# Environmental Value of Applying Compost:

## Improving Soil Health for Stormwater Management, Contaminated Site Remediation, Ecosystem Restoration, Landscaping and Agriculture

U.S. Environmental Protection Agency
Office of Research and Development
January 2025
EPA/600/X-25/015

# Disclaimer

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Any mention of trade names, manufacturers or products does not imply an endorsement by the United States Government or the U.S. Environmental Protection Agency. EPA and its employees do not endorse any commercial products, services, or enterprises.

# Reviewers

EPA would like to thank the following people for their independent peer review of the report:

Sally Brown, Ph.D., University of Washington
Nora Goldstein, BioCycle
Richard Stehouwer, Ph.D., Pennsylvania State University

# Acknowledgments

This report was prepared with support from TetraTech, Inc., under U.S. EPA Contract No. 68HERC22D0026. The graphic on page 17 was prepared by Ocupop and Eastern Research Group Inc. under U.S. EPA Contract No. 68HERC21D0003. This research was supported in part by an appointment to the U.S. EPA Research Participation Program administered by the Oak Ridge Institute for Science and Education (ORISE) through an interagency agreement between the U.S. Department of Energy (DOE) and the U.S. EPA. ORISE is managed by Oak Ridge Associated Universities under DOE contract number DE-SC0014664. The external peer review of the report was coordinated by Eastern Research Group Inc. under U.S. EPA Contract No. 68HERH23A0019. The cover photo of compost-amended bioretention swales allong a residential street is courtesy of Seattle Public Utilities.

EPA would like to thank the following people for their contributions to the report: Rory Coffey, Patrick Lizon, Greg Currey, Rachel Buzzeo, Regina Scheibner and Amanda Cano (Tetra Tech) and Juliana Beecher (ORISE).

# Table of Contents

# List of Figures

# List of Tables

# Abbreviations and Acronyms

| | |
|---|---|
| °C | degrees Celsius |
| °F | degrees Fahrenheit |
| $ac^{-1}$ $yr^{-1}$ | acres per year |
| ASP | Aerated Static Pile |
| B | boron |
| BMP | best management practice |
| C | carbon |
| C:N | carbon-to-nitrogen ratio |
| Ca | calcium |
| Cd | cadmium |
| CEC | cation exchange capacity |
| $CH_4$ | methane |
| Cl | chloride |
| $CO_2$ | carbon dioxide |
| Cr | chromium |
| Cu | copper |
| DOT | Department of Transportation |
| DRP | dissolved reactive phosphorus |
| EPA | Environmental Protection Agency |
| EREF | Environmental Research and Education Foundation |
| FAO | Food and Agriculture Organization of the United Nations |
| Fe | iron |
| GHG | greenhouse gas |
| GI | green infrastructure |
| in | inch |
| K | potassium |
| lbs | pounds |
| LEED | Leadership in Energy and Environmental Design |
| LEED-NC | Leadership in Energy and Environmental Design-New Construction |
| Mg | magnesium |
| mmhos/cm | millimhos per centimeter |
| Mn | manganese |
| MSW | municipal solid waste |
| N | nitrogen |
| $N_2$ | nitrogen gas |
| $N_2O$ | nitrous oxide |
| $NH_3$ | ammonia |
| Ni | nickel |
| $NO_3$ | nitrate |
| NRCS | Natural Resources Conservation Service |
| $O_2$ | oxygen |
| OFMSW | organic fraction of municipal solid waste |
| ORD | Office of Research and Development |
| PAHs | polycyclic aromatic hydrocarbons |
| Pb | lead |
| PCBs | polychlorinated biphenyls |
| PENVEST | Pennsylvania Infrastructure Investment Authority |
| PFAS | per- and polyfluoroalkyl substances |

| | |
|---|---|
| PRFP | Processed to Further Reduce Pathogen |
| SB | State Bill |
| SCC | social cost of carbon |
| SOC | soil organic carbon |
| SOM | soil organic matter |
| S | sulfur |
| t | tons |
| TMDL | total maximum daily load |
| TN | total nitrogen |
| USD | United States dollars |
| USDA | United States Department of Agriculture |
| wt | weight |
| Zn | zinc |

# Executive Summary

This report summarizes the state of the science about the environmental value of compost use in various sectors, including green infrastructure and stormwater management, ecosystem conservation and restoration, contaminated site remediation, horticulture and landscaping, and agriculture. The report examines the potential benefits of increasing the use of compost at scales that better align with the volume of organic materials (e.g., food waste) available for composting. The challenges associated with compost use are also discussed to provide context, when relevant, about possible adverse impacts. In addition, the report identifies research needs that would improve understanding of the advantages and disadvantages of compost use and better inform key stakeholders. The intended audiences for this report are policymakers and current and potential users of compost in the public sector (e.g., local and state government agencies) and the private sector (e.g., commercial businesses).

Despite differences among scientific studies (e.g., locations, variability in compost treatments, magnitude of benefits observed), the overarching consensus in the scientific literature is that the use of compost improves soil health. Soil health is the basis for cascading benefits to the environment and various sectors of the economy. Table ES-I provides a summary of high-level findings related to soil health improvements that have been observed with compost application.

*Table ES-I. Summary of Compost Benefits for Soil Health.*

| Soil characteristic | Benefit |
|---|---|
| Physical | • Soil density/compaction reductions up to 35%. (1,2)<br>• Water infiltration rate increases up to 183%. (3)<br>• Soil water-holding capacity increases of 35% to 57%. (4,5)<br>• Reductions in soil erosion of up to 97%. (6) |
| Chemistry | • Soil organic carbon increases of up to 200%. (5)<br>• Provides nitrogen (N), phosphorus (P), potassium (K) and various other plant nutrients (potential for ≥ 50% reduction in inorganic fertilizