58 Mg hectare. Carbon stored per hectare is equal to the C concentration (%) * bulk density. This is converted to CO_2 by multiplying by 44/12. For the 50:50 mixture, the carbon stored was deducted in the control/ fertilizer treatments to find the difference in carbon storage. For the surface application of compost, this was considered as a new soil horizon and counted all of the added organic matter as additional. Results from this are shown below. Here it is important to note that estimates for the material that was surface applied and that was mixed with fill are almost identical. They are also both lower than the WARM and BEAM estimates for carbon storage.

	Bulk Density	Carbon	Carbon storage	CO_2 per Mg compost
	g cm_3	%	Mg ha_{-1}	
Control	1.66	2.24	3.72	
Fertilizer	1.66	2.41	4	
Food/Yard Compost high	0.3	11.2	3.36	0.21
50:50 Compost: Fill	1	7.24	7.24	0.20

Table 3. Observed changes in soils at the Vashon Borrow pit following compost addition

It is possible to see how these values compare with other regional restoration projects. Mine sites in Washington and British Columbia were sampled that had been restored with biosolids (Trlica and Brown, 2013). The site in Centralia was a coal mine, in Highland Valley, a hard rock copper mine and in Sechelt a sand and gravel mine. In Centralia, very high loading rates along with a heavy application of topsoil sourced from outside the area resulted in a low Mg CO_2 per Mg biosolids. For the other two sites, where lower rates of amendment were applied, similar and higher rates of storage were observed. This project also included an estimate of tree growth response for sites that are restored to forestry. The study, which focused on response to biosolids amendment, anticipated an additional >200 Mg CO_2 per ha^{-1} in above ground tree biomass over a thirty-year period. Tree growth response will be discussed in the landscape section.

	Application rate	Excess soil C storage	CO_2
		Mg C per Mg amendment	
Centralia	560	0.03	0.11
Sechelt	50-486	0.31	1.14
Highland Valley	135	0.28	1.03

Table 4. Carbon storage from use of compost at mine sites (Trlica and Brown, 2013)

The results from Sechelt and Highland Valley show higher storage than was observed at the Vashon site. The important point here is that storage associated with restoration projects will vary based on initial site conditions, quantity of amendment and targeted end use. It also makes clear that picking a single figure for restoration sites is problematic. The results suggest that somewhere between 0.2 and 1.0 Mg CO_2 per Mg compost is a reasonable range. To be conservative, it would seem that 0.4 Mg CO_2 per Mg compost would be a reasonable approximation. This is equivalent to:

0.4 Mg CO_2 per Mg compost * 0.2 Mg food scraps per ton compost = 0.08 Mg CO_2 per ton food scraps.

Home Garden and Public and Commercial Landscapes

The original request by the Solid Waste Division, as well as the distributions reported by Cedar Grove and Lenz, separates this end use into multiple categories. However, for all of these, the final landscape and level of maintenance is likely very similar. The vegetation for these categories is almost certainly a mix of grasses and landscape plants. Whether this is in someone's home garden or on the property of a commercial or public building, there is a high potential for the landscapes to be well tended and watered. The carbon benefits associated with this type of end use will depend on the level of maturity of the landscape. A new garden, characteristic of new construction will likely have poor soil and will respond with relatively high rates of carbon storage. In contrast, compost use in a well- tended older garden typical of a garden on a home greater than thirty years old will likely result in lower carbon storage as the soil is already enriched. Here also transportation can play a more significant role as this is one category where individual homeowners are likely to use personal vehicles to buy relatively small quantities of compost.

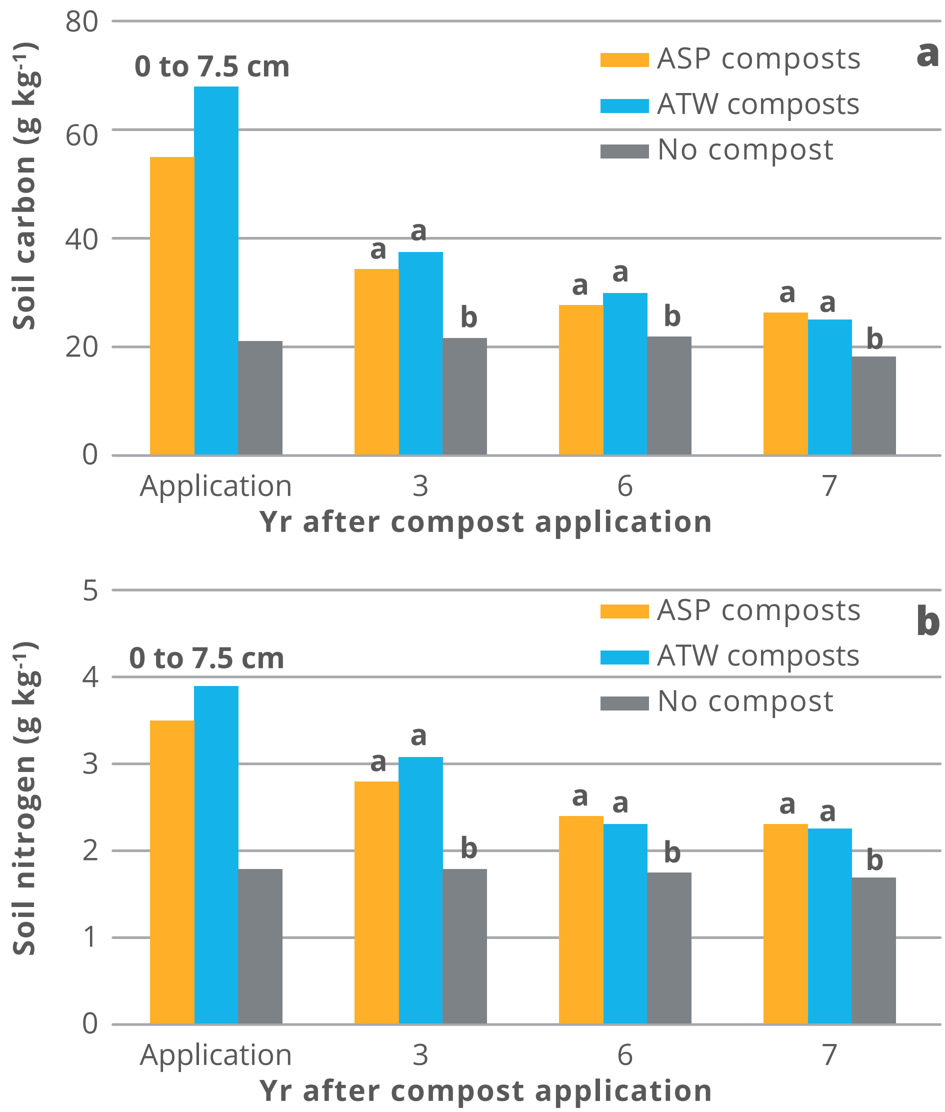

Figure 3. Effect of aerated static pile (ASP) and aerated turned windrow (ATW) composts on soil C (a) and N (b) concentration. Bars with a different letter within a sampling date are significantly different at P = 0.05. Soil C and N concentration for the compost-amended soil at application (Year 1; 1993) was calculated using the compost C and N application rate listed in Table 1, assuming that all of the compost was incorporated into the Oto 7.5 cm depth.

Lawns, or turf grass, cover the largest acreage of any irrigated crop in the US. Studies have looked at cycling of carbon and nitrogen in these systems and generally found them to be carbon sinks (Groffman et al., 2009; Martinez et al., 2014; Milesi et al., 2005; Pouyat et al., 2006). Lawns can accumulate carbon for several decades after establishment (Golubiewski, 2006). One study found a rate of C accumulation of 0.08 kg C m^{-2} yr^{-1} for urban soils converted from agriculture to turf grass (Raciti et al., 2011). Accumulation for soils converted from forest to lawns was much less significant. This study was conducted on yards in Maryland and so forest soils were likely coniferous. This and other studies have also seen that differences in soil series have minimal impact on characteristics and carbon storage in soils under well- established turf grass.

There is a significant amount of research related to use of compost for turf grass. For example, a recent study tested different depths of compost addition +/- incorporation for turf establishment in Virginia (Evanylo et al., 2016). The higher rate of compost (a pulp sludge-based material) had increased carbon in comparison to the other treatments. All composts showed superior growth in comparison to the fertilizer treated soil. There has also been work done in the Pacific Northwest. Sullivan et al (2003) sampled long-term turf grass plots that had received yard/ food compost and measured changes in soil nitrogen and carbon. They observed persistent increases in concentrations in both elements. Results are shown below. The soil in this study was classified as a Mollisol. This soil type has very high carbon concentrations in the surface horizon. That likely impacted the fraction of total carbon that remained in the soil over time. The authors found that with an amendment addition rate of 155 Mg ha^{-1}, 18% of the added C remained in the soil 7 years after addition.

A more recent study sampled long-term local sites for the specific purpose of quantifying soil carbon storage as a result of amendment addition (Brown et al., 2011). This included sampling soils from the above- mentioned study. Most of the data shown below was collected from sites 7 to 15 years post application of amendments. Roadside was the exception with sampling two years post amendment addition. All of the turf sites sampled for this type of end use had relatively high starting carbon concentrations ranging from 1.94 % C to 3.55 % C. The Landscape study and the Roadside study had relatively low carbon concentrations to start; 1.01 and 0.4%, C, respectively. Results show a relatively consistent rate of carbon storage per Mg of amendment added for turf and landscape ranging from 0.15 to 0.29 Mg CO_2 per Mg amendment. The one exception here was compost addition to roadside soils. This study showed much higher rates of carbon storage (1.28-1.72 Mg CO_2 per Mg amendment). This could be the result of the shorter time since amendment addition and/or the much more disturbed condition of the control soil. The disturbed condition of the control soil is evidenced by the low carbon content and high bulk density (>2.0 g cm^3).

	Planting	Soil type	Amendment	Total application	Net C per Mg amendment	As CO_2
				Mg ha^{-1}		
Landscape	mixed shrubs	Mollisol	Compost	224	0.08	0.29
Roadside	mixed shrubs	Disturbed	Compost/biosolids	Compost	0.35	1.28
				Biosolids	0.47	1.72
Turfgrass	turf	Inceptisol	Compost	149	0.06	0.22
				224	0.08	0.29
				298	0.06	0.22
Fescue compost	turf	Mollisol	Compost	157	0.06	0.22
Fescue biosolids	turf	Mollisol	Biosolids	67	0.08	0.29
				134	0.09	0.33
				201	0.04	0.15

Table 5. Compost storage per dry Mg amendment for urban end use sites in WA state sampled in Brown et al., 2011

These results can be used as a basis for estimates of carbon sequestration for use in landscape projects. For the study on biosolids compost that was done for King County, different rates of sequestration were used for well-established landscapes and new landscaping done on disturbed or low -quality soils (Brown and Beecher, 2019). This publication suggested a range of potential credits for compost use on well-maintained landscapes ranging from 0.01-0.1 Mg C per Mg compost. The publication used 0.01 Mg C as a low- end conservative estimate (CO_2 of 0.036). However, it is also reasonable to consider the other end of the range (-0.36 Mg CO_2 per dry Mg compost) for well -established lawns. A more significant credit of -1.1 Mg CO_2 was used for newly established landscapes. As the food/

yard compost will have similar nutrient characteristics as the biosolids composts, and as results shown above were similar for the two materials, it is reasonable to use the same values for this estimate. This is equivalent to:

-0.36 Mg CO_2 per dry Mg compost * 0.2 dry tons of food scraps per dry Mg compost = 0.073 Mg CO_2 per wet ton food scraps

-1.1 Mg CO_2 per dry Mg compost * 0.2 dry tons of food scraps per dry Mg compost = 0.22 Mg CO_2 per wet ton food scraps

Construction projects

Regional composters report that a portion of their compost is used on construction projects. The Solid Waste Division also asked for a balance for this end use. The results here are also directly applicable to a Compost EPD for the EC3 tool. During construction, it is common for topsoil to be removed or stockpiled. Subsoil is typically exposed. The stockpiled topsoil is returned to the exposed landscape post construction. Depending on the care taken during removal and storage, there is a potential that a portion of the topsoil will consist of subsoil and that some of the organic fraction of the stored material will be lost. In all of these cases, the remaining surface soil is likely to be relatively low in organic matter and would respond to compost additions. It is also likely that the gardens/ yards/ landscapes that receive the compost, once established will be well maintained. This type of end use would fall under the higher rate of sequestration of -0.22 Mg CO2 per wet ton food scraps. Construction projects will typically require sufficiently large enough loads of compost to require delivery by a commercial vehicle. In addition to higher rates of carbon sequestration, this type of use would also have lower transportation emission costs.

Established gardens/ landscapes

A significant volume of compost is used for private consumer use. The Lenz facility replied that 50% of their compost sales were to private consumers. Cedar Grove did not provide a breakdown but replied that sales of bagged product (almost certainly to individual homeowners) were a significant portion of their distribution. For both of these cases, it is likely that the primary use is to dress established gardens. Here sequestration rates would fall into the lower range- -0.073 Mg CO_2 per wet ton food scraps. The Lenz website offers product delivery. The likelihood here is that loads would be larger than 1 yard and would be made using a larger capacity truck. For the bagged material sold by Cedar Grove, transport would most likely be done using personal vehicles.

Stormwater infrastructure

Stormwater infrastructure is increasingly relying on alternatives to engineered systems. Bioretention systems and raingardens are examples of Green stormwater infrastructure. These systems are typically constructed using a combination of sand and compost. Compost has been shown to be highly effective at limiting metal and organic movement and allowing for rapid infiltration of stormwater. The compost is also a critical component of these systems to facilitate plant growth. While these systems offer a wide range of benefits, they will tend to cover relatively small areas. There has been work to document the benefits associated with green stormwater infrastructure. As they, manufactured soils, are new, it seems logical to use the value for construction projects or new landscapes to estimate sequestration potential for these sites.

Roadside

There are a number of ways that compost can be used on right of ways (Brown, 2020). Soils along roadsides are never naturally occurring. They are engineered and typically leveled and compacted. This is one of the reasons that compost use along roadways is so effective at improving water infiltration and reducing erosion. Roadside use of compost is one of the largest single end markets for compost in Washington. With that there is potential to expand use. The only measure of soil carbon sequestration associated with roadside use was from a research project alongside Hwy 18 in Tacoma (Brown et al., 2011). Here very high sequestration rates (-1.28 Mg CO_2 per Mg compost or -0.26 Mg CO_2 per wet Mg compost) were observed. As this is a local measure, reported in a peer review journal, and as there are no comparable measures elsewhere in the literature, it seems appropriate to use this as a default value.

Agriculture

Agriculture is a potential end use of composted food scraps. Much of the default estimates from the EPA WARM model, the BEAM model and the peer review literature are based on agricultural use. A recent study measured changes in soil carbon with depth and found that adding compost was the only practice that resulted in soil carbon sequestration (Tautges et al., 2019). While winter cover crops increased carbon in the surface horizon by 3.5%, subsoil samples revealed a decrease of 10.8% in the 30-200 cm horizon. When compost was included in the rotation with cover crops a net gain of 12.6% (21.8 Mg C ha^{-1}) across the full profile depth was observed. The compost used was made from poultry manure and was applied at 4 Mg ha^{-1} for 19 years. Poultry manure is very high in nitrogen and so this material was likely added at lower rates than a food/ yard compost would have been. In addition to this study, recent work sponsored by the Marin Carbon project has also documented significant carbon benefits from use of composted dairy manure on rangeland in California. These more recent studies suggest that benefits from use of compost in agriculture may be underestimated.

For this estimate, data from long-term local sites was used, specifically samples agricultural sites for their measures of soil carbon storage (Brown et al. 2011). Two of the sites were orchards on the East side of the Cascades and another was from a study conducted at the Washington State University research center in Puyallup. All of the sites showed increased soil carbon in the surface horizons following compost addition. Net sequestration per dry ton of compost ranged from 0.37- 1.98 Mg CO_2. Expressed as wet tons of food scraps, this is equivalent to **0.073- 0.4 Mg CO_2 per wet Mg food scraps**. East side sequestration rates were similar to or higher than sequestration seen at the West side site. Here using the EPA WARM default value of **0.2 Mg CO_2 per Mg food scraps**, seems to be sufficiently conservative. It is also more appropriate to use that value instead of the literature values which are derived from studies done in Europe.

Site	Planting	Soil type	Amendment	Total application	Net C per Mg amendment	As CO_2
				Mg ha^{-1}		
Durfey		Aridisol				
	Pear		Compost	84	0.12	0.44
	Grape			91	0.14	0.51
	Cherry			105	0.15	0.55
	Hops			140	0.24	0.88
Dryden	Orchard	Mollisol	Compost	134	0.54	1.98
Puyallup	Vegetable rotation	Mollisol	Compost	68	0.1	0.37
				153	0.17	0.62

Table 6. Compost storage per dry Mg amendment for agricultural sites in WA state sampled in Brown et al., 2011

Alternative Daily Cover

An alternative use of compost is as daily landfill cover. Landfills are required to cover open cells with material to prevent erosion of materials inside the cells. This is in some ways similar to mechanical biological treatment of organics (MBT) that has been used as a means to reduce fugitive emissions from organics destined for landfills (Bilitewski et al., 2011; Montejo et al., 2013). The goal of MBT is to stabilize organics to reduce the potential for CH4 generation prior to landfilling. MBT can also include diversion to anaerobic digestion as an alternative to landfilling the organics. A newly released study used life cycle assessment (LCA) and a range of Monte Carlo simulations to compare the benefits of using compost derived from MSW as ADC or for home gardens (Sardarmehni et al., newly accepted). This study found that the use of compost, produced from the organic fraction of MSW, for ADC generally outperformed the use of the compost as a peat substitute. A range of assumptions were made in the study that led to this conclusion. For example, while this accounting has focused on food scraps, Sardarmehni et al included the organic fraction of MSW as a whole. The high rates of carbon storage predicted by WARM for yard waste and organics other than food scraps, almost certainly altered the impact of this analysis. The authors note the uncertainty in these assumptions and the variability in compost characteristics. Small changes in these assumptions would alter the outcome of the analysis. For example, the authors assumed that the compost would replace excavated soil as the default material for ADC. CalRecycle lists a range of waste derived materials that are approved for use as ADC. These include ash and cement kiln dust, auto shredder waste, construction and demolition debris, contaminated sediment and shredded tires. Compost is also listed. Basing the analysis on the use of an alternate waste material instead of soil might have resulted in a different outcome.

However, it does seem that use of finished compost for ADC would result in carbon storage and likely eliminate the majority of fugitive gas emissions associated with unstabilized organics. Sardarmehni et al. assumed that a portion of the compost would degrade in the landfill producing a mixture of CO_2 and CH_4. They also assumed that the organic material that did not degrade would remain sequestered in the landfill. With that said, it is difficult to derive specific sequestration factors for this end use. Assuming the full credit for methane avoidance, it seems logical to use the EPA WARM default value for the portion of carbon remaining from food scraps (16%) as a value for carbon sequestration in the landfill. Continuing with the WARM assumptions, the total carbon in food scraps is 51% on a dry weight basis (WARM model). That puts carbon storage per dry ton of food at 0.08% or 82 kg. Expressed as CO_2 on a wet weight basis with a solids content of 20%, that is **total storage of 0.06 Mg**. EPA reports this value as 0.077 Mg because of a higher % solids assumption. Using woody waste materials as ADC might be an option to consider. The high carbon sequestration rates that the WARM model provides for these materials in a landfill environment and their relatively low nutrient content suggest that using a portion of recycled woody material would maximize benefits associated with end use of these materials.

End use comparisons

I summed up the carbon costs/ credits for each of the different end uses. The values used are shown in the table below. As the SWD does not directly sell the compost and as end use of the product is not regulated, it is not possible to precisely define where the compost goes. In addition, without replicated trials for each end use with the specific compost, the default values should be considered as approximate values.

Methane avoidance was the most significant factor for each end use. The WARM value for CH_4 avoidance (-0.43 Mg CO_2 per Mg food scraps) was higher than the equivalent value generated by the BEAM model (-0.33 Mg CO_2 per Mg food scraps). The two models also have different factors for emissions during the composting process. The WARM default of 0.05 is based on fugitive emissions from composting. It is not clear that that would be a factor here as both Lenz and Cedar Grove use forced air systems that should minimize emissions. The BEAM debit is associated with energy use during composting. WARM has a debit for transport to the compost facility, however as transport would be required to the landfill, this wasn't considered in this accounting. Both the WARM and the BEAM provide default values for soil carbon storage, -0.2 and -0.17 Mg CO_2 per wet Mg food scraps. The WARM model does not include fertilizer avoidance. The BEAM model does and it is included in the -0.17 Mg CO_2 per Mg food scrap value. There is also a default value for carbon storage from the literature (-0.073). This is derived primarily from European studies of compost use in agriculture.

From the default values, there are region and end-use specific values and two values for transport. Both are based on a similar distance but one is by personal vehicle (0.018 Mg CO_2 per Mg food scraps) and the other by commercial truck (0.001 Mg CO_2 per Mg food scraps). The only end use where personal vehicles would be predicted is for bagged product for established landscapes. A fertilizer offset based on the reported N and P concentrations for the Cedar Grove compost (-0.22 Mg CO_2 per Mg food scraps) were also included. Values for different end use options are shown on next page. These are the different carbon sequestration values from local studies or best estimates.

