Evaluation of Climate, Energy, and Soils Impacts of Selected Food Discards Management Systems

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Executive Summary

The Oregon Department of Environmental Quality (DEQ) commissioned a study to provide a systematic current literature review and harmonization of life cycle assessment (LCA) studies that cover one or more of four targeted food waste treatments:

1. Aerobic composting (AC),
2. Anaerobic digestion (AD),
3. In-sink grinding via a food waste disposer (ISG), flushing to sewer, and management with other sewerage at a wastewater treatment plant, and/or
4. Landfill (LF).

DEQ selected Dr. Sally Brown (University of Washington), Mr. Matt Cotton (Integrated Waste Management Consulting, LLC), Dr. H. Scott Matthews (Avenue C Advisors, LLC), and Dr. Jeffrey Morris (Sound Resource Management Group, Inc. – the designated project contractor on behalf of this consulting team) Funding for the project was provided through a grant from Metro, the regional government in the Portland, OR metropolitan area.

The consulting team was directed to record and assess climate, energy and soil productivity impacts for each of the food waste treatments. In addition to inventorying greenhouse gas (GHG) emissions and energy use for these treatments, the assessment noted energy displacements (e.g., electricity from AD or LF methane combustion replacing Oregon grid electricity), fertilizer and peat displacements by soil amendments produced via AC, AD and ISG, and other soil productivity benefits.

Material outputs from AC (compost), AD (digestate), and ISG (biosolids) have been shown to have potential for positive impacts on soil productivity. In general the LCA literature does not directly address soil productivity as an impact category. To supplement the review and harmonization of LCAs, Dr. Brown chronicled the scientific literature on increased plant and soil productivity resulting from organic amendments. From these studies, she developed a qualitative ranking for the four treatments for each of four separate categories of potential soil productivity benefits:

1. Soil carbon sequestration,
2. Fertilizer replacement,
3. Water conservation, and,
4. Yield increase.

Each of these benefits has the potential for impacts on climate and energy use. For example, soil carbon sequestration removes carbon from the atmosphere. Fertilizer replacement avoids energy use and emissions associated with the manufacture of synthetic fertilizers (and associated supply chain emissions). Water conservation can conserve energy associated with irrigation, and yield increase can reduce the carbon and energy footprint of each unit of food produced. However, each of these potential benefits also has additional benefits that extend beyond climate and energy impacts. For example, fertilizer replacement can reduce other environmental impacts (such as eutrophication) associated with the use of synthetic fertilizers. Soil carbon sequestration can improve water retention and increase yields. Water retention can reduce irrigation demands and conserve surface and ground waters for other uses. It can also increase yield, which has important impacts on food security.

Generally speaking, climate and energy impacts of fertilizer replacement and climate impacts of soil carbon sequestration are quantified in this study. Other benefits associated with soil productivity are not.

Rankings for climate and energy impacts from the LCA harmonization activity and the soil productivity benefits are displayed in Table ES-1. The rankings use 1 for best and 4 for worst.

Table ES-1: Impact Rankings for Food Waste Treatments

Treatment	Climate	Energy	Soil Carbon	Fertilizer Replacement	Water Conservation	Yield Increase
AC	2	4	1	2	1	1
AD	1	2	2	1	2	1
ISG	3	1	3	3	3	3
LF	4	3	4	4	4	4

As indicated in Table ES-1, each treatment's rankings vary depending on impact category. Aerobic composting (AC) and anaerobic digestion (AD) always rank first or second, except that AC ranks last on energy. This occurs because AC does not produce an electric power output whereas the other three do. Landfill (LF) always ranks last, except for energy where it ranks third, ahead of AC. In-sink grinding (ISG) is always third except for energy where it ranks first.

Section 3 of the following report discusses soil quality and the four soil productivity rankings in detail. Section 5 describes the harmonization process step-by-step that resulted in the rankings for climate and energy impacts.

Table ES-2 provides summary detail on harmonized impacts for each treatment's food waste management stages and the harmonized credits for the energy and material outputs of each of the 4 food waste management methods. Section 2 of the following report outlines the selection process for the 28 LCAs that were harmonized to produce Table ES-2. These 28 LCAs represent 19% of the 147 LCAs that were critically reviewed by the project team. The main reasons over 80% of the reviewed LCAs could not be harmonized were that a study turned out not to be an LCA despite the study title sounding like it would be, results were reported on a basis that could not be easily related to food waste quantity treated, and lack of sufficient information to do the detailed calculations necessary for harmonization.

Section 2 also discusses the reasons for conducting harmonization. Basically the non-harmonized LCAs use a wide range of assumptions and estimates for critical parameters such as nitrogen content of soil amendments produced by AC, AD and ISG; the LF methane capture rate and rate of using captured methane to generate electricity; and the extent to which soil amendments are used in ways that actually reduce the use of synthetic fossil fuel based fertilizers. Harmonization re-calculates each LCA's results on a consistent basis for important determinants of treatment impacts.

The other main reason for harmonizing results was that DEQ sought to make the results Oregon specific in terms of the carbon footprint for the credit from generating electricity, landfill methane capture efficiency, and the uses of soil amendments by Oregon households and businesses. For the latter purpose the project tasks included surveying Oregon businesses that compost food wastes and/or the digestate output from AD treatment. Based on the type of purchasers of compost the project team was able to portray some of the likely uses for AC, AD and ISG produced soil amendments. Section 4 of the report provides a discussion of the survey and survey results.

Table ES-2: Comparison of Harmonized Climate & Energy Impacts for Food Waste Treatment Options

Activity	Climate Impact (kg eCO_2 per kg food waste)				Energy Impact (MJ per kg food waste)			
	Aerobic Composting	Anaerobic Digestion	In-Sink Grinder	Landfill	Aerobic Composting	Anaerobic Digestion	In-Sink Grinder	Landfill
(LCA Sample Size)	(25)	(10)	(5)	(15)	(10)	(1)	(3)	(5)
Collection & Transport	0.04	0.02	0.05	0.03	0.68	0.68	0.39	0.51
Processing	0.11	0.09	0.23	0.69	0.66	0.58	0.54	0.57
Carbon Storage	-0.12	-0.08	-0.03	-0.12				
Fertilizer Displacement	-0.03	-0.02	-0.05		-0.09	-0.15	-0.22	
Peat Displacement	-0.04				-0.03			
Electricity Displacement*		-0.17	-0.18	-0.08		-0.83	-1.03	-0.48
Total Impact (Net)	**-0.05**	**-0.17**	**0.03**	**0.52**	**1.23**	**0.29**	**-0.32**	**0.60**

*Oregon grid carbon footprint reflected in electricity displacements for climate impacts. However, the Oregon grid primary energy demand footprint is not used for calculating the energy value of electricity displacements. Electricity displacements are calculated at the energy value of a kilowatt hour (kWh) -- 3.6 megajoules (MJs). Conversion of electricity to energy using the 3.6 MJ/kWh ratio is known as the direct equivalence method. However, different electricity generation sources have different conversion efficiencies. Using the primary energy equivalent method to account for these sources would increase electricity displacements by a factor that varies based on the source. Fossil fuel factors range from 2 to 3, and renewable source factors range from 1 to 10. A rough estimate of the overall factor for Oregon is likely between 3 and 5 based on US EPA eGRID 2010 data.

Table of Contents

1. Introduction 1
Project Purpose & Summary of Project Tasks 1
2. Literature Search and LCAs Selection & Need for Harmonization 3
Acquisition of LCA Studies for Initial Review 3
Selection of LCAs for Harmonization 3
Initial Review Reveals Need for Harmonization 5
Distinguishing Food Waste Contribution to Treatment Impacts for Mixed Organics 7
3. Soils -- Organic Amendments & Their Impacts on Soil Productivity 9
Role of Soils 9
Ranking of Soil Productivity Benefits for Food Waste Treatment Methods 10
Current State of Soils 12
Organic Amendments and Soils 12
Summary 24
Agriculture in Oregon 24
References 28
4. Oregon Composters Survey Results 35
Type 3 Food Scraps Composting in Oregon 35
Survey Data 36
End Uses for Compost 36
Compost Analysis 38
Digestate 38
Previous Survey of Composters in Oregon 38
Conclusions 40
5. Harmonization Results for Climate & Energy Impacts 41
Step-by-Step Harmonization Results 43
Limitations and Future Research Recommendations 54
6. Appendix A – LCA Bibliography 56
7. Appendix B – Soil Qualities 68
Soil Basics 68
8. Appendix C – Composters Survey Instrument 73

1. Introduction

Project Purpose & Summary of Project Tasks

The Oregon Department of Environmental Quality (DEQ) commissioned a study to provide a systematic current literature review and harmonization of life cycle assessment (LCA) studies that cover one or more of four targeted food waste treatments:

5. Aerobic composting (AC),
6. Anaerobic digestion (AD),
7. In-sink grinding via a food waste disposer (ISG), flushing to sewer, and management with other sewerage at a wastewater treatment plant, and/or
8. Landfill (LF).

DEQ selected Dr. Sally Brown (University of Washington), Mr. Matt Cotton (Integrated Waste Management Consulting, LLC), Dr. H. Scott Matthews (Avenue C Advisors, LLC), and Dr. Jeffrey Morris (Sound Resource Management Group, Inc. – the designated project contractor on behalf of this consulting team) Funding for the project was provided through a grant from Metro, the regional government in the Portland, OR metropolitan area.

Impact factors the consulting team recorded and assessed in the literature review are energy, greenhouse gases (GHGs), and agricultural practices/soil productivity – for example, increased soil carbon and water holding capacity and decreased soil erosion. In addition to inventorying energy use and GHG emissions from these treatments noted in the reviewed literature, the consulting team assessed energy displacements (e.g., electricity from AD, ISG or LF methane combustion replacing grid electricity), synthetic soil supplement displacements in agricultural practices (e.g., AC compost or AD digestate as a nutrient source for plants replacing synthetic fertilizer and thereby reducing fertilizer manufacturing energy and GHG emissions), and soil productivity improvements (e.g., higher soil carbon as a result of both compost/digestate amendments and increased plant productivity, with the latter in turn due to those amendments).

DEQ requested review of research regarding soil productivity related to the use of organic soil inputs from the treatment methods (compost, digestate and sludge) because soil productivity directly affects food production and climate and energy impacts. In general the LCA literature does not directly address soil productivity as an impact category. The LCAs we reviewed also did not discuss soil productivity impacts such as water holding capacity or decreased soil erosion. For these reasons Dr. Brown chronicled the scientific literature on increased plant and soil productivity resulting from organic amendments. Her findings are discussed in Section 3 (Soils, Organic Amendments & Amendment Impacts on Soil Productivity).

The initial literature review selected a subset of LCAs for harmonization. Section 2 (Literature Search, Selection of LCAs for Harmonization & Need for Harmonization) narrates methodology for finding studies to review, harmonization subset selection procedure and need for harmonization. Section 2 also provides methodology used in the harmonization process for sorting out food waste impacts from overall organic waste impacts in an LCA that studies organic wastes that include a mixture of food wastes and other organic discards.

Section 3 (Soils, Organic Amendments & Amendment Impacts on Soil Productivity) includes a brief discussion of soil science. This provides context for that section's review of findings on soil productivity effects of compost and digestate amendments in agriculture and horticulture. Research findings discussed in this section are mostly reported in the agriculture experimental and growth trials literature rather than the LCA literature. Hence a summary of that research is provided in this section to supplement the harmonization of food waste LCAs. This is necessary especially because reviewed LCAs did not directly address soil productivity impacts and benefits from soil amendments that are produced as a result of food waste treatment. This section also provides a qualitative ranking of the 4 food waste treatment options with respect to soil carbon sequestration, fertilizer replacement, water conservation and crop yield increase.

Section 4 (Oregon Composters Survey Results) outlines results from our survey of composters and anaerobic digesters operating in Oregon. The survey investigated, among other things, whether composters accept food wastes and what types of users buy or use compost and digestate products from these compost producers.

Section 5 (LCA Harmonization Results for Climate and Energy Impacts) summarizes findings from our harmonization of food waste LCAs and the resultant rankings of the four food waste treatments with respect to GHG emissions and energy use. Carbon storage and the impacts of fertilizer/peat replacement on GHG emissions and energy use are taken into account in the harmonization. However the harmonization only dealt with these organic soil amendment benefits in so far as they influence GHG emissions or energy use for each of the 4 treatments. For this reason Section 3 provides a qualitative ranking for the 4 treatments with respect to each of 4 separate categories of soil productivity benefits from organic amendments, 2 of which are soil carbon sequestration and fertilizer replacement.

2. Literature Search and LCAs Selection & Need for Harmonization

Acquisition of LCA Studies for Initial Review

We reviewed 147 studies, most of which were completed during the past fifteen years, from a wide variety of sources. Most studies were published in peer-reviewed journals such as *Agronomy for Sustainable Development; BioResources; Bioresource Technology; Compost Science Utilization; Critical Reviews in Environmental Science & Technology; Critical Reviews in Plant Sciences; Energy Conversion & Management; Energy & Environmental Science; Environmental Modeling & Assessment; Environmental Science & Technology; International Journal of Energy & Environmental Engineering; International Journal of Life Cycle Assessment; Journal of Cleaner Production; Journal of Environmental Engineering; Journal of Environmental Management; Journal of Environmental Quality; Journal of Hazardous Materials; Journal of Industrial Ecology; Renewable & Sustainable Energy News; Renewable Energy; Resources, Conservation & Recycling; Science of the Total Environment; Waste Management; Waste Management & Research; Water & Environment Journal; and Water Science & Technology*.

Other studies came from trade journals such as *BioCycle*, LCAs funded by private and public sector entities, or publications of public agencies such as U.S. EPA. Some of these works were themselves formally peer-reviewed, and nearly all were at least reviewed in some manner by their funders or publishers.

We acquired reference to these studies through internet and academic database searches, a bibliography of 82 LCA and other studies on organics waste management previously developed by two team members for the Alberta Ministry of the Environment, bibliographies supplied by DEQ staff, bibliographies suggested by other applicants for this project, references found in searches by EPA Region 9 library staff, references in reviews of LCAs on food waste management, and consultations with colleagues. Appendix A provides the list of all 147 studies collected for the initial review.

Selection of LCAs for Harmonization

Table 1, Exclusion Criteria & Counts for Excluded LCAs, lists the criteria used to decide that a reviewed LCA was lacking in some aspect that was needed to provide the study with potential for successful harmonization. The criteria, which were proposed by the study team and vetted by DEQ, are listed in the order in which they typically were applied. Once a study was determined to be lacking according to one of the listed criteria, it was dropped from scrutiny for the other criteria. Hence the counts do not reveal whether any LCAs would be excluded on more than one criterion.

The first exclusion criterion is that the study was not an LCA. It's often difficult to determine from a study's title whether it relies on formal LCA methodology and provides its quantitative results using LCA techniques. 40 of the 147 reviewed studies turned out not to be LCAs. For example, some studies provided growth experiment results useful in evaluating the likely impacts on agricultural productivity from amending soils with compost or biosolids. However, such studies did not attempt to measure LCA impacts such as greenhouse gas emissions or energy use of any particular food waste treatment method across a reasonably comprehensive set of activities for a treatment that would be necessary to produce these soil amendments.

Table 1: Exclusion Criteria and Counts for Excluded LCAs

Criteria for Excluding LCA from Harmonization	LCA Study Counts
Reviewed LCA Studies	147
Not an LCA	40
Review Study of LCAs	16
No Assessment of Targeted Food Waste Treatments	8
Functional Unit Not Food Waste Based	36
System Boundary Not Clear	0
Input-Output Data Not Detailed	12
Duplicative	7
Studies Harmonized	28

Another 16 studies reviewed LCAs on food waste management methods, but did not themselves conduct LCAs. At the same time, these studies were useful for providing references to additional LCAs included in our review. LCA reviews also proved useful for checking on LCA parameters and assumptions that are important for the harmonization process. In fact, 108 of the 147 studies were noted for having information on treatment method parameters and/or performance that could inform determination of values for parameters and assumptions that require harmonization.

Eight of the reviewed LCAs did not include any of the four food waste treatment methods targeted for this project. Furthermore, 36 did not have a functional unit that could be readily related to this project's functional unit of one ton of food waste across the various treatment methods. Lack of functional unit comparability prevents use of results from these 36 LCAs.

After excluding LCAs for the four reasons just discussed we did not find any of the remaining LCAs that were unclear about system boundary issues, such as whether an LCA addressed energy and/or material displacements as a result of energy or material outputs of the food waste treatment methods.

Twelve of the reviewed LCAs had summary results, but did not report quantitative results for the unit processes and energy or material outputs that were assessed to determine the summary results for the wastes the targeted system was treating. Lastly, 7 LCAs were duplicative. For example, the supporting

LCA documents for the Canadian EPA's Waste Reduction (WARM) model for the most part covered LCA results discussed in supporting documents for U.S. EPA's WARM model. This is no accident since both sets of documents were prepared by the same consulting firm.

The 28 LCAs that passed all exclusion criteria and were selected for harmonization are marked with an asterisk in Appendix B.

Initial Review Reveals Need for Harmonization

Review of the 147 LCAs revealed a wide variation in results, even for the same impact from just one of the targeted treatments for managing food wastes. One might expect different treatments to have very different results for a given impact. However, finding that the estimated impact for a given treatment also varies substantially from one LCA to another is rather surprising. It also is indicative of the need to harmonize results of different studies prior to relying on those studies to provide guidance or rankings for the four targeted food waste treatments.

Table 2, Ranges for Non-Harmonized Climate and Energy Impacts per Metric Ton of Food Waste, shows the range of results (from minimum to maximum) prior to harmonization for climate and energy impacts in the 28 LCAs selected for harmonization. The table indicates in parentheses the number of LCAs addressing each impact for each treatment method. Impact measures detailed in Table 1 are:

- Global Warming Potential (GWP) Increase (>0) or Displacement (<0) – greenhouse gas (GHG) emissions measured in metric tons (MT) of carbon dioxide equivalents (eCO_2) per metric ton of food waste treated.
- Energy Use (>0) or Displacement (<0) – measured in gigajoules (GJ) per metric ton of food waste treated.

Table 2: Ranges for Non-Harmonized Climate and Energy Impacts per Metric Ton of Food Waste

Treatment Method	GWP (MT eCO_2)	Energy (GJ)
AC	-1.12 to 0.47 (25)	0.18 to 3.63 (10)
AD	-0.48 to 0.03 (10)	-2.25 (1)
ISG	0.00 to 0.44 (5)	0.19 to 0.81 (3)
LF	-0.26 to 0.91 (15)	-2.15 to 1.20 (5)

The main finding represented in Table 2 is the wide range of impact estimates for each treatment, except in the case of AD energy impacts which were assessed in only one study. For example, aerobic composting one metric ton of food waste had climate impacts across 25 LCAs ranging between -1.12 and +0.47 MT eCO_2. At the extreme low end, one LCA estimated that applying FW compost produced by an

AC facility to lawns, gardens or agricultural land increases carbon sequestered in soil and reduces the use of synthetic fertilizer, with a resultant savings of the fossil carbon emissions needed to produce chemical fertilizer. These fossil emissions reductions offset the GHG burden of AC to such an extent that overall GHG emissions were over a metric ton lower than what they would be if the lawns, gardens or agricultural land were treated with chemical fertilizers.

On the other hand, the high end LCA outlier estimated that food waste composting would increase GHG emissions by 0.47 MT eCO_2 per MT of food waste composted. This LCA did not include any estimates for soil carbon storage, fertilizer displacement or any other potential benefit from the use of produced compost. In short, the unharmonized results show substantial quantitative differences in composting impacts, and vary from indicating composting has a positive climate impact to showing that composting harms the climate

A second example of variation in results and the possible causes of such variations is provided by the 15 LCAs that assessed the landfill treatment method for food wastes. These LCAs' estimates for climate impacts ranged between -0.26 and +0.91 MT eCO_2. The low end LCA used an offset for electricity generated from captured landfill methane that assumed the displaced electricity was generated by a mix of power plants fired 72.5% by coal and 27.5% by natural gas. The high estimate assumed that landfill methane capture efficiency of just 45%, with only 12% of this captured methane used to generate electricity.

These two examples illustrate some of the reasons for pursuing harmonization of the factors that caused results among the 28 selected LCAs to differ so substantially. Some of the factors that can have significant effect on LCA results are illustrated in these examples. They suggest questions that need to be addressed before using results from the selected LCAs to rank food waste treatment methods with respect to climate and energy impacts:

- Which benefits from using compost and digestates are included?
- What energy and material quantities are displaced by energy and materials generated by food waste treatment?
- What type energy is displaced by energy generated from food waste treatment?
- Is landfill carbon storage included?
- What LFG capture rate is used in the LCA?
- Are infrastructure, facility, machinery and vehicle production impacts included?
- Are food waste collection impacts included in AC, AD and LF LCAs?
- Are collection bag and container manufacturing impacts assessed?
- Should biogenic CO_2 emissions be included?

The harmonization results reported in Section 5 deal with these questions and attempt to resolve inconsistencies in the LCAs due to different researchers having different approaches for, and answers to, such questions.

The second thing to notice about the entries in Table 2 is that GWP impact estimates have been included more often in LCAs for each treatment than are energy impacts for each treatment. Furthermore, soil quality and productivity impacts are not addressed in the table at all. This raises a concern that relying on existing LCA literature for selection of treatment methods may be too one dimensional, as existing studies may devote too little attention to important environmental and human health impacts such as soil productivity impacts, and impacts not researched for this project such as human and ecosystem health impacts of air, water and land emissions from the four targeted food waste treatments. The latter was one of the findings of the research on organic waste management methods that two of the team members were part of conducting for the Alberta Ministry of the Environment.[1]

The LCA literature does not include soil quality or productivity as an impact category. This gap needed to be addressed by expanding the project's literature review to include studies on the soil productivity benefits of soil amendments produced by the food waste treatments examined in this review. Section 3 provides a discussion and compendium of this research and the resultant qualitative ranking of the four treatment methods with respect to four categories of soil productivity benefits:

- Soil carbon sequestration
- Fertilizer replacement
- Water conservation
- Yield increase

The qualitative rankings for soil productivity benefits displayed in the following section are intended to be companion results for use with the quantitative rankings for climate and energy impacts developed from the 28 LCAs harmonized according to the methodology detailed in Section 5.

Distinguishing Food Waste Contribution to Treatment Impacts for Mixed Organics

In addition to providing critical review and harmonization of current LCAs on four food waste treatment methods, DEQ also requested the project team to indicate methods that were used to isolate impacts of food waste when analysis of the literature indicated that food waste was mixed with other organic feed stocks, such as yard debris..

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[1] Morris, J.; Matthews, H.S.; Morawski, C. Review and Meta-Analysis of 82 Studies on End-of-Life Management Methods for Source Separated Organics. *Waste Management*, **2013**, 33(3), 545-551; Morris, J.; Matthews, H.S.; Morawski, C. Review of LCAs on organics management methods & development of an environmental hierarchy **2011**, prepared for Alberta Environment by Sound Resource Management Group, Inc.

The method used to disentangle results in the LCA by Yoshida *et al* (2012) provides the best example of our methodology. This study was the only one that presented a problem in this regard because other studies selected for harmonization tended to focus only on food wastes.

Our methodology was based on quantity and quality information provided in the Yoshida study for the mixed organics stream used to estimate results in that study. The availability of such detailed data was important in the decision to select this study for harmonization. Data included, among other things, wet weight, methane potential, moisture content, carbon content and nitrogen content for each feedstock – food scraps, contaminated paper, yard waste, pet waste and diapers. Given estimates for such variables as fertilizer substitution by AC compost or methane captured for LF electricity, it was straightforward to estimate the food waste component. For example, based on the methane potentials for each feedstock we computed the weighted mean methane potential for the mixed organics and compared that to methane potential for food waste alone.[2] Similar calculations were done for nitrogen. These calculations showed that food waste had 1.27 times more methane potential than the mean for collected organics, and 1.18 times more nitrogen. These factors were then applied to the Yoshida study estimates for LF electricity generation and AC compost fertilizer substitution to obtain the estimates for these two variables from just the food waste component of the mixed organics.

Similar calculations were carried out to disentangle the food waste component for other outputs of the AC, AD and LF treatments assessed in this study. In addition, for LF carbon storage we had to bring in information from other research studies to determine the percent of carbon in a material that is not degraded under the anaerobic conditions in a landfill. Laboratory scale studies by Dr. Morton Barlaz at North Carolina State University, referenced in Morris (2010a), provided estimates of carbon storage for organic materials in landfills. We combined those estimates with the material quantity and carbon content estimates in Yoshida *et al* (2012) to calculate that food waste stored only 30% as much carbon as the mean storage estimate for the mixed organics.

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[2] This calculation assumed that all the organic materials had the same decay rate over time in a landfill.

3. Soils -- Organic Amendments & Their Impacts on Soil Productivity[3]

--- by Sally L. Brown, University of Washington

Role of Soils

Soils play a critical role in a range of ecosystem services. The value of ecosystem services was quantified as $33 trillion annually (Costanza et al., 1997). These services include production of raw materials such as food and fiber, supporting natural processes including nutrient cycling, cultural services, and regulating services including waste treatment and air and water regulation (Millennium Ecosystem Assessment). Each of these can be related directly or indirectly to soil. A soil's ability to hold and store water, to transform wastes and nutrients, to store carbon (soil is the third largest carbon sink, behind oceanic reserves and fossil fuels), and to support plant growth are clear services attributed to soils (Clothier et al., 2009; Costanza et al., 1997; Doran, 2002; Robinson et al., 2013). There have been recent efforts to quantify the value of soils in relation to these services. One study attributed 17% of the gross national product of New Zealand directly to soil resources (Kirkham and Clothier, 2007). The value of macropores, the larger void spaces in soils that allow for movement of water and diffusion of gas to and from the atmosphere into the soil, in soils and the services associated with those pores was valued at $304 billion annually (Clothier et al., 2008).

Soil valuation has not progressed to the point where the value of a particular soil can be quantified. While tools like life cycle assessment have enabled a fuller understanding of the environmental ramifications of different systems, no comparable tools have been developed for soils and their associated services.

Despite the growing recognition of the importance and value of soils for supporting ecosystem services, there are very few to no incentives in the US that encourage soil preservation and improvement. Currently the best tool available in the US for quantifying the value of soils is the USDA Conservation Reserve Program (CRP) that pays farmers to leave sensitive soils fallow in order to preserve and protect them. The program currently includes 140,000 km^2 with annual payments of $1.8 billion (Robinson et al, 2013). This is equivalent to a payment of $241,000 to develop 15 cm of topsoil at a soil formation rate of 0.008 cm yr.

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[3] See Appendix B for a discussion of the basics for soil science.

Ranking of Soil Productivity Benefits for Food Waste Treatment Methods

The LCA literature does not have an impact category that directly addresses soil quality and soil productivity. At the same time LCAs reviewed for this project did account for the climate impacts of changes in soil carbon storage and displacements of synthetic fertilizers and pesticides induced by use of composts, digestates and biosolids produced from food wastes. To provide a more direct assessment of the relative impacts of the four food waste treatment options examined in this report, a qualitative ranking was developed for their impacts on four separate categories of potential soil productivity benefits:

- Soil carbon sequestration
- Fertilizer replacement
- Water conservation
- Yield increase

Each end use/disposal category was ranked on a scale of 0 to 5 with 5 representing optimal benefits for each of the different categories. This is meant to be a qualitative ranking with general trends represented rather than exact values. Table 3 displays the results of this qualitative ranking exercise.

Table 3: Qualitative Assessment of Food Waste Management Options on Soil Related benefits (based on Brown *et al*, 2010; Brown and Cotton, 2010; Brown *et al*, 2011; Trlica and Brown, 2013; and Recycled Organics Unit)

	Soil carbon	Fertilizer replacement	Water conservation	Yield increase
AC	5	4.5	5	5
AD	5	5	4	5
ISG	2.5	2.5	2	2.5
LF	1	0	0	0

Each of these benefits has the potential for impacts on climate and energy use. For example, soil carbon sequestration removes carbon from the atmosphere. Fertilizer replacement avoids energy use and emissions associated with the manufacture of synthetic fertilizers (and associated supply chain emissions). Water conservation can conserve energy associated with irrigation, and yield increase can reduce the carbon and energy footprint of each unit of food produced. However, each of these potential benefits also has additional benefits that extend beyond climate and energy impacts. For example, fertilizer replacement can reduce other environmental impacts associated with the use of synthetic fertilizers. Soil carbon sequestration can improve water retention and increase yields. Water retention can reduce irrigation demands and conserve surface and ground waters for other uses. It can also increase yield, which has important impacts on food security.

As noted above, climate and energy impacts of fertilizer replacement and climate impacts of soil carbon sequestration are already included in the climate and energy impacts quantified in this study. Other benefits associated with soil productivity (including non-climate and energy benefits of soil carbon sequestration and fertilizer replacement) are not. Thus the study provides this additional evaluation of the impact of food waste treatment methods of soil productivity, and the characteristics of soil carbon, fertilizer replacement, water conservation and yield increase.

For soil carbon sequestration the highest rankings were given to AC and AD. Here it was assumed that AC, AD, and ISG would result in end products that were land applied rather than landfilled. If material outputs from AC, AD or ISG were landfilled, the score for soil carbon would be the same as for landfilling. AC and AD were given the highest scores because, although each would lose a portion of the fixed carbon during the stabilization process, the remaining carbon would be used to improve soil quality. Improved soil quality would result in increased plant growth, further increasing soil carbon sequestration over time. ISG was rated lower as a significant portion of the fixed carbon is likely to be lost during aerobic treatment at the wastewater treatment plant. Landfilling results in some soil carbon credit. However, as the sequestered carbon does not enhance plant growth and as a portion of the carbon that is landfilled is likely to evolve as methane (CH4), the ranking value for LF is low.

Fertilizer replacement showed very similar and high rankings for AC and AD. Anaerobic digestion preserves nitrogen and phosphorus whereas composting can result in a loss of a portion of the total nitrogen. The nutrients in the digestate are also typically concentrated in comparison to the compost. For these reasons, AD was ranked slightly higher than Compost. ISG was lower as a portion of the nitrogen is likely to be lost during secondary treatment at the wastewater plant. The nutrients in the landfilled material are not used to support plant growth so the score for that option is zero.

AC compost ranked highest for water conservation. Composts are often applied at high rates as a soil conditioner. High rates of organic amendment are required, either as multiple applications over time or a high single application, to show water conservation benefits. Digestate from AD ranked slightly lower, primarily because application rates for these materials are typically made to meet the fertilizer requirements for a crop. It is expected that over time, AD benefits would be similar to AC. ISG ranked lower, again because of the carbon volatilized during aerobic digestion. Finally no increases in water use would be seen with landfilled materials, so this end use option is ranked as 0.

Finally, yield increase was considered as a benefit for land application of the different products. As discussed in the remainder of this section of the report, yield increases have been observed in multiple cases where organic amendments are used instead of synthetic fertilizers. If material is being added to soil to grow agricultural or commercial crops, there will be a clear dollar value associated with increased yield. The market may also recognize a dollar value increase due to quality increases of the food products due to better nutrient availability, such as higher protein in wheat. If material is added to landscaped areas, the financial benefits are more difficult to quantify. Both AC compost and AD digestate have been shown to improve yields and so both are equally and highly ranked here. ISG is again lower because of volume loss during aerobic digestion. Landfilling is given a 0 score as the residuals would not be used to grow plants.

Current State of Soils

The health of soils in the US has been declining. This decline has been accompanied by a decrease in functionality (Amundson et al., 2003; Banwart, 2011). This decline has far reaching real world impacts. As we depend on soils to grow our food, declines in soil quality impact both food quality and quantity. Lower quality soils will produce lower yields per acre, requiring more acreage in production to meet demands. Farmers currently utilize other available tools such as improved crop varietals and increased fertilizer inputs as a way to improve yields. It is not clear that sufficient additional tools are available to compensate for declining soil quality. The decline in soil quality is primarily the result of loses in soil carbon reserves ranging from about 30-40 tons of carbon per hectare (Lal et al., 2007).

Part of this loss of soil carbon and associated decline in soil quality can be related to conventional agricultural practices that result in erosion of between 0.2 and 1.67 mm per yr. (Montgomery, 2007). This is far in excess of the rate of soil formation which is estimated at between 0.06-0.8 mm per yr. (Montgomery, 2007). Tillage increases erosion in two ways. It allows excess oxygen to enter into the soil resulting in rapid oxidation of carbon (mineralization) of soil organic matter resulting in releases of carbon dioxide to the atmosphere. The plow will also break up soil aggregates resulting in increased compaction. Large- scale reliance on synthetic fertilizers instead of manures or cover crops has also reduced soil organic matter and subsequently soil quality. In addition to providing fertility, cover crops and manures add organic matter to soils. Crop residues, organic material that has not had any commercial value is also traditionally left on the soil surface. These residues also help to maintain carbon concentrations in soils. Interest in crop residues as a feedstock for biofuels has the potential to further damage the health of agricultural soils as these materials would be removed from soils rather than being allowed to decay and increase soil organic matter.

Increasing the organic matter concentrations of soils is recognized as the most effective way to restore soil health and function (Doran, 2002; Lal et al., 2007).

Organic Amendments and Soils

This review will focus on land application of composts and digestates. Composts are the aerobically stabilized, typically low nutrient material produced from a combination of high carbon feedstocks (wood waste, yard waste) and wetter, higher nitrogen feedstocks (manures, biosolids, food scraps).

Digestates are materials that are the residual product from anaerobic digestion. They are typically high in nutrients and water with solid contents ranging from 3-25%. There is little available data on digestates coming from food waste only digestion. There is information on digestates from mixed substrates where food scraps are mixed with other materials such as animal manures or bioenergy crop residues. Digestates can contain some pathogens and their use may be restricted based on regulatory requirements to agronomic crops or crops where the edible portion of the crop does not come into direct contact with the soil. Salmonella and other food related pathogens are potential concerns and are likely to require testing and potentially treatment prior to land application of digestates.

Composts and composted digestates are required to go through processes to eliminate pathogens and so this will not be a concern for use of these products from properly managed facilities. Composts require more time to produce than digestates. They are also typically more costly to produce than digestates.

While little research has been performed on the soil impacts of food waste digestates, considerable research has been performed on the soil impacts of a similar material, biosolids. It was the judgment of the research team that the large amount of data on these materials and the long history of wastewater treatment make these materials a proxy for the soil impacts of the materials coming from food waste digestion. However, due to the lack of research studies on the specific content and soil impacts of digestate from AD, further research is warranted before conclusive statements can be made.

The residual from municipal wastewater treatment, biosolids are often anaerobically digested before land application. The characteristics of biosolids in soils are expected to be similar to characteristics of digestates produced from anaerobic digestion of food scraps. For most municipalities, the influent into municipal wastewater treatment plants typically consists primarily of water and the wastes it carries from homes. In King County, WA, for example, 97% of the influent into treatment plants is from homes. The remaining 3%, industrial flows into the plants, in many cases originate from food processing facilities. Food waste is often introduced into municipal systems through the use of sink food disposal units. There are also numerous examples of treatment plants accepting food waste directly into digesters where they are co- digested with the biosolids (Bolzonella et al., 2006; Jupe and Brown, 2010; US EPA Region 9). Note that there still remain concerns over the similarity of this material and source-separated food that has been anaerobically digested.

Total carbon

Soil carbon cycle

Increasing soil carbon storage has been advocated as a means to both reduce net carbon emissions and increase the resiliency of soils for climate change (Lal, 2004; Lal et al., 2007). Agriculture is a significant type of soil disturbance. In fact, emissions of CO2 from soils since 1850 total approximately 78 ± 12 gigatons (1 Gt= 1 billion tons) of CO2. In comparison emissions related to fossil fuel use over the same time frame total 270 ± 30 Gt of CO2. Total soil organic carbon sequestration potential in the US considering only cropland is 45-98 Mt (Lal et al., 2007).

Soil carbon storage is complicated by the fact that increased soil carbon is not simply a case of adding carbon to soils and having that carbon remain in place for decades. Organic matter in soils is part of the annual cycle of growth and decay. Even as a portion of the existing carbon is mineralized by soil microbes, more carbon is being added via plant growth and decay. Increasing carbon will result in net increases in primary productivity (plant growth). This increase in productivity will result in increased carbon inputs into soil. A portion of this increased productivity will remain in the soil as detritus from above and below ground plant biomass. While a fraction of this added carbon decomposes and returns to the atmosphere as CO_2 a portion becomes incorporated into soil organic matter. As soil carbon reserves increase, the rate of carbon addition is higher than the rate of carbon mineralization. So even though adding more carbon to soil will increase mineralization, this mineralization is considered to be the short- term carbon cycle and so does not count as a carbon emission. The rate of C mineralization will also be lower than the total rate of carbon addition (amendment application rate + increase in primary productivity). For example, one study on strip mined land amended with biosolids attempted to differentiate between the portion of applied carbon remaining and the new carbon added to soil as a result of higher plant productivity (Tian et al., 2009).

Carbon will continue to accumulate in soils until equilibrium conditions are reached. For healthy and undisturbed soils, it is likely that this balance between carbon inputs and carbon mineralization is already in equilibrium. For disturbed soils, however, it is likely that net carbon accumulation can occur for several decades, as long as compost or other carbon-containing amendments are added (Brown et al., 2011; Lal, 2004; Lal et al., 2007; Trlica and Brown, 2013). Research has shown similar rates of carbon accumulation for agricultural and mined soils as a consequence of organic amendment addition (Brown et al., 2011; Trlica and Brown, 2013).

Understanding soil carbon sequestration

Low carbon or disturbed soils will have higher rates of net carbon sequestration than less disturbed soils. This will continue until these soils approach equilibrium carbon concentrations (Lal, 2004; Powlson et al., 2012). Researchers have attempted to understand the processes that result in increased soil carbon concentrations. A recent study used X-ray adsorption spectroscopy to determine forms of carbon in soils that had historic applications of biosolids or composts (Li et al., 2013). The authors saw increased evidence of more weathered carbon compounds in the amended soils and suggest that the formation of more stable, weathered carbon compounds in the amended soils was partially responsible for the increased carbon concentrations in those soils. A study on California rangelands receiving a single compost application confirmed these results (Ryals et al., 2013). Another study looked at soil carbon storage and associations as a function of tillage and biosolids application (Stewart et al., 2011). Biosolids had been applied once, 3-5 years prior to sampling at agronomic rates (8-14 t/ha). The authors noted increased soil carbon storage in the biosolids amended soils compared with the fertilized soils (33.1 ± 1.8 vs. 28.4 ± 1.1 t C ha^{-1}). Evaluation of the soils indicated that organic matter associated with silt and clay particles was near saturation but that particulate organic matter could adsorb additional carbon. Another study looked at carbon accumulation in soils amended with compost or fertilizer and then evaluated carbon mineralization rates from micro and macro aggregates (Yu et al., 2012). Eighteen years of compost application increased soil carbon by 71-122%. While compost increased mineralization in comparison to the control, this increase was less than the rate of carbon accumulation. The authors found that compost amendment also decreased the rate of carbon mineralization in soil microaggregates and silt and clay fractions in comparison to the control and fertilized soils.

There is some discussion that increased temperatures will result in increased carbon mineralization and in fact, that the heat produced by this mineralization will in turn result in even higher temperatures (Luke and Cox, 2011). However, this discussion is typically focused on high organic matter soils rather than soils with depleted carbon reserves.

Carbon storage versus carbon concentration

Soil carbon concentrations are typically measured as the percentage of carbon in the soil. This can be converted to the total carbon stored in a soil (tons per acre) by multiplying the percent concentration by the weight of the soil (bulk density). Changes in soil carbon can be reported as increases or decreases in percent carbon or as differences in the quantity of carbon stored in soils (tons per hectare). The latter takes into account the bulk density or weight of the soils. It is more commonly used when soil carbon storage is a focus of the work. For example an early review by Khaleel et al. (1981) noted changes in soil carbon concentration in response to addition of biosolids, composts and manures. These were observed across a range of amendment loading rates, different soil types, and over different time periods. Increases (reported as % net increase in soil carbon) ranged from 0.03 for annual application of manure at 4.7 t/ha over 18 years to silt loam soil to 4.65 after annual applications of manure at 125 t/ha over 3 years to a silty clay loam. Changes in soil carbon storage were not reported.

Table 4: A Summary of Results Showing Increased Soil Carbon Storage Following Organic Amendment Addition (full citations provided in references for this section)

Study	Amendment	Cumulative Application Rate (tons ha^{-1})	Net C per Ton Amendment	Notes
Rou 2003	Compost		0.07	Modeled value after US EPA
Li & Evanylo 2013	Biosolids	42-210	0.04-0.075	Study conducted on VA soils; Decreasing efficiency with increased application rate
	Biosolids	14-98	0.03-0.12	
	Compost	126	0.11	
	Compost	202	0.1	
Brown *et al* 2013	Compost	134	0.54	Orchards
	Compost	84-140	0.12-0.24	Orchards
	Compost	157	0.06	Turf
	Compost	224	0.08	Landscape
	Compost	150	0.35	Highway
	Biosolids	67-202	0.04-0.09	Turf
	Biosolids	18-40	0.34-0.43	Wheat
	Biosolids	147	0.47	Highway
Powlson *et al* 2012	Compost		0.06	Review of UK sites
	Biosolids		0.18	
Trlica & Brown 2013	Biosolids	135	0.28	Mine sites
	Biosolids/pulp sludge	50-486	0.31	
	Biosolids/compost	128-337	0.15	
	Biosolids	560	0.03	

Other studies have reported changes in soil carbon on a ton of carbon stored per hectare basis. In some cases, carbon storage efficiency, or carbon stored per unit of amendment applied is reported. A summary of papers showing carbon storage per ton of amendment applied is shown in the table below.

In general, carbon storage per ton of amendment added is higher in sites with initially lower carbon concentrations. For example, total carbon concentration in two of the sites reported in Brown et al. (2011) that showed low carbon storage efficiency had carbon storage ranging from 30-40 tons per hectare in the control sites. Areas that showed increased carbon storage efficiency had initial carbon storage ranging from 13-25 tons per hectare. The data also suggests that there is likely a potential to over-apply amendments. Carbon storage efficiency ranged from 0.15-0.28 in mine sites restored with biosolids or composts (Trlica and Brown, 2013). In a site where 560 tons/ha of biosolids was added to a site that had also received over a meter of topsoil, this rate fell to 0.03 tons C per ton amendment.

Total nutrients

Plants require mineral nutrients in addition to the carbon from photosynthesis in order to grow. These nutrients are typically categorized as macro and micro-nutrients based on the quantities required by the plants. Nitrogen (N), phosphorus (P) and potassium (K) are the most widely used fertilizer macronutrients. Others include calcium and sulfur. Micronutrients include copper, cobalt, boron, manganese, magnesium, iron, and zinc. Gardeners and farmers will typically add fertilizer to soils as some combination of N-P-K. Other nutrients are rarely added. Deficiencies of other plant nutrients can and do occur, potentially limiting yields. Organic or residuals derived amendments such as composts, digestate, biosolids and manures, being derived from plant material and manures, will contain the full suite of required plant nutrients. Composts, digestates, and biosolids can be added to soils to meet the nutrient needs of a crop. Composts can also be added to soils as a soil conditioner or as a mulch. Soil conditioners are typically incorporated into the surface 6" or 15 cm of the soil. Mulch is applied to the soil surface without incorporation. Conditioners are used to provide nutrients and organic matter to soils. Mulches are added to reduce evaporation from the soil and control weeds. They typically have low nutrient value.

The nutrient availability of the amendment will depend on initial total nutrient concentrations and the rate at which these nutrients become plant available. Because the nutrients in these materials are typically present in organic forms, they will function as a slow release fertilizer in soils. For example, in a study of food waste compost applied to turf grass in Washington, a single application of compost provided nitrogen to the turf for the 7 year course of the study (Sullivan et al., 2003). Grass yield and total nitrogen uptake were increased in comparison to fertilizer addition. Studies have reported mineralization of about 50% of total nitrogen during a first cropping season after biosolids addition and mean nitrogen recovery of 62% for annual biosolids application to turfgrass in Washington State (Cogger et al., 1999; 2001). Increases in phosphorus availability were also reported. Nitrogen uptake on the same plots continued for several years after the end of biosolids application with residual soil phosphorous remaining elevated 9 years after the cessation of amendment application (Cogger et al., 2013). Other studies have also reported increase in soil fertility (using a range of indexes) for compost and biosolids amended soils in comparison to control soils (Brown et al., 2011; Brown and Cotton, 2011; Christie et al., 2001; Evanylo et al., 2008; McIvor et al., 2012).

In certain cases, amendments with a high Carbon: Nitrogen ratio can result in nitrogen immobilization (Cogger, 2005; ROU, 2003). Soil microbes use added carbon as a food source. A portion of this is used for energy with some used to build biomass. Much the same as people, they also require a certain amount of nutrients to be able to use the carbon to build biomass. If the added amendments are high in carbon and low in nitrogen and other nutrients, the microbes will use up all of the added N and render the soil nitrogen deficient for plant growth. This process is referred to as nitrogen immobilization.

Use of organic amendments may also impact nutrient losses from soils. Nitrogen movement to groundwater was lower for manure compost amended plots in a study that tested manure composts or fertilizer for turfgrass (Easton and Petrovic, 2003). Studies have suggested low potential for phosphorous movement from biosolids amended soils in comparison to conventionally fertilized soils both via surface flow and leaching (Elliot et al., 2002; 2005). Compost would also be expected to have low phosphorous movement potential because of the ability of compost to reduce soil erosion and the low solubility of phosphorous in composts (Evanylo et al., 2008; ROU, 2003).

The greenhouse gas emissions associated with fertilizer production have been used as a means to quantify the benefits of using organic amendments in place of synthetic fertilizers (Brown et al., 2010). Total emissions for production of 1 kg of nitrogen are about 4 kg of CO_2. Emissions associated with production of 1 kg phosphorus are about 2 kg CO_2.

Bulk density and aggregation

Increasing soil carbon concentration improves soil physical properties by increasing the number and stability of soil aggregates. Aggregates are conglomerations of small soil particles (typically loam and clay sized particles) that are held together usually by carbon 'glues'. When a soil is well aggregated it will typically also have lower bulk density. Many studies have reported on the ability of biosolids and composts to improve soil aggregation and/or reduce bulk density. For example Wallace et al. (2009) noted an increase in larger as well as water stable aggregates 4-5 years after surface application of 60 tons per ha of biosolids to rangeland. Aggelides and Londra (2000) also saw improvements in aggregate stability with application of a town waste and biosolids compost to loamy and clay soils in a semi-arid environment. Decreases in bulk density and increases in porosity were also observed. Results were more pronounced for the loamy soil and at higher amendment loading rates. Similar results have been observed in a wide range of studies with different types of organic amendments (Albiach et al., 2001; Annabi et al., 2007; Bresson et al., 2001; Brown and Cotton, 2011; Brown et al., 2011; Bulluck et al., 2002; Caravaca et al., 2001; Evanylo et al., 2008; Khaleel et al., 1981; ROU, 2003)

Water relations

Soil plays a critical role in the hydrologic cycle. Water travels through soil both to groundwater and to surface waters through subsurface flow. Flowing through soil water is filtered and is brought to an appropriate temperature. Water stored in soils is referred to as green water. Soil water also provides the primary source of water for plants. Soil water relations are generally a complicated interaction of a number of variables. Water enters the soil as a result of irrigation or rainfall events. The first stage of the interaction between water and soil relates to the speed at which water can infiltrate soils. This is referred to in the literature as the infiltration rate or hydraulic conductivity of the soil. Typically sandy soils will have much faster infiltration rates and conductivity rates than clayey soils. Organic amendments have been shown to increase water infiltration rates across different soil types and end uses (Brown and Cotton, 2011; McFarland et al., 2007; McIvor et al., 2012).

The next factor for soil water relations is the ability of the soil to provide water for plants. Water that enters the soil will either drain through the soil or remain in the soil. Field capacity is the term used to describe the water that remains in the soil after a rain and after gravity flow has drained water from the larger pore spaces. This is an ideal condition for plant growth. Several studies have measured differences in total soil water concentration at field capacity or conditions of low moisture tension (readily available water for plant uptake). The soil will become increasingly drier as plants use the water. Water can also evaporate from the soil surface.

A final point in the soil water spectrum is referred to as the permanent wilting point. This is the level of dryness that results in sufficient drought stress that plants cannot recover. In some cases differences in plant available water is considered to be the differences in total water from field capacity to permanent wilting point. If a soil amendment results in increased total water at field capacity but also increased water at the tension equivalent to permanent wilting point, scientists will conclude that there is no increase in plant available water. Not all studies measure water at all tension levels or share the same perspective on plant available water.

Organic amendments including digestates and composts can either be surface applied or incorporated into a soil. Surface applications are appropriate for perennial crops. Incorporation is suitable for annual crops or in cases where perennials are being established. Incorporation may also be recommended for digestates as incorporation reduce odor potential. One study showed more benefits for soils when amendments were incorporated rather than surface applied (Brown et al., 2011). Amendments can alter soil water relations in several ways:

- Increase the infiltration rate
- Reduce evaporation rate from soil surfaces
- Increase total soil water at field capacity
- Increase net water from field capacity to wilting point

Research results have generally identified increases in at least one of these parameters as a result of amendment addition. An early survey paper (Khaleel et al., 1981) looked at the impact of organic amendments on soil water holding capacity by reviewing previously published studies. They did not distinguish between municipal biosolids, animal manures, and composts. They found that 80% of the variability in soil water holding capacity at both field capacity and permanent wilting point varied based on soil texture and total carbon concentration. Changes in water holding capacity as a result of increases in soil carbon were much more pronounced for sandier soils.

A more recent survey paper quantified benefits for soil water associated with compost application (ROU, 2003). Here, two types of applications were modeled: Compost used as a soil conditioner/fertilizer incorporated into the surface soils and compost added to the soil surface as a mulch. The authors found a much weaker relationship than was reported in the earlier study with an R^2 value of 0.34 for composts incorporated into the soil. Increasing compost application rate (t/ha) was associated with a % increase in plant available water according to the following equation:

$$Y= 2 \times E\text{-}05\ x^3 - 0.003x^2 + 0.159x$$

Where x= compost application rate (tons per ha) and y= % increase in plant available water.

A much more significant relationship was observed for the relationship between compost that was surface applied as mulch (cm depth) and % increase in soil moisture. Increase in soil moisture was related to the depth of mulch cover by the following equation:

$$Y = -0.044x^2 + 1.42x \ (R^2=0.83)$$

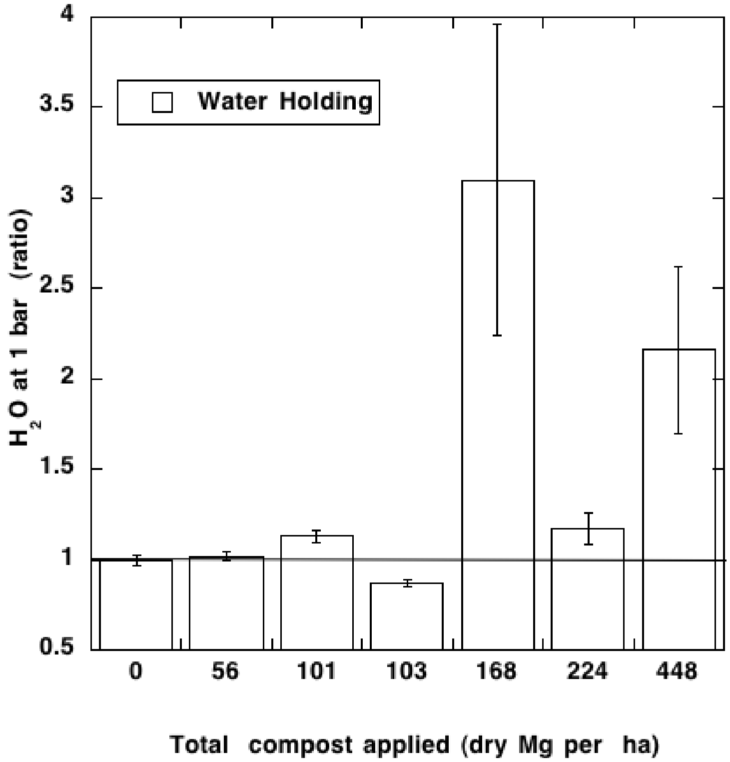
Where x = mulch cover (cm) and y= % increase in soil moisture

The authors then modeled predicted water savings for two crops grown in New South Wales, Australia. A 12 t /ha application of compost incorporated into the soil was predicted to result in water savings of 1.5% of the total quantity of irrigation water applied. For compost applied as mulch to a 10 cm depth (about 335 tons per hectare), water savings were predicted to be about 10% of the total irrigation water supplied.

Brown and Cotton (2010) sampled a number of working farms with a history of compost application in California. Soil water holding capacity was measured at 1 bar (100 kPa) of tension, or at the point where irrigation water would likely be applied. The sites that had received the highest loading rates (165 and 448 t/ha) also saw the most significant increases in soil water. This difference was most pronounced for the two sites with sandier soils (loamy sand texture). The site with a silty loam soil that had received 224 t/ha had only a minor increase in plant available water. Results from that sampling are shown below.

A study of long term biosolids and compost amended sites in Washington State also found significant increases in soil water for some of the sites (Brown et al., 2011). This was observed across different soil types, amendments and amendment loading rates, precipitation patterns, and cropping systems. Here increases were seen for compost added to irrigated fruit orchards, hops and turf, and biosolids to dryland wheat. The amendments for all sites were incorporated into the soil. The implications of the potential increase in water availability are discussed below.

Figure 1: Changes in Soil Water Holding Capacity Following Compost Addition at Working Farms in California (each bar represents a different farm)



Source: Brown and Cotton (2010)

For example, at the fruit orchard site, the soil was a silt loam. The farmer had applied about 50 tons of compost to each acre over a several year period. A 50% increase in plant available water (the difference in total soil water between field capacity and 1 bar of moisture tension) was observed in the compost amended soils. Cherries in Washington State are typically irrigated with 3.5 acre feet (an acre foot is equivalent to 325,850 gallons). Compost here should have reduced irrigation demand by about 1 acre foot per acre.

Source: Kate Kurtz

The dryland wheat was grown in loamy sand. Adding a total of 18-40 t/ha of biosolids over a 16 year period resulted in increased soil carbon of 8-14 t/ha. This in turn increased water holding capacity at field capacity by about 10%. As this site is moisture limited, this increase was significant. The authors used a model developed by Washington State University to predict yield increase associated with the increase in water holding capacity. A total yield increase of 10-20% was predicted. An actual yield increase of 16% across all harvests was observed. For dryland wheat grown in Washington average yield is 67.3 bushels per acre. A 16% yield increase would bring that to 78 bushels per acre. For current wheat prices, this would result in per acre revenue of $593 compared with $512.

Source: Craig Cogger, Washington State University

Table 5: A comparison of Reported Yield Benefits for Different Crops Grown in Compost or Biosolids Amended Soils

Study	Amendment	Crop	Control	Amended	Added revenue
McFarland *et al* 2007	Biosolids	Rangeland	84 lbs. /acre	129-664 lbs./acre	
Bowden *et al* 2010	Compost & poultry litter	Soybeans		9-21%	$140-326/acre
Christie *et al* 2001	Biosolids	Barley grain Barley straw	4.51 t/ha 1.85 t/ha	4.99 t/ha 2.28 t/ha	$45/ha
Speir *et al* 2004	Compost	Silver beet	Yield elevated over	control for all compost	
Reeve *et al* 2012	Compost	Dryland wheat 2 years later 16 years later	1.3 t/ha 0.5 t/ha	3.6 t/ha 1 t/ha	$952/ha $534/ha
Koenig *et al* 2011	Biosolids	Dryland wheat		0-47% increase	0-$263/ha
Sullivan *et al* 2009	Biosolids	Dryland wheat		315 kg ha increase	
Tester 1989	Compost	Turf		60-70% yield increase	
Sullivan *et al* 2002	Compost Food/yard/paper Food/wood	Turf	1.66 t/ha	1.98 t/ha 2.2 t/ha	$200-$341/ha - biomass increase
Cogger *et al* 2013	Biosolids	Turf	Increased yield vs. synthetic fertilizer	10 years amendment & 9 yrs. post amendment	
Loschunkohl & Boehm 2001	Compost	Turf 3 grass cultivars	2.1 g m^{-2} 3 g m^{-2} 1.8 g m^{-2}	7.6 g m^{-2} 3.4 g m^{-2} 3.8 g m^{-2}	
Cogger *et al* 2008	Compost incorporated, bark mulch	Landscape plants		Growth response first 4 years of trial	
ROU 2007	Compost mulch Compost soil conditioner	Orchard crops 14 trials in Australia Australian trial		Increases of 20% to 104% for cherries. No yield increase for peaches.	Assuming a 50% yield increase for blueberries $6807/ha

***approximate added revenue per acre for Oregon crops based on total acreage in production, total revenue and total yields (Source: http://www.nass.usda.gov/Statistics_by_State/Oregon/Publications/facts_and_figures/facts_and_figures.pdf)**

Plant yield

The value of organic amendment addition for soil carbon sequestration, synthetic fertilizer avoidance, and increased water use efficiency has been discussed. There are also cases where use of organic amendments has resulted in increased plant yield in comparison to conventional fertilizers or control soils. It is not always clear what factors relating to organic amendments are responsible for the observed yield increase. It may be availability of nutrients such as sulfur in the amendments. It can also be related to improved soil tilth or improved soil water relations. Reported yield increases have not been consistent across crops or years. A summary of reported yield increases for different crops is shown in Table 5 above.

Summary

Use of food scrap based composts or digestates as a soil amendment will improve soils in Oregon over time. These improvements will likely be seen in soil structure, soil carbon storage and soil fertility. Ancillary benefits with respect to soil water will likely also be seen. There may be benefits related to increased crop yield as well. These benefits will require multiple agronomic applications of composts or digestates to be fully realized. From a GHG accounting perspective, the most significant benefits will be for soil carbon storage and synthetic fertilizer avoidance. If a default value for soil carbon credits is taken- this should be in the range of 0.1 tons of carbon per dry ton of compost used. Nutrient credits can be based on the total concentration of N and P in the material (dry weight basis) (Brown et al., 2010). There is previous work that justifies the use of 4 kg CO_2 for each kg N and 2 kg CO_2 per kg P (Brown et al., 2010). While addition of organic amendments to soil will increase soil productivity and resilience, there is currently no tool to quantify those benefits.

Agriculture in Oregon

Agriculture is a significant source of revenue within the state. There are multiple agricultural regions within the state. The Oregon Department of Agriculture provides a list of the top crops in the state in terms of net revenue. Top crops, associated annual revenue, and the counties where production is centered are shown in Table 6.

Crops for which Oregon is one of the top 10 producers nationwide are hops, apples, cherries and pears, blueberries and strawberries. Cherries are grown primarily in Hood River and Wasco Counties. Pears are grown in Hood River and Jackson, and Umatilla County now leads the state in apples. Oregon also produces significant quantities of berries with berry growing concentrated in the Portland, Salem and Eugene corridor.

Table 6: The Top Value Crops Grown in Oregon Based on Gross Sales Revenue

Top Crops	Value (millions)	Counties
Hay	$752	Klamath, Lake, Harney, Umatilla
Greenhouse & Nursery	742	Willamette Valley
Wheat	503	Umatilla, Morrow, Sherman, Gilliam, Wasco
Grass Seed	341	Willamette Valley
Potatoes	188	Umatilla, Morrow, Union, Baker, Malheur
Blueberries	117	Willamette Valley
Corn (grain & silage)	109	
Christmas Trees	99	

Source: Oregon Department of Agriculture

For this report, high production in the Willamette Valley and the Columbia Basin may provide the most realistic end use options for composts and digestates produced from food scraps. The Willamette Valley is an agricultural region that is the shortest haul distance from the urban areas that generate the largest quantities of food scraps. The Columbia basin, although a greater distance from the source of food scraps is a center for agriculture in the State. It also supports both high value and agronomic crops. The basin also has a lower population density suggesting that there would be a lower potential for odor complaints if digestates were used.

Columbia Basin

Production of dryland wheat and hay are high in this area. These are both listed as top crops in the state. Hay is the most important crop, with annual revenue of $752 million. Wheat production is also significant with annual production of $503 million. There has been significant research on use of biosolids and composts for wheat and hay production. Currently, all of the municipal biosolids produced by Portland and many other municipalities in the State is land applied in Umatilla to a range of crops at Madison Farms in Hermiston. There is more than sufficient acreage to absorb all of the potential digestate or compost that could be produced. Both wheat and hay are low value crops, meaning that revenue per acre is low. Compost may be too expensive to produce and transport to be used for these crops. Direct use of digestate would be appropriate as both are agronomic crops.

A NRCS Web Soil Survey soil map for a section of Umatilla shows that over 70% of the soils are in the Walla Walla series which is a silt loam. This series is classified as a Mollisol. If the soil has been cultivated using conventional tillage practices, it is almost certain that a portion of the organic carbon in the soils has been mineralized. The soil will definitely increase carbon reserves with the use of organic amendments.

Willamette Valley

For this report we can focus on two high value crops from this region of the state. Greenhouse and nursery crops are one of the most significant sources of agricultural related revenue in the state, bringing in sales of $742 million in 2011. Much of this production is centered near urban areas where the food scraps are also generated. This would represent a high end use of compost, and would likely generate significant revenue. Table 7 summarizes results from previous studies. Grass seed is also a highly significant crop with revenues of $341 million.

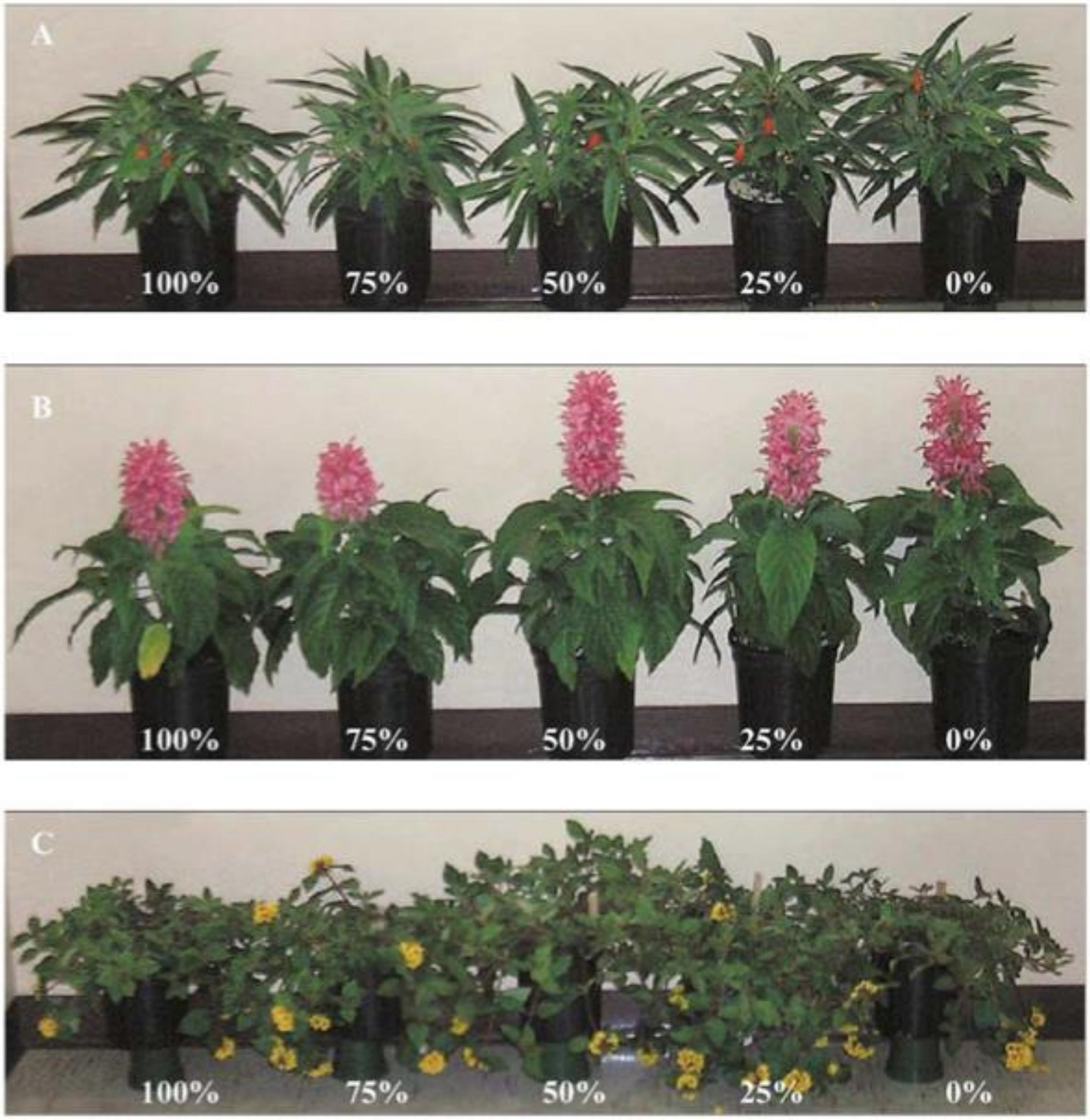
Greenhouse and nursery crops

Table 7: Findings of Research on Different Composts Used as Potting Media

Design and Results	Source
Tested range of properties- pH, EC, CEC, Water holding and porosity on a broad number of composts Did not include food scraps separately, generally found composts inferior, noted salinity as an issue	Corti et al., 1998
Tested compost in mixtures with peat as a substitute for a portion of the peat for growing tomatoes Mixture of 30% compost +65% Peat+ 5% perlite was comparable to commercial peat mixtures	Herrara et al., 2008
Tested composts made with biosolids or dairy manure as a substitute for peat in greenhouse production of chrysanthemums with supplemental fertilization Most biosolids composts performed as well as the commercial peat mixture and did not respond to higher levels of N addition, suggesting the potential to reduce fertilizer use	Krucker et al., 2010
Grew Lpidum sativum and Hordeum vulgare in mixtures of compost and peat or bark. The compost was produced from anaerobically digested wastes Growth response was reduced for most mixtures because of salts. Response to and composted pine bark was comparable to peat	Moldes et al., 2007
Tested growth of geraniums on mixtures of peat and compost with no additional fertility. compost was up to 50% of mixture by volume Saw salt damage at higher compost rates. Also saw some nutrient deficiencies. Best results with 10-20% compost	Ribeiro et al., 2000

The previous section on the benefits of organic amendments for soils did not consider the case where amendments can function as a substitute for commercial potting mixtures. There has been significant research on the use of composts in potting mixtures. However, this research has typically been on biosolids composts or on composts from MSW rather than work specifically on food waste derived composts. The authors of these studies typically don't provide detailed information on the compost feedstocks other than that they were sourced from the solid waste stream. A list of studies and results is shown in Table 7 above.

Figure 2: Comparisons of Flower Growth for Different Percentages of Biosolids Compost Used in the Potting Mixture



Source: Wilson *et al*, 2002

Flowers grown in the Wilson *et al* (2002) study with varying levels of biosolids compost as a substitute for peat are shown in Figure 2. The percentages shown reflect the percent of biosolids compost used in the potting mixture.

For these crops, there is likely a significant potential market for use of composts derived from food scraps. This market would not be appropriate for digestates. Digestates are often not stable and some can be highly odorous. As this is such a high value market it is critical that the composts be tested in pot trials such as the one shown above. Results from trials should be used to develop testing criteria that would be required before the use of compost products is promoted. There is a much larger market here than food scrap based composts could potentially fill. It is also a year round market so that composts could be used throughout the year.

Grass seed

The soil factors for growing grass seed are similar to what are required for growing turf. Both composts and digestates have been shown to be excellent soil amendments for these crops. Again, there is a much larger market for amendments here than can be met by food scrap based composts or digestates. Compared with the Greenhouse and Nursery market, the grass seed soil amendment requirements will have a lower potential for poor performance. Producers may not be willing to accept digestates because of handling concerns and the possibility of odors. Grass seed is typically harvested from grasses that are left in place for several years. As a perennial crop with an extensive root system, grass is good for building soil carbon.

The Jory soil, the state soil of OR is common in the Willamette Valley. Many crops including grass seed are grown in this soil (http://urbanext.illinois.edu/soil/st_soils/or_soil.htm). It is a weathered soil and will have much lower native carbon reserves than the Walla Walla series. It will also gain stored carbon through the use of organic amendments although the total carbon storage for a perennial crop like grass seed will likely be lower than for annual crops .

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4. Oregon Composters Survey Results

--by Matthew Cotton, Integrated Waste Management Consulting

Type 3 Food Scraps Composting in Oregon

Composting is well established in Oregon, with over 600,000 tons of feedstocks being destined for compost in 2012[4]. There are as many as 50 permitted composting facilities ranging from agricultural and food processing composters, to municipal and commercial compost facilities. Most of these are located in the western part of the state concurrent with population density, though some are located in more rural areas, and in agricultural settings. Of the 50 permitted facilities, there are approximately twelve composters licensed to take “Type 3” materials. Type 3 materials include “dead animals, meat and source-separated mixed food waste and industrially produced non-vegetative food waste”. Type 3 feedstocks also include digestate that was made from Type 3 feedstocks. Composters receiving Type 3 materials are the focus of this investigation.

Table 8: Composting Facilities Permitted to Accept Type 3 Feedstock

Facility	Location
Coburg Production Facility	Eugene
Dirt Hugger	Hood River
JC Compost Yard	Junction City
Knott Pit Landfill	Bend
Lane Forest Products	Eugene
McGarva Ranch	Lakeview
Nature’s Needs	North Plains
Pendleton Transfer Station	Pendleton
Pacific Region Compost	Corvallis
Recology McMinnville	McMinnville
Recology Aumsville	Aumsville
WastePro Compost	La Grande

In order to understand where the compost made from food scraps was being used, a survey instrument was created to try to standardize responses to phone interviews. The Survey Instrument is contained in Appendix C. Most compost facilities report some or most of this information to DEQ, so interviews focused on the end use of the compost itself. Phone interviews were conducted with each of the

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[4] Oregon DEQ Data, 2012.

identified facilities. Of the 12 facilities taking Type 3 feedstock, interviews were completed with 11, though 4 of these reported no longer processing Type 3 feedstocks (or not processing it in 2013).

Based on data reported to DEQ in 2012, the twelve Type 3 facilities process a total of about 48,000 tons of food scraps, though the bulk of those tons was handled by two facilities. Most of this comes from the Portland Metro area, or from the area surrounding the subject facility. Survey respondents indicated a total of 212,443 tons of compost being sold in 2013. The differences in these numbers probably has to do with moisture content and the fact that all interviewed composters mix their Type 3 feedstocks with either some or a lot of yard trimmings. The 12 facilities processed over 325,000 tons of compostable materials. Food scraps as a percent of total feedstocks ranged between 0% and 100%.

Survey Data

Two-thirds (66%) of the facilities interviewed technically co-compost the food materials they receive, that is, they compost the received food scraps with a larger volume of chipped yard and garden, or wood waste. So the resulting compost is a mix of yard trimmings (typically) and food. Food as a feedstock contains a great deal of water which is lost during the compost process. The remaining third (33%) have a specific food scraps stream and add only enough yard and garden trimmings to makes an efficient compost mix. So some facilities produce one compost, containing yard trimmings and food scraps. Others create more than one product, though typically only one product containing food.

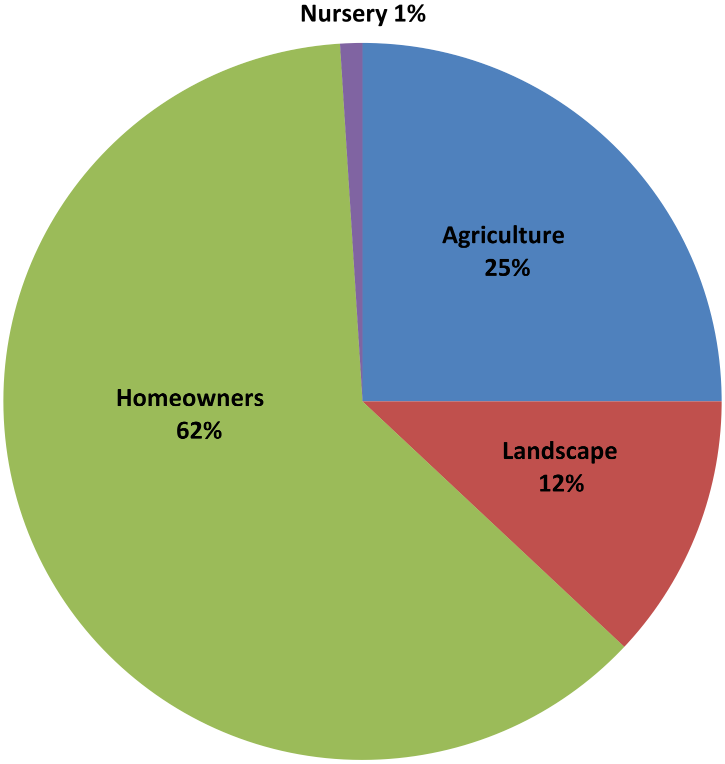
Since the compost is co-composted with yard and garden trimmings and/or wood waste and then the compost is screened, the food-containing compost is a mix of food and woody materials. In most cases this is screened prior to being sold. Facilities report a very wide range of end uses for the material, from retail bagging and on-site sales to commercial agriculture.

End Uses for Compost

Of the 11 facilities responding, a wide variety of end uses were reported. Because compost is a relatively heavy and low value soil amendment, it is not typically marketed far from where it is manufactured. Thus many of the facilities reported selling the compost to the markets that were close to their facilities. These included homeowners, landscapers, nurseries, and into bulk agriculture. Figure 3 shows the breakdown of these end uses.

The agricultural markets identified included hazelnuts (an important crop in Oregon), vineyards, grass farmers (annual rye grass is an important crop in the Willamette valley) and vegetable crops. Only two composters reported selling food scraps compost into certified organic agriculture (it is unclear whether this is due to lack of compost demand – organic agriculture can be an important market for composters – or for lack of trying). There is some reluctance on the part of some commercial composters to sell relatively new products into technically demanding markets like organic agriculture. Composters generally reported little difficulty in marketing their products and most reported increasing market success. However, some did mention they were concerned with the amount of contamination (primarily plastic) in the food scraps feedstock – particularly those taking food scraps from municipal sources.

Figure 3
Distribution of Type 3 Feedstock-Containing Compost



Some composters that are selling into agriculture provide spreading services, while others use contractors or rely on the grower to spread the compost. Many of the larger composters are part of the US Composting Council's STA program and provided detailed analysis of their compost. This analysis is summarized below in Table 9.

In general, Oregon has the potential for expanded markets for compost. The state has significant agricultural production of relatively high value crops (the types that tend to support annual additions of soil amendments, like compost). It is likely that markets will exist for the foreseeable future. The current challenges with food containing compost probably has more to do with supply than demand. Food scraps collection programs are in their infancy, both in Oregon and nationwide. As more programs come on line, more compost will be made and with the right education and technical assistance, it will find willing agricultural markets.

Compost Analysis

Many of the Type 3 composters in Oregon conduct regular laboratory analysis of their compost. A summary of provided results is shown in Table 9. The range of nitrogen reported in the analyses provided is from 1.1 to 1.9 percent. All of the provided analysis is within expected parameters. Nutrients, bulk density, moisture content, and other parameters are within the range that would be expected of these types of products.

A simple comparison of reported analytical results did not show any significant variation between the yard-only and yard & food composts. This may be because the ratio of food to yard trimmings varies considerably. Some composts with higher percentages of food scraps added show slight increases in nitrogen, which is of some value to some growers, though typically growers do not buy compost for the nitrogen value alone.

Digestate

Only one anaerobic digester taking Type 3 feedstock is operating in Oregon, and should be considered to be in start-up mode. This facility receives Type 3 feedstocks, primarily from the metropolitan Portland area and converts the material into three products: electricity, a liquid digestate, and a solid digestate. The liquid digestate is delivered to nearby farms for application as a liquid fertilizer. This practice is very new and no data was available to review. The solid digestate is sent to co-located composter. The volume of food-containing digestate is thus far, so small, that no conclusions can be made as to how it is being used. According to a commenter who operates the only anaerobic digester in Oregon dedicated to food processing, they provide up to 60 tons per day to wheat growers.

Previous Survey of Composters in Oregon

A previous project interviewed 7 Type 3 composters and the one anaerobic digester in the Willamette Valley (as well as 6 yard debris-only composters). This project reported similar results to the current study, though no specific crop types (other than orchards) were mentioned. These results would seem to be consistent with the current study in confirming that the compost and anaerobic digestion industry in Oregon is growing.

Table 9: Example Compost Analysis

Compost Parameter	Units	Facility #1		Facility #2		Facility #3	Facility #4	Range
Feedstock		Yard Only	Yard & Food	Yard Only	Yard & Food	Yard & Food	Yard & Food	
Plant Nutrients	Dry Weight							
Nitrogen	%	1.4	1.5	1.9	1.9	1.1	1.23	1.1 – 1.9
Phosphorus	%	0.66	0.51	0.73	0.73	0.17	0.23	0.17 – 0.73
Potassium	%	1.2	0.98	1.2	1	0.63	0.71	0.63 – 1
Calcium	%	1.9	1.5	1.7	1.7	-	2.1	1.5 – 2.1
Magnesium	%	0.5	0.32	0.44	0.38	-	0.54	0.32 – 0.54
Organic Matter Content	%	51.4	63.4	50.9	52	65.6	37	37 – 65.6
pH		7.54	6.83	7.81	7.74	5.6	7.9	5.6 – 7.9
Conductivity	EC5	2.0	3.7	2	1.7	3.93	3.3	1.7 – 3.93
Bulk Density	#’s/cf	23	19	29	19	27	33	19 - 33
Ash		48.6	36.6	49.1	48	-	-	36.6 – 49.1
C:N ratio		19	23	13	15	32	18	13 – 23
Moisture Content	As Rcvd.	46	61	56.2	58.6	55.5	21.4	21.4 - 61

Conclusions

Food scraps are being accepted and processed at Oregon composting facilities and anaerobic digestion facilities. Some, though not all, of the food-containing compost is being sold into agriculture. Food-containing compost appears to be accepted by end users, though there are concerns regarding contamination, primarily plastics but also some glass and metal, in the end product. No interviews were conducted with growers to determine their concerns with food-containing compost or their expectations for performance in the field. No evidence was revealed as to why growers were using compost (i.e., for organic matter, for soil amendment, for slow release organic nutrients or other purposes.).

The potential uses of compost produced from food waste in Oregon are significant. There is sufficient agricultural production even in Western Oregon to support a vibrant composting industry. However, more research, such as that being done by Metro in Portland, needs to be conducted to understand why more agricultural producers are not using compost and digestate and how to get more of them to adopt these materials to improve their soils and yields.

5. Harmonization Results for Climate & Energy Impacts

--by Jeffrey Morris, Sound Resource Management Group, & H. Scott Matthews, Avenue C Advisors

The harmonization activity in this project, as introduced and motivated above, followed the general approaches of LCA meta-analysis pioneered by Heath and others at US DOE's National Renewable Energy Laboratory (NREL) for energy generation systems as published in a special issue of *The Journal of Industrial Ecology* in 2012 (for summaries see Brandao *et al*, Heath and Mann, and Zumsteg *et al* in that special issue). While meta-analysis is a common tool for aggregating results of previous research, various LCA-specific approaches have been refined and promoted, including both statistical adjustments and quantitative harmonization of parameters and other LCA modeling assumptions.

Results from harmonizing 28 LCAs on food waste management are summarized in Table 10, Comparison of Harmonized Climate and Energy Impacts for Food Waste Treatment Options. The numeric results in the table reflect means for the harmonized impact estimates from the 28 LCAs. There were 25 and 10 separate estimates, respectively, for aerobic composting (AC) climate and energy impacts. For anaerobic digestion (AD) there were 10 estimates for climate impacts and just 1 estimate for energy use. For in-sink grinding and management via anaerobic digestion at a waste water treatment plant (ISG) there were 5 estimates of climate impact and 3 estimates of energy use. For landfill disposal (LF) the estimates for climate and energy impacts numbered 15 and 5, respectively.

The first thing to notice in Table 10 is how the rankings of management options differ for climate and energy. The rankings for climate and energy are (from lowest to highest impact):

- Climate: AD, AC, ISG, LF
- Energy: ISG, AD, LF, AC

Climate and energy impacts are typically highly correlated. However, they differ here due to fugitive methane emissions, from landfills and perhaps from the other three treatment methods as well, that provide a climate burden and no energy benefit. In addition, the AC option typically provides no direct energy output. The other three options typically generate electricity as an output from processing food wastes. Also, note that AD energy impacts were considered in only one LCA, and that climate impacts for all food waste management options were considered in many more LCAs than were energy impacts. Smaller sample sizes give impact rankings lower statistical confidence levels.

Table 10: Comparison of Harmonized Climate & Energy Impacts for Food Waste Treatment Options

Activity	Climate Impact (kg eCO$_2$ per kg food waste)				Energy Impact (MJ per kg food waste)			
	Aerobic Composting	Anaerobic Digestion	In-Sink Grinder	Landfill	Aerobic Composting	Anaerobic Digestion	In-Sink Grinder	Landfill
(LCA Sample Size)	(25)	(10)	(5)	(15)	(10)	(1)	(3)	(5)
Collection & Transport	0.04	0.02	0.05	0.03	0.68	0.68	0.39	0.51
Processing	0.11	0.09	0.23	0.69	0.66	0.58	0.54	0.57
Carbon Storage	-0.12	-0.08	-0.03	-0.12				
Fertilizer Displacement	-0.03	-0.02	-0.05		-0.09	-0.15	-0.22	
Peat Displacement	-0.04				-0.03			
Electricity Displacement*		-0.17	-0.18	-0.08		-0.83	-1.03	-0.48
Total Impact (Net)	**-0.05**	**-0.17**	**0.03**	**0.52**	**1.23**	**0.29**	**-0.32**	**0.60**

* Oregon grid carbon footprint reflected in electricity displacements for climate impacts. However, the Oregon grid primary energy demand footprint is not used for calculating the energy value of electricity displacements. Electricity displacements are calculated at the energy value of a kilowatt hour (kWh) -- 3.6 megajoules (MJs). Conversion of electricity to energy using the 3.6 MJ/kWh ratio is known as the direct equivalence method. However, different electricity generation sources have different conversion efficiencies. Using the primary energy equivalent method to account for these sources would increase electricity displacements by a factor that varies based on the source. Fossil fuel factors range from 2 to 3, and renewable source factors range from 1 to 10. A rough estimate of the overall factor for Oregon is likely between 3 and 5 based on US EPA eGRID 2010 data.

The mean climate impact for AD is significantly lower than the mean climate impact for AC at a statistical confidence level greater than 99%. The same is true for AD compared against LF. The confidence level that AD has lower climate impact than ISG is somewhat lower at 96% due to the small sample size and large standard deviation for ISG climate impacts. For these reasons, as well as the higher climate impact of AC, AC is better for the climate than ISG at only an 82% confidence level. AC is better for the climate than LF at greater than 99% confidence. ISG has a lower climate impact than LF at a confidence level greater than 99%. Here the large difference in mean climate impacts between ISG and LF more than compensates for the small sample size and large standard deviation for ISG.

For energy impacts, AD has a sample size of only one and, thus, cannot be statistically compared to energy impacts for the other three food waste treatment options. ISG has lower energy use than LF at just under 99% confidence level and lower energy use than AC at greater than 99% confidence level. LF has lower energy use than AC at a statistical confidence level of 94%.

The second thing to notice in Table 10 also shows that grid electricity displacement tends to have the highest mean GHG emissions and energy use reduction among the four benefits – carbon storage, synthetic fertilizer displacement, peat displacement and grid electricity displacement – produced by outputs from the three food waste treatment methods that produce electricity (AD, ISG and landfill).[5] Only for LF climate impacts does electricity displacement come in second, in this case to carbon storage.

Aerobic composting as currently practiced does not provide electricity outputs. For the AC food waste management option, carbon storage in soils amended with compost has the highest GHG reduction benefit. Energy benefits from fertilizer displacement exceed peat displacement benefits under current compost utilization patterns in Oregon. The influence of compost, digestate and biosolids utilization on the means shown in Table 10 is discussed in more detail below in the analysis of the harmonization process step-by-step results.

Third, energy use for collection/transport and for treating food wastes represent roughly equal portions of total energy usage, with collection and transport, consuming the greater amount of energy for the three options (AC, AD, and LF) that rely on trucks for collecting and transporting food wastes to processing facilities. The fact that managing food wastes at a landfill has high mean energy use is due to a very high estimate in one of the 5 studies contributing to the means for landfill energy impacts. In fact, excluding that study's estimate reduces the processing mean for landfills by nearly 55% to about 0.26 MJ per kilogram landfilled. The possible influence of outliers is discussed further in the sensitivity analysis section of this chapter.

Fourth and finally, AD is the only treatment option with treatment method outputs of sufficient magnitude to more than offset the climate impacts of inputs used by a treatment method. For energy impacts, ISG is the only treatment for which outputs yield energy reductions that more than offset energy used for collection, transport and processing. For AD it is the climate offset for electricity compared with its relatively small carbon footprints for collection and processing that yield a net climate benefit. For ISG it is displacement of energy for synthetic fertilizer production and grid electricity generation that yields a net energy use benefit.

Step-by-Step Harmonization Results

Harmonization of the 28 LCAs aligned boundary conditions for the 4 food waste treatment options -- for example, by including food waste collection method impacts in all assessments. Once those aspects were aligned and consistent, the LCA boundaries for all 28 studies were expanded to include carbon storage, fertilizer and peat displacements and displacement of grid electricity. These steps harmonized LCAs that excluded one or more of these benefits of the treatment options. Next, the LCAs were harmonized to reflect Oregon specific estimates for the carbon footprint of grid electricity, mean landfill gas capture efficiency and mean rate of utilization of captured landfill methane for generation of electricity. Finally, estimates of current utilization rates for compost, digestate and biosolid outputs as

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[5] Note that benefits are shown as negative values in Tables 10 and 11, indicating that they reduce carbon emissions and energy use.

well as electricity outputs were inserted to better reflect the actual displacements in Oregon generated by outputs of the four food waste treatment methods.

Table 11, Step-by-Step Cumulative Results from Harmonization, shows the effects on mean impacts from each harmonization process step. The table also shows minimum and maximum impact estimates among the LCAs that studied climate and/or energy impacts for a particular treatment method. Table 11 indicates the number of LCAs providing impact estimates for each management method. These numbers range between 25 LCAs that provided detailed climate impacts for aerobic composting down to a single study that provided energy impacts for anaerobic digestion. Aerobic composting and landfilling tended to be the most studied. In-sink grinding and wastewater treatment plant processing with anaerobic digestion of biosolids was studied by only a handful of LCAs.

The following report subsections detail each harmonization step leading up to the final cumulative results displayed in Table 10 above and on the last line of Table 11 above.

Published LCA Results – Starting Point for Harmonization Process

The first line of Table 11 exhibits means and ranges for impacts of each management method from studies that passed the exclusion criteria. The ranges are in some cases quite wide, and provide a major motivation for carrying out this systematic review and harmonization of available LCAs on food waste management methods, as discussed in Section 1. The other major motivation was to adapt LCA results to Oregon specific conditions for electricity carbon footprint, landfill gas collection and utilization, digestate or biosolids utilization for energy recovery, and utilizations of compost, digestate and biosolids as substitutes for fertilizer and/or peat.

Total net impact estimates that resulted from the harmonization process are shown in the summary Table 10. They also are shown in the last row labeled Net Harmonized Results, of the step-by-step Table 11. Comparing the first and last rows of the step-by-step table indicates the extent by which harmonization narrowed the range of climate impact results for three management methods, and increased the range for ISG. At the same time, harmonization did not change the rankings for climate impacts.

On the other hand harmonization did change the rankings for energy impact, with ISG moving up from third to first, AD falling from first to second, and LF moving down from second to third.

Harmonization also narrowed the distance between minimum and maximum impacts for climate and energy for all treatment methods, except for ISG’s climate range which increased and AD’s energy range that remained unchanged due to having a sample size of one.

Table 11: Step-by-Step Cumulative Results from Harmonization

Harmonization Steps	Aerobic Composting Impacts						Anaerobic Digestion Impacts						In-Sink Grinding & WWTP AD Impacts						Landfill Impacts					
	Climate (eCO2/kg)			Energy (MJ/kg)			Climate (eCO2/kg)			Energy (MJ/kg)			Climate (eCO2/kg)			Energy (MJ/kg)			Climate (eCO2/kg)			Energy (MJ/kg)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Published LCA Results	0.01	-1.12	0.47	1.15	0.18	3.63	-0.15	-0.48	0.03	-2.25	-2.25	-2.25	0.19	0.00	0.44	0.49	0.19	0.81	0.44	-0.26	0.91	0.19	-2.15	1.20
(LCA Sample Size)	(	25	)	(	10	)	(	10	)	(	1	)	(	5	)	(	3	)	(	15	)	(	5	)
Cumulative Estimate Including:																								
Accounting Adjustments	0.02	-0.71	0.47	1.15	0.18	3.63	-0.15	-0.48	0.03	-0.41	-0.41	-0.41	0.18	0.00	0.44	0.49	0.19	0.81	0.46	0.02	0.91	0.51	-0.58	1.20
IPCC 2007 GWPs	0.02	-0.71	0.47	1.15	0.18	3.63	-0.15	-0.48	0.03	-0.41	-0.41	-0.41	0.18	0.00	0.44	0.49	0.19	0.81	0.51	0.06	1.10	0.51	-0.58	1.20
Added Collection	0.04	-0.71	0.47	1.36	0.30	3.63	-0.14	-0.46	0.03	0.27	0.27	0.27	0.25	0.00	0.47	0.49	0.19	0.81	0.51	0.06	1.10	0.61	-0.08	1.20
Subtracted Collection Bags	0.04	-0.71	0.47	1.30	0.27	3.63	-0.14	-0.46	0.03	0.27	0.27	0.27	0.25	0.00	0.47	0.49	0.19	0.81	0.51	0.06	1.10	0.60	-0.08	1.20
Subtracted Facility Construction	0.03	-0.71	0.47	1.27	0.27	3.34	-0.14	-0.46	0.03	0.27	0.27	0.27	0.22	-0.04	0.44	0.14	-0.24	0.67	0.51	0.06	1.10	0.54	-0.11	1.07
Added Offsets:																								
Carbon Storage	-0.03	-0.71	0.35	1.27	0.27	3.34	-0.19	-0.46	-0.03	0.27	0.27	0.27	0.20	-0.06	0.42	0.14	-0.24	0.67	0.44	-0.04	0.98	0.54	-0.11	1.07
Displaced Synthetic Fertilizer	-0.05	-0.71	0.31	1.19	0.27	3.34	-0.19	-0.46	-0.03	0.27	0.27	0.27	0.17	-0.06	0.37	0.04	-0.32	0.67	0.44	-0.04	0.98	0.54	-0.11	1.07
Displaced Peat	-0.10	-0.71	0.30	1.14	0.19	3.34	-0.20	-0.46	-0.03	0.27	0.27	0.27	0.17	-0.06	0.37	0.04	-0.32	0.67	0.44	-0.04	0.98	0.54	-0.11	1.07
Displaced Electricity	-0.10	-0.71	0.30	1.14	0.19	3.34	-0.20	-0.46	-0.03	0.27	0.27	0.27	0.10	-0.14	0.29	-0.32	-0.41	-0.24	0.38	-0.04	0.98	0.40	-0.11	1.07
OR Specific Adjustments																								
Electricity Offset CO_2 Footprint	-0.10	-0.71	0.30	1.14	0.19	3.34	-0.18	-0.37	0.00	0.27	0.27	0.27	0.03	-0.21	0.28	-0.32	-0.41	-0.24	0.40	-0.02	0.94	0.40	-0.11	1.07
LFG Capture Efficiency	-0.10	-0.71	0.30	1.14	0.19	3.34	-0.18	-0.37	0.00	0.27	0.27	0.27	0.03	-0.21	0.28	-0.32	-0.41	-0.24	0.48	0.08	0.91	0.42	-0.06	0.99
Offsets Utilization	-0.05	-0.43	0.28	1.23	0.29	3.26	-0.17	-0.30	0.00	0.29	0.29	0.29	0.03	-0.21	0.28	-0.32	-0.41	-0.24	0.52	0.11	0.94	0.60	0.12	1.24
Net Harmonized Results	**-0.05**	**-0.43**	**0.28**	**1.23**	**0.29**	**3.26**	**-0.17**	**-0.30**	**0.00**	**0.29**	**0.29**	**0.29**	**0.03**	**-0.21**	**0.28**	**-0.32**	**-0.41**	**-0.24**	**0.52**	**0.11**	**0.94**	**0.60**	**0.12**	**1.24**

Accounting Adjustments

The first step for the harmonization process was to adjust published results to attain accounting consistency. Several of the studies estimated carbon storage from amending soils with compost, digestate, or biosolids, or from landfilling food wastes, but did not provide an LCA credit for storage. Results for these studies were adjusted to include credits for carbon storage.

There also was a discrepancy in accounting for the energy value of displaced electricity. Most of the LCAs selected for harmonization used an energy offset credit of 3.6 megajoules (MJ) per kilowatt hour (kWh) output by the treatment method's food waste processing technology. 3.6 MJ is the energetic value of a kWh. However several studies used an energy credit based on the energy value of the fuels used to produce electricity, which is a much larger number (as much as 3 to 5 times as large) that depends on the type of fuels used for power generation and the energy conversion efficiency of power generation facilities. Electricity offsets for management options studied in those LCAs were converted to 3.6 MJ per kWh to conform to the offset used in most of the harmonized LCAs.[6]

Finally, there were what appeared to be computational errors in a few LCAs. These were corrected in this initial step.

The accounting adjustments in this first harmonization step changed mean energy impact estimates for anaerobic digestion and landfill substantially. There also were minor changes in mean climate impacts from the accounting adjustments and computational corrections for aerobic composting, in-sink grinding and landfilling.

Adjust Carbon Emissions to 2007 IPCC Global Warming Potentials

The 2007 Intergovernmental Panel on Climate Charge (IPCC) global warming potentials (GWPs) -- 25 for methane and 298 for nitrous oxide – were used in most LCAs to convert methane and nitrous oxide emissions to carbon dioxide equivalents (eCO_2). However, a number of studies used the older IPCC GWPs of 21 and 310 for methane and nitrous oxide, respectively. Thus, carbon dioxide equivalent estimates for emissions of methane and nitrous oxide during food waste processing in the latter LCA studies were adjusted to reflect 2007 GWPs.

This adjustment had no discernable effect on the mean climate impact for management methods other than landfilling, where methane emissions are a major component of climate impacts and increasing the GWP for methane raised the mean, minimum and maximum.

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[6] Converting the energy value for displaced electricity to the energy value of fuels used to generate that electricity for each LCA would require knowledge of the fuels used for electricity generation in each LCA. Assembling this information, if even available, would have exceeded the project's timeline and budgetary constraints.

Add Collection Impacts

Eleven of the 25 LCAs that provided climate impact estimates for aerobic composting, and 3 of the ten providing energy usage estimates, did not include collection impacts. For anaerobic digestion 7 of the 10 with climate impact estimates did include collection. The one study on AD energy impacts did not include collection. One of the five LCAs on climate impacts for ISG did not include full collection system impacts; all 3 providing energy impacts for this treatment option included collection energy. Two of the 15 estimating landfilling climate impacts and 1 of the 5 calculating energy use did not include collection.

Using the mean for studies that did provide collection estimates for a particular method and impact, harmonization added those means to studies that were missing collection impact estimates. The one exception is for the collection energy added to the one study on AD energy impacts. In this case mean AC collection energy was used as an estimate of AD collection energy. Collection energy is not likely to depend on whether the processor is an AC or AD facility, and the one LCA that examined AD energy impacts did not provide an estimate for collection energy.

The added collection impacts increased means, and sometimes minimums and/or maximums, in all cases having missing collection data, except for landfilling climate impacts. For landfilling, adding collection emissions to the two studies missing a collection GHG emissions estimate did not change the overall mean for the 15 studies that assessed climate impacts of landfilling.

Subtract Collection Bag Impacts

One of the 25 AC studies assessing climate impacts and 2 of the 10 assessing energy use for AC included estimates for the effects of collection bags or bins. One study assessed collection bags and/or cans for garbage collection. These data do not provide a sound basis for gauging the impacts of collection bags, cans, carts and bins, and so were excluded in this step of the harmonization process.

As a result climate and energy impact estimates for AC and energy impacts for landfilling decreased.

Subtract Impacts of Facility Construction and In-sink Grinder Production

Three studies assessed AC facility construction climate impacts and 4 assessed AC facility construction energy impacts. The estimates for energy impacts differed by more than 3 orders of magnitude. The estimates for climate impacts of facility construction differed by nearly a factor of 7. There was only one assessment for AD facility construction climate impacts. There were 3 estimates for climate and energy effects of landfill cell construction. These differed by more than 3 orders of magnitude, and one of the climate estimates was estimated as essentially zero.

Due to the highly uncertain nature of these assessments, facility construction was removed as a process included in the boundaries of the harmonized LCAs. This resulted in decreases in mean climate and energy impacts for AC and mean energy impacts for landfilling.

The LCAs chosen for harmonization did not include production impacts for collection vehicles, roads or wastewater conveyance pipes. All the ISG LCAs provided climate and energy assessments for grinder production. None of the ISG LCAs provided either assessment for waste water treatment facilities. To be consistent with the lack of impact assessments for production of food waste collection vehicles for the AC, AD and LF options, grinder production impacts were also removed in this harmonization step. This resulted in decreases in both climate and energy impacts for ISG.

Add Missing Offsets

Benefits of food waste treatment assessed in some of the harmonized LCAs included carbon storage, displacement of synthetic fertilizers and/or peat, and generation of energy that displaces fossil energy sources. In order to bring all LCAs to an equal basis in terms of inclusion of benefits from food waste treatments, the harmonization process added in offsets wherever they were missing in the LCAs.

Carbon Storage

Carbon storage is taken into account in the food waste treatment LCAs when a treatment option results in a portion of the carbon in food wastes not being released to the atmosphere during the 100-year time frame of these LCAs. For example, this may occur when AC compost, AD digestate, or ISG biosolids are used as soil amendments. It also occurs in landfills due to resistance of some materials to biodegradation under the anaerobic conditions in landfills.

Eleven of the 25 AC climate impact studies assessed soil carbon storage in soils amended with AC compost. These 11 estimated a mean increase in soil carbon of 0.12 kg eCO_2 per kg food waste composted, with a range between 0.01 and 0.27 kg eCO_2.[7] Four of the 10 AD climate impact studies assessed soil carbon storage in soils amended with composted AD digestate. These 4 estimated a mean increase in soil carbon of 0.08 kg eCO_2 per kg food waste digested, with a range between 0.01 and 0.22 kg eCO_2. Two of the 5 ISG climate impact studies assessed soil carbon storage in soils amended with ISG biosolids. The 2 estimated a mean increase in soil carbon of 0.03 kg eCO_2 per kg food waste disposed through in-sink grinders, ranging between a lower estimate of 0.02 and a higher estimate of 0.03 kg eCO_2.[8] Lastly, 7 of the 15 landfill climate impact LCAs included landfill carbon storage at a mean of 0.12 kg eCO_2 per kg food waste landfilled, with a range between 0.07 and 0.33 kg eCO_2.

LCAs were harmonized by adding carbon storage to the studies that did not include this benefit. The additions for a particular treatment were at the mean carbon storage benefit estimated by studies on that treatment that included carbon storage. These additions decreased the net climate impact for all

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[7] One of these studies, however, excluded carbon storage as an offset when calculating the total climate impact for AC.

[8] One of these studies, however, excluded carbon storage as an offset when calculating the total climate impact for ISG.

four management methods by at least 10%. In the case of aerobic composting harmonization changed the net impact from a burden of 0.03 kg eCO_2 to an overall benefit of -0.03 kg eCO_2.

Displacement of Fossil-Based Synthetic Fertilizer

Thirteen of the 25 AC climate impact studies assessed climate benefits of fertilizer displacement in soils amended with AC compost. These 13 yielded a mean climate benefit of 0.08 kg eCO_2 per kg food waste composted, with a range from nearly zero to 0.51 kg eCO_2. Three of the 10 AC energy impact LCAs looked at the energy benefit of substituting AC compost for synthetic fertilizer. That mean energy benefit was 0.25 MJ per kg food waste composted, ranging between 0.15 and 0.39 MJ per kg.

Nine of the 10 AD climate impact LCAs assessed climate benefits from fertilizer displacement in soils amended with composted AD digestate. Their mean climate benefit was 0.02 kg eCO_2 per kg food waste digested, with a range from nearly zero to 0.09 kg eCO_2. There was only one LCA on AD energy impacts. That study estimated the energy benefit for replacing synthetic fertilizers with composted AD digestate at 0.15 MJ per kg food waste processed by an AD system.

Two of the 5 ISG climate impact studies assessed climate benefits from fertilizer displacement in soils amended with ISG biosolids. The 2 estimated a mean fertilizer displacement of 0.05 kg eCO_2 per kg food waste disposed through in-sink grinders, ranging between the lower estimate of 0.04 and the higher estimate of 0.05 kg eCO_2. One of the three studies assessing energy impacts of the ISG treatment option included an estimate for the energy benefit of substituting ISG biosolids for synthetic fertilizers. That study's estimated benefit was 0.3 MJ per kg food waste processed through an in-sink grinder.

LCAs for the three treatments that produced a soil amendment that could replace synthetic fertilizers were harmonized by adding fertilizer displacement climate and energy benefits to the studies that did not include this benefit. The additions for a particular treatment were at the mean climate or energy benefit estimated in studies on that treatment that included climate and/or energy offsets for fertilizer substitution.

These additions decreased net climate and energy impacts for AC and ISG between 6% and over 60%. There was no significant change in the climate impact for AD because 9 of the 10 AD climate impact LCAs already included that benefit. The one AD energy impact LCA already included that benefit.

Displacement of Peat in Growth Media

Four of the 25 AC climate impact studies assessed climate benefits of peat displacement by AC compost in plant growth media. These 4 yielded a mean climate benefit of 0.28 kg eCO_2 per kg food waste composted, with a range from 0.12 to 0.42 kg eCO_2. Only 1 of the 10 AC energy impact LCAs looked at the energy benefit of substituting AC compost for peat, estimating a benefit of 0.19 MJ per kg food waste composted.

Only 1 of the 10 AD climate impact LCAs assessed climate benefits from substituting composted AD digestate for peat. That study estimated a benefit of 0.14 kg eCO_2 per kg food waste digested. There was only 1 LCA on AD energy impacts. That study estimated the energy benefit for replacing peat with composted AD digestate at 0.18 MJ per kg food waste processed by an AD system.

None of the 5 ISG climate impact studies assessed climate benefits from peat displacement with ISG biosolids. Similarly none of the three studies assessing energy impacts of the ISG treatment option included an estimate for the energy benefit of substituting ISG biosolids for the use of peat as a plant growth media. It's likely that WWTP biosolids were not assessed for this use because they are not a very suitable replacement for peat.

LCAs for AC and AD were harmonized for peat displacement by adding climate and energy benefits to the studies that did not include one or both of these benefits. The additions for a particular treatment were at the mean climate or energy benefit estimated in studies on that treatment that included climate and/or energy offsets for peat substitution.

These additions decreased net climate impacts for AC by 100% and net energy impacts by almost 5%. There was a 5% decrease in the net climate impact for AD. The one AD energy impact LCA already included the benefit of peat displacement.

Displacement of Grid Electricity

All 10 climate impact LCAs and the one energy impact LCA for AD included displacement of grid electricity so no harmonization was needed for the AD studies. The mean climate impact for electricity displacement was 0.18 kg eCO_2 per kg food waste digested. The energy benefit of electricity production from AD processing of food waste in the one study on AD energy impacts was 0.83 MJ per kg of food waste digested.

Two of the 5 ISG climate impact studies assessed climate benefits from displacing grid electricity with electricity generated from methane produced from food waste treatment at a WWTP followed by anaerobic digestion of biosolids. The 2 estimated a mean grid electricity carbon footprint displacement of 0.11 kg eCO_2 per kg food waste disposed through in-sink grinders, ranging between the lower estimate of 0.09 and the higher estimate of 0.13 kg eCO_2. Two of the three studies assessing energy impacts of the ISG treatment option included an estimate for the energy benefit of electricity production. The 2 studies' estimated mean benefit was 1.03 MJ per kg food waste processed through an in-sink grinder, ranging between a lower estimate of 0.67 and a higher estimate of 1.4 MJ.

Nine of the 15 climate impact LCAs for landfilling assessed the climate impacts of generating electricity from captured methane. Those nine estimated a mean benefit of 0.15 kg eCO_2 per kg food waste landfilled, ranging between 0.10 and 0.20 kg. Four of the 5 energy impact LCAs for landfilling included the benefit of displacing grid electricity with electricity produced from captured landfill methane generated by buried food wastes. The mean estimated benefit was 0.68 MJ per kg food wastes, ranging between 0.57 and 0.82 MJs.

LCAs for ISG and LF climate and energy impacts were harmonized for grid electricity displacement by adding benefits to the studies that did not include such benefits. The climate impact additions were at the mean climate benefit estimated in studies for a particular treatment that included climate offsets for grid electricity substitution.

The adjustment for the one ISG study lacking an energy benefit from electricity production was based on the electricity production estimate -- 0.3 kWh generated per kilogram of food waste processed by ISG -- used in that study to calculate the climate benefit from electricity production. The adjustment for the one LF study lacking an energy benefit from electricity production was based on the mean electricity production benefit for the 4 LF LCAs that included estimates for this offset.

These additions decreased net climate impacts for ISG by 41%. They changed net energy impacts from a burden to a benefit. They decreased net climate impacts for LF by 14% and net energy impacts by 26%. AD LCAs for climate and energy impacts did not require harmonization because all those studies assessed the benefits of grid electricity displacement. AC LCAs did not require harmonization because AC was not assessed as having electricity generation capability.

Adjust for Oregon Specific Conditions

The final harmonization steps adjusted the LCA results for Oregon specific conditions. These included the carbon footprint of grid electricity, landfill gas capture efficiencies, landfill gas utilization rate for electricity generation, and utilization rates for compost, digestate and biosolids in ways that facilitate carbon storage, fertilizer substitution and/or peat substitution. The following subsections provide details on each of these adjustments.

Oregon Carbon Footprint for Grid Electricity

According to EPA's eGRID data, Oregon's 2010 carbon footprint for non-baseload electricity is 1.35 pounds eCO_2, or 0.61 kg, per kWh based on 2007 IPCC global warming potentials for methane (i.e., GWP=25) and nitrous oxide (i.e., GWP=298).[9] This compares with a mean for 9 AD LCAs of 0.66 kg eCO_2 per kWh, ranging between 0.43 and 1.02 kg; a mean for 2 ISG LCAs of 0.42 kg eCO_2 per kWh, ranging from 0.24 to 0.60 kg; and a mean for 9 LF studies of 0.75 kg eCO_2 per kWh, ranging from 0.44 to 1.02 kg eCO2 per kWh.

The non-baseload footprint was chosen for the Oregon grid electricity adjustment because it represents the footprint of power generation facilities that are used to meet peak power demand. As such they

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[9] Available at http://www.epa.gov/cleanenergy/documents/egridzips/eGRID_9th_edition_V1-0_year_2010_Summary_Tables.pdf

more closely measure the marginal rather than the average climate impact for power generation in Oregon. It is the marginal – i.e., last to be used – power sources that are apt to be displaced by electricity generated at AD, ISG or LF facilities.

Adjusting all LCAs to the Oregon footprint increases the climate impact for AD by 10% and the LF climate impact by 5%. It reduces the climate impact for ISG by 70% because the ISG LCAs' mean grid electricity carbon footprint is a third lower than the Oregon non-baseload footprint.

Oregon Food Waste Landfill Gas Capture Efficiency and Utilization Rate for Electricity Generation

Thirteen LF LCAs had an estimated landfill gas (LFG) capture efficiency mean of 67.2%, ranging between 45% and 81%. Food waste landfill gas capture efficiency in Oregon's existing landfills is estimated By DEQ staff to average 62% over the subsequent 100 years, the time frame that has been chosen for most landfill LCAs. This represents a statewide average; landfill-specific efficiencies will vary. The landfill oxidation of fugitive methane is estimated at 10% by DEQ staff, which is quite close to the 10.5% mean in 11 LF LCAs that detailed oxidation rate estimates. Further DEQ staff estimate that 72.6% of captured LFG methane is used to generate electricity whereas the remainder is flared. This utilization rate of LFG for energy recovery is taken into account in the utilization rates adjustments detailed in the next subsection.

Adjusting the landfill climate and energy impacts to Oregon specifications for LFG capture efficiency and fugitive methane in-landfill oxidation increases LF net climate impacts by 20% and LF net energy impacts by 5%.

Oregon Estimated Utilizations for Compost, Digestate and Biosolids

The project team's survey of Oregon aerobic composters of food wastes and survey results are discussed in Section IV. The survey results suggest that 25% of compost that has been produced with some food waste inputs is sold to agriculture users, 62% to households, 12% to landscapers and 1% to nurseries. Assuming that all agriculture users land apply these composts as a fertilizer substitute, the utilization rate for fertilizer displacement by compost is 25%. Assuming that nurseries use compost as a peat substitute the peat substitute utilization rate is 1%. It is assumed that landscapers do not use compost as a substitute for either fertilizer or peat.

Compost producers do not have detailed knowledge of household uses of compost. However, one of the harmonized LCAs (Andersen *et al* 2010b) included results from a survey of households in Denmark. While this may not be particularly accurate for Oregon households, the survey at least provides actual estimates of household behavior. That survey found that 18% of compost was used as a soil amendment replacing synthetic fertilizers, 11% replaced manures, 20.5% replaced peat, and the other 50.5% did not provide any of these benefits. Applying these percentages to the 62% of household purchased compost for Oregon and adding the results to the utilization rates of agriculture and nurseries yields estimated utilization rates of 36% uses that displace fertilizers and 14% uses that displace peat.

The survey did not cover AD digestate or digestate compost markets or ISG biosolids or biosolids compost markets. Casual observations by DEQ staff and food waste management system stakeholders suggest that all the outputs of AD digestate and ISG biosolids in Oregon are used in agriculture. Hence it is assumed that AD and ISG have utilization rates of 100% for fertilizer displacement.

There are a wide variety of ways in which composts, digestates and biosolids may be used – for example, agricultural crop land soil amendment, home garden soil amendment, lawn top dressing, mulch, back fill, and plant growth media. Regardless of use, it is assumed that soil carbon storage is attained at the rates estimated in the harmonized LCAs from incorporation into agricultural or home garden soils. Those mean estimates per kilogram of food waste processed are 0.12 kg eCO_2 for AC compost, 0.08 kg eCO_2 for AD composted digestate, and 0.03 kg eCO_2 for ISG biosolids.

Applying these utilization rates for AC, AD and ISG increases or leaves unchanged climate and energy impacts because the LCAs assumed utilization rates of 100%, except when both fertilizer and peat substitutions were considered the utilization rates were 50% each. AC climate impacts per kg food waste increase from -0.10 to -0.05 kg eCO_2 and energy impacts by 8% from 1.14 to 1.23 MJ per kg food waste. AD climate impacts increase slightly from -0.18 to -0.17 kg eCO_2 per kg food waste, and energy impacts by 7% from 0.27 to 0.29 MJ per kg food waste. ISG climate and energy impacts remain unchanged at 0.03 kg eCO_2 per kg food waste and -0.32 MJ per kg food waste. Finally the 72.6% utilization rate for captured methane in production of electricity increases LF climate impacts by 8% from 0.48 to 0.52 kg eCO_2 per kg food waste, and energy impacts by 43% from 0.42 to 0.60 MJ per kg food waste.

Climate and Energy Impact Rankings Sensitivities and Non-Sensitivities

There are parameters and assumptions that are such that climate and energy impact rankings are particularly influenced by them and others for which the rankings are relatively robust. These include:

- Climate rankings for AC, AD and ISG are particularly sensitive to the carbon footprint of displaced electricity. The harmonized results used Oregon's non-baseload electricity footprint. This footprint is between 10% and 15% higher than the carbon footprint of natural gas fired power generation. If the footprint for displaced electricity were to be based on solar power then AC would jump ahead of AD in being best for the climate. If the footprint were to be based on coal fired power, then ISG would move into second place behind AD and AC would fall to third.
- Climate impact ranking for LF is not sensitive to the carbon footprint of displaced electricity due to LF's relatively low electricity output compared to the high total climate impact for LF.
- Energy impact rankings for AC, AD, ISG and LF are not sensitive to whether primary energy demand or the energetic value of electricity is used to measure the energy impact of displaced electricity. Recall that the energetic value of electricity is used in the harmonization results.

- Climate and energy impact rankings for AC and AD are sensitive to the utilization rate for amendments as a substitute for fertilizer or for peat. 36% is the fertilizer displacement utilization rate and 14% is the peat displacement rate used for AC harmonization, and 100% is the fertilizer substitution rate for AD.
- Climate rankings are likely not to be sensitive to other estimates of soil carbon storage rates from use of soil amendments produced by AC, AD, or ISG. For example, the carbon storage factor for AC compost would have to double for AC to pull even with AD in the climate ranking. ISG's soil carbon storage factor would have to increase by a multiple of 5 for ISG to jump ahead of AC.
- Rankings may be sensitive to outliers that substantially skew mean climate or energy impacts of a unit process. For example, one of the five LF LCAs that estimated LF energy use has an estimate for LF processing energy that is very high. Removing that outlier reduces LF processing energy by more than half. This would lower LF total energy impact below AD, pushing AD into last place in the energy usage ranking.

Limitations and Future Research Recommendations

- The unit of evaluation in the report was tons of food waste processed in the four systems selected for study; not tons of food waste generated. The study did not account for the variability of generator behavior, such as the lack of100% utilization of one system when others might also be available. It also did not address limitations in the technology, such as the inability of ISG systems to handle many kinds of food waste, such as starchy or fibrous material.
- An exhaustive search found a general lack of LCA studies on food waste processing systems. For example, the research team found only one LCA study for the energy impacts of anaerobic digestion. This limits the conclusions we can draw about AD's ranking for this factor. In general, the number of available studies for harmonization was very limited. Only for climate impacts of aerobic composting and landfill were there more than 10 studies suitable for harmonization. This severely limits confidence in the conclusions one can draw from the harmonization results. Further research on each of the selected treatment systems would help to provide a higher level of certainty for the relative rankings of technologies.
- The LCA literature does not have an impact category that directly addresses soil quality and soil productivity. At the same time LCAs reviewed for this project did account for the climate impacts of changes in soil carbon storage and displacements of synthetic fertilizers and pesticides induced by use of composts, digestates and biosolids produced from food wastes. To provide a more complete assessment of the relative impacts of the four food waste treatment options examined in this report on soils, measures should be developed to expand the analysis of future LCAs for these additional impact categories.
- In Section 3, biosolids were selected as a proxy for the soil impacts of AD digestate due to a lack of research studies on soil impacts of digestate from AD. There was disagreement about how

similar the two products are in terms of nutrient density and field application, and their suitability as a substitute for peat. There was also concern raised about the levels of toxic compounds and metals found in municipal sewage sludge and their impacts on soil health, concerns not associated with AD. More research is needed on the actual soil impacts of digestates.

- Section 3 ranking of nitrogen quantities in AC compost versus AD digestates or composted AD digestates suggested that AD soil amendment outputs provide greater potential for fertilizer substitution than AC compost. However, the LCA studies selected for harmonization had mean estimates of fertilizer substitution potential that were higher for AC compost than for soil amendment outputs of either AD or ISG. This suggests that soil quality research is not adequately reflected in LCA studies on food waste management systems.
- In general, the LCA literature did not adequately assess the primary energy demand implications of energy inputs and outputs for food waste processing systems. As a result electricity displacements had to be calculated at the energy value of a kilowatt hour (kWh) -- 3.6 megajoules (MJs). Conversion of electricity to energy using the 3.6 MJ/kWh ratio is known as the direct equivalence method. However, different electricity generation sources have different conversion efficiencies. Using the primary energy equivalent method to account for these sources would increase electricity displacements by a factor that varies based on the source. Fossil fuel factors range from 2 to 3, and renewable source factors range from 1 to 10. A rough estimate of the overall factor for Oregon is likely between 3 and 5 based on US EPA eGRID 2010 data. Fortunately the ranking of technologies in terms of harmonized total energy impacts would not change using the primary energy equivalent method. However using primary energy equivalent factors for Oregon for all aspects of energy uses and offsets would yield results more consistent with the accounting methods used to calculate climate impacts in the harmonized LCAs.
- The LCAs reviewed used the 100 year global warming potential for methane, which has a global warming potential of 25 averaged over this time, according to the IPCC. However, methane is a gas that has a residence time of 12 years in the atmosphere, much shorter than carbon dioxide and has an initially large global warming potential that diminishes over longer time periods. Many climate researchers are concerned that the most meaningful time period for preventing run-away temperature increases is the near term. In a 2013 report, the IPCC has calculated methane's global warming potential as 86 times that of carbon dioxide when it is measured over 20 years. It is possible that if the 20 year time frame was used, impacts such as methane emissions from virgin peat mining, from AC piles that go anaerobic for a period of time, or from process stages of the other selected technologies could have changed the relative rankings. Future LCA studies using this shorter time frame could help with this understanding.

6. Appendix A – LCA Bibliography

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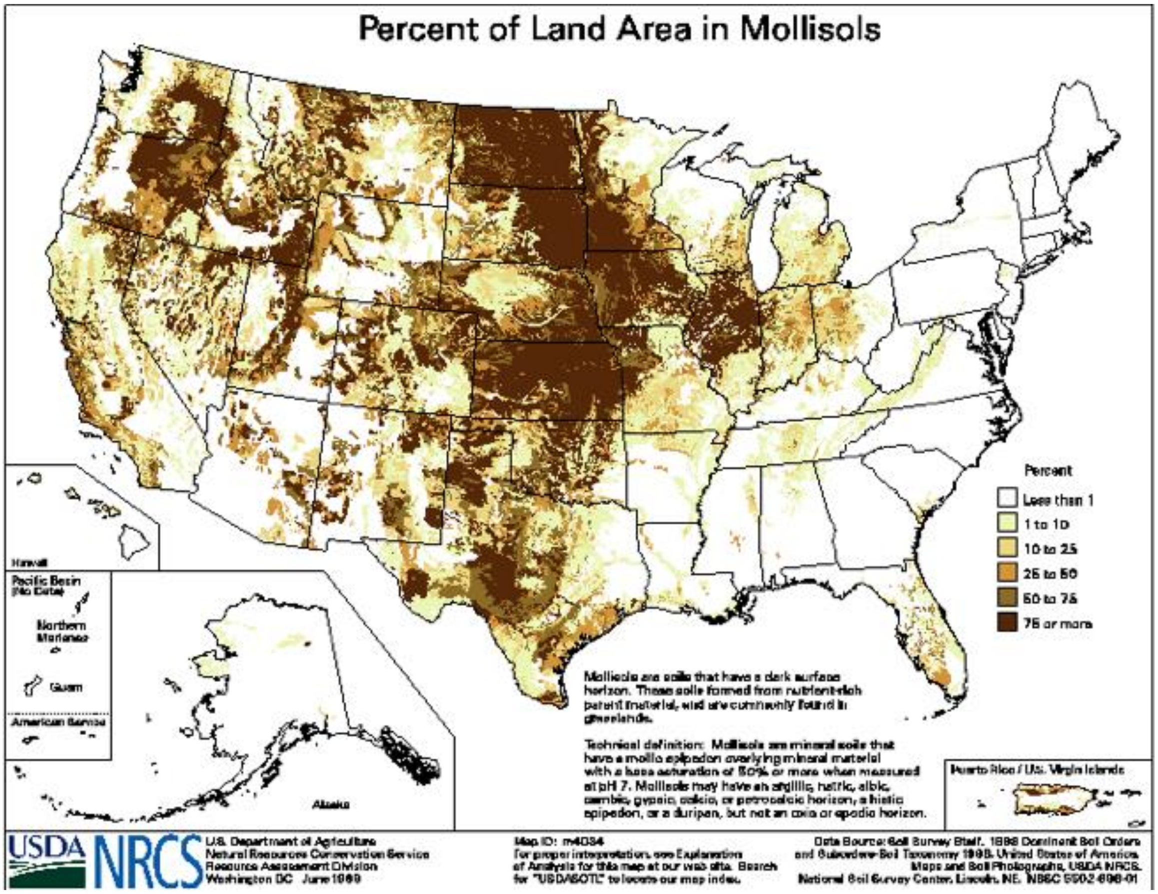
7. Appendix B – Soil Qualities

Soil Basics

This appendix provides a basic overview of soil, which is critical to understanding the benefits associated with land application of composts and digestates. Soil is the medium to which these materials will be added.

Soils develop from rock over time as a result of biological and chemical processes. Soil formation is typically described as dependent on five factors: parent material, time, climate, topography and biology.

Soil formation is a time intensive process with formation occurring over thousands of years (Banwart, 2011; Brady and Weil, 2002; Montgomery, 2007). One estimate puts the rate of soil formation at 0.058-0.083 mm per year (Montgomery, 2007). Soils across the world vary greatly as a result of different parent materials, climates, ages and management practices. They all however, consist of a combination of a mineral fraction (sand, silt and clay particles), organic matter, and void space. There are a number of systems of soil classification that group soils based on similar characteristics. The US system has twelve master categories of soils (http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/?cid=nrcs142p2_053588). Within these categories, entisols is the term used to describe newly developed soils with minimal changes from parent material as a result of soil forming factors. Mollisols are the richest soils, developed under grasslands with very thick organic horizons. A map of the national distribution of mollisols is shown below. Note that the highest concentrations of mollisols are in the Corn Belt.



Percent of Land Area in Mollisols

Mollisols are soils that have a dark surface horizon. These soils formed from nutrient-rich parent material, and are commonly found in grasslands.

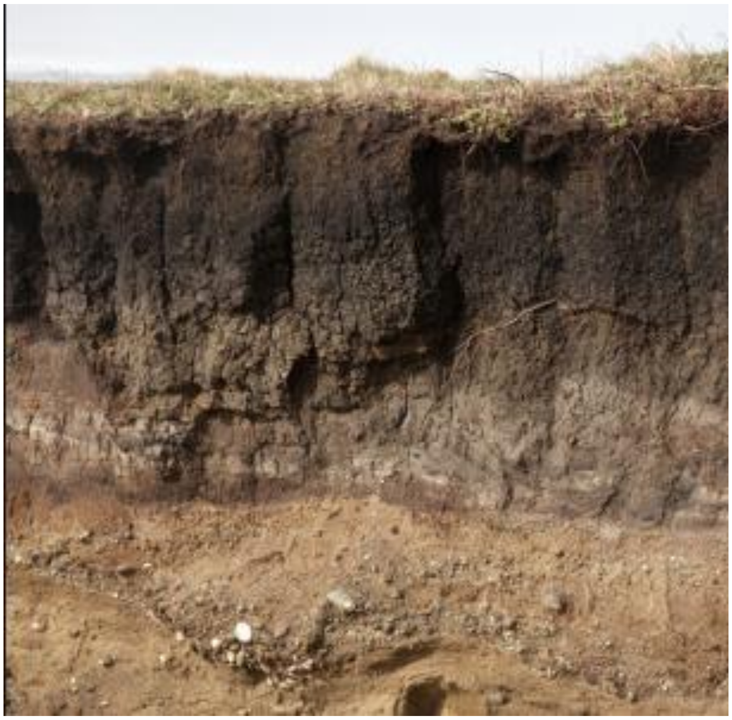
Technical definition: Mollisols are mineral soils that have a mollic epipedon overlying mineral material with a base saturation of 50% or more when measured at pH 7. Mollisols may have an argillic, natric, albic, cambic, gypsic, calcic, or petrocalcic horizon, a histic epipedon, or a duripan, but not an oxic or spodic horizon.

U.S. Department of Agriculture
Natural Resources Conservation Service
Resource Assessment Division
Washington DC June 1999

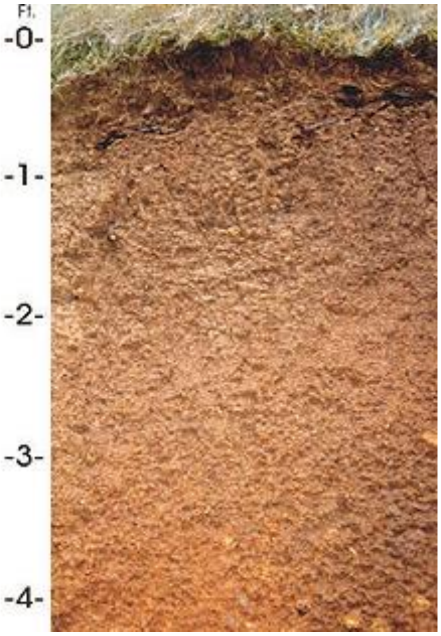
Map ID: m4034
For proper interpretation, see Explanation of Analysis for this map at our web site. Search for "USDASOTL" to locate our map index.

Data Source: Soil Survey Staff. 1998 Dominant Soil Orders and Suborders-Soil Taxonomy 1998. United States of America Maps and Soil Photographs, USDA NRCS. National Soil Survey Center, Lincoln, NE. NSSC 5502-698-01

A mollisol from coastal Oregon is shown below. Notice how deep the surface horizon is and how it is enriched with organic matter.



The State soil of Oregon is the Jory soil, a weathered ultisol that is found in the Willamette valley. These soils will have a high clay content and low reactivity. Organic matter will also be low. A soil profile from a Jory soil and a map of the series distribution in OR is shown below.



The productivity of a soil depends on a number of physical and chemical characteristics.

Soil mineral fraction

Soil parent material and age both determine the characteristics of the mineral fraction of soils. There are two components of the mineral fraction that are important. These are soil texture and clay mineralogy. Soil texture describes the relative amounts of sand, silt and clay particles in a soil. Sand (0.05-2 mm) is the coarsest of these, with silt (0.002-0.05 mm) and clay (<0.002) describing finer factions. Soil texture is a critical factor for soil water relations. Sandy soils will allow rapid water infiltration but will also drain very quickly, making soils highly vulnerable to drought. In contrast, high clay soils typically allow for slow water infiltration but will hold onto water tightly once it has infiltrated. These soils are prone to ponding and compaction. Clays have a much greater surface area than silt or sands, with different types of clay also being a significant factor.

Total surface area of soil colloids can vary from 10 m^2 per g to 800 m^2 per g. Ability to hold onto nutrients is a function of surface area and mineralogy. Clay mineralogy describes the nature of the individual soil particles, often referred to as colloids because of their small size. The mineralogy will determine the base fertility of the soils. Clay minerals derive from the type of rocks that form the parent material for the soil. Different types of minerals will have different characteristics based on the chemical composition of the minerals. These differences can have a big impact on the nature of the soil that is formed. As the rocks weather and are transformed into soil particles, the individual particles will have different levels of internal charge based on the parent rocks. Because of their high surface area, clays will be much more reactive than sands or silts. Clays with high internal charge will have a high cation exchange capacity (CEC). The cation exchange capacity or CEC is the term used to describe the ability of a soil to bind nutrients. Soils with higher CEC can hold onto nutrients more effectively and so are considered to be inherently more fertile than soils with a low CEC. Units for CEC are meq/ 100 g of soil or milli equivalents of charge per volume of soil. Sands and silts have low CEC (2 meq per 100g) with the CEC of clays ranging from 10 meq per 100 g in weathered clays to 25-100 meq per 100 g in active clays.

Soil texture

In addition to the mineral fraction, soils consist of organic matter and pore space. A healthy soil will consist of about 45% mineral, 5% organic and 50% pore space (Brady and Weil, 2002). Having sufficient pore space will allow for rapid water infiltration and diffusion of oxygen, both critical for plant growth. The mineral fraction of a soil typically weighs 2.65 g per cm^3. Organic matter is much lighter, with a density ranging from 0.3-0.5 per cm^3. An ideal density for soil, referred to as bulk density (BD) is anywhere from 0.8-1.2 g per cm^3.

Soil organic matter (SOM)

Having sufficient organic matter in a soil is critical for soil quality. Soil organic matter enhances several soil properties. Organic matter tends to have a high CEC (ranging from 250-400 meq/100g). In addition, soil organic matter contains all of the nutrients required for plant growth. When organic matter is mineralized (returned to the atmosphere as CO_2) by soil microorganisms, a portion of the nutrients are released into soil solution where they become available for plant uptake. This is why organic matter is typically considered as a slow release fertilizer. Organic matter can also serve to improve soil aggregation. Soil aggregates are stable composites of smaller particles. Typically these particles form aggregates that are held together by SOM. A well- aggregated soil has low bulk density and improved tilth. A well aggregated soil will also allow for rapid water infiltration. Organic matter, having a high water holding capacity, will also increase a soil's ability to stay moist after a rain or irrigation event.

Soil salinity

Soil solution typically contains a range of different ions that are suspended in the solution. Diffusion of soil water to plant roots also brings these ions to the root surface. This is a key process for providing plants with the nutrients that they require. In arid areas the concentrations of these ions in soil solution can increase to the point where the water becomes too salty and can actually be a detriment to plant growth. The soil salinity is measured as the ability of the soil to conduct an electrical charge (electrical conductivity or EC) and reported in units of charge- deciSiemens per meter or dS/m. Typical ions in soil solution include calcium, magnesium, potassium and sodium. All of these with the exception of sodium are necessary for plant growth. If soils become too salty, particularly in cases where sodium concentrations are high, water within the plant can be drawn out into soil solution in an attempt to reduce the salinity in proximity to the roots. Plants in salty soils can suffer from a lack of accessible water even in cases where soils are saturated. In areas where there is sufficient precipitation, rains will flush excess salts out of the root zone and so salinity is typically not a concern. In certain cases, use of reclaimed waters or composts can add salinity to the soil. If the area is wet enough, these added salts will quickly be removed. In container growing systems or in arid areas, the salinity of the growing medium should be considered. High salt soils can typically be remediated by excess irrigation with low salt water, addition of calcium to decrease the percent saturation with sodium, or addition of organic matter (Brady and Weil, 2003).

8. Appendix C – Composters Survey Instrument

SURVEY OF OREGON COMPOSTERS

Facility Name: ______________________________________ **Date:** ____________________

Contact: ____ **Phone:** ____________________

☐ **Food Scraps?** ☐ **STA?**

A. FEEDSTOCKS

1. What types of feedstock does this facility accept?

2. Is feedstock volume constant or is it seasonal

Green material				
☐	**Residential**	________tons/year,	☐ **Constant**	☐ **Seasonal**
☐	**Commercial**	________tons/year,	☐ **Constant**	☐ **Seasonal**
☐	**Wood waste**	________tons/year,	☐ **Constant**	☐ **Seasonal**
☐	**Construction & Demo. Wood**	________tons/year,	☐ **Constant**	☐ **Seasonal**
☐	**Manure**	________tons/year,	☐ **Constant**	☐ **Seasonal**
Agricultural residue				
☐	**Grape pomace**	________tons/year,	☐ **Constant**	☐ **Seasonal**
☐	**Cannery waste**	________tons/year,	☐ **Constant**	☐ **Seasonal**
☐	**Other:** ________________	________tons/year,	☐ **Constant**	☐ **Seasonal**
Food scraps				
☐	**Residential**	________tons/year,	☐ **Constant**	☐ **Seasonal**
☐	**Commercial**	________tons/year,	☐ **Constant**	☐ **Seasonal**
☐	**Institutional**	________tons/year,	☐ **Constant**	☐ **Seasonal**
☐	**Liquid waste**	________tons/year,	☐ **Constant**	☐ **Seasonal**
☐	**Biosolids**	________tons/year,	☐ **Constant**	☐ **Seasonal**
☐	**Other:** ________________	________tons/year,	☐ **Constant**	☐ **Seasonal**

Comments:

4. What is the incoming processing capacity of this facility?

○ 0 – 50 tpd ○ 50 – 100 tpd ○ 100 – 200 tpd
○ 200 – 300 tpd ○ 300 – 400 tpd ○ 400 – 500 tpd ○ +500 tpd

5. The facility processes about ____________________ tons per year.

6. The site is approximately________ acres.

B. QUANTITY OF ORGANIC PRODUCTS SOLD

1. What general types of products does this facility produce by volume?

☐ Compost _____ cu. yds per yr. Average bulk density ______ yds/ton
☐ Mulch _____ cu. yds per yr. Average bulk density ______ yds/ton
☐ Boiler fuel _____ cu. yds per yr. Average bulk density ______ yds/ton
☐ Beneficial reuse at landfills _____ cu. yds per yr. Average bulk density ______ yds/ton
☐ Other: ________________ _____ cu. yds per yr. Average bulk density ______ yds/ton

2. How many different products does this facility produce?

○ 1 – 5 ○ 5 – 10 ○ 10 – 15 ○ 16 or more

3. What percentage of your production is sold into these market segments and how has this changed in the past 12 months?

☐ Agriculture _____% ☟ Increased or ☟ decreased by _______%
☐ Landscape _____% ☟ Increased or ☟ decreased by _______%
☐ Nursery ____% ☟ Increased or ☟ decreased by _______%
☐ ODOT ____% ☟ Increased or ☟ decreased by _______%
☐ Boiler Fuel ____% ☟ Increased or ☟ decreased by _______%
☐ Municipal projects ____% ☟ Increased or ☟ decreased by _______%
☐ Beneficial reuse at landfills ____% ☟ Increased or ☟ decreased by _______%
☐ Other: _____________ _____% ☟ Increased or ☟ decreased by _______%

4A. Of the products made, what percentage is sold wholesale, retail, or given away?
(Should add up to 100%)

A. <u>WHOLESALE</u>
☐ Agriculture ___%
☐ Landscapers ___%
☐ Nurseries ___%
☐ Boiler fuel ___%
☐ ODOT ___%
☐ ADC ___%
☐ Beneficial reuse at landfills ___%
☐ Bagging plant ___%
☐ Other ______________________ ___%

B. <u>RETAIL</u>
☐ Directly to consumers __%

C. <u>GIVE AWAY</u>
☐ Contractual to City ___%
☐ On-site give away ___%
☐ Used in-house ___%

4B. If you are selling compost into agriculture, what are the major crop types you sell to? (For example, table grapes, citrus, etc.) Please list.

5. **What additional services (e.g., bagging, spreading, delivery, etc.) Do you provide at the point of sale?**

☐ Blending
☐ Delivery
☐ Bagging
☐ Spreading
☐ Testing/Analysis
☐ Certified Organic Registration
☐ USCC STA participation
☐ Product Knowledge
☐ Other

6. **I see that you are a member of the USCC's STA program. Would you be able to send us your most recent Compost Technical Data Sheet?**

☐ Yes, Will send

☐ No.
Reason given:______________________

7. **Where do you see the market for compost (or digestate) going in the future, especially compost made with food scraps?**

☐ Stay the same
☐ More to ODOT uses
☐ More to AG
☐ More to Landscaping/Horticulture