	EPA WARM	BEAM	Literature	Local use
		Mg CO_2 per wet Mg food scraps		
Landfill diversion	-0.43	-0.33		
Composting process	0.05	0.017		
Compost use general	-0.2	-0.17	-0.073	
Transport				
Commercial				0.001
Personal				0.018
Fertilizer offsets			-0.022	
Restoration				-0.08
Landscaping				
New				-0.22
Established				-0.073
Highway				-0.26
Agriculture				-0.2
Daily Cover				-0.06
Stormwater				-0.22

Table 7. Summary of carbon values for default models and local end uses

Adding the different values for each end use and also showing the default values from the WARM and BEAM model, the total carbon balance for each end use is shown below. For each local end use, the EPA WARM model methane avoidance credit was used, as well as the EPA value for compost related emissions. Results for all end uses are generally similar. The least carbon is stored in mature landscapes where personal vehicles are used to pick up compost (-0.046 Mg CO_2 per Mg food scraps). The highest rates of storage are associated with use in new landscapes, highways, agriculture and stormwater systems.

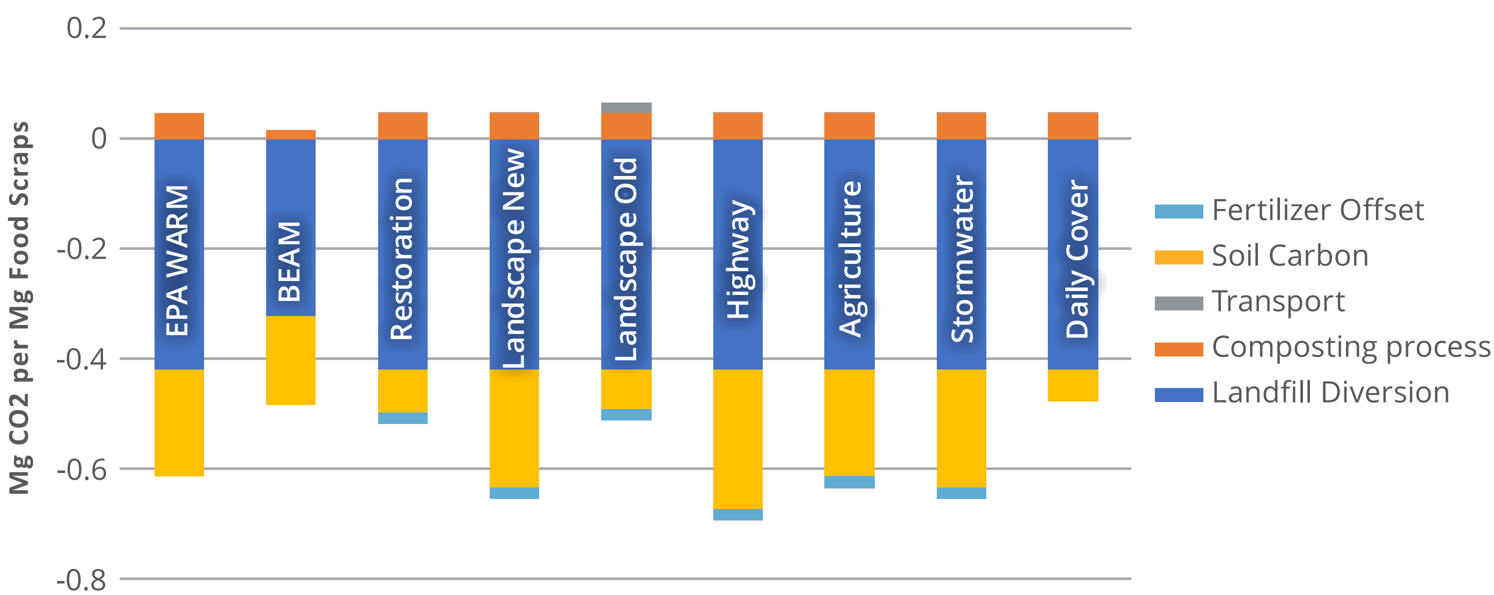

Figure 4. End summary/ balance for carbon balance of different end uses for composted food scraps

King County
Department of
Natural Resources and Parks
Solid Waste Division

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Carbon Accounting for Food Scrap Composting in King County, WA

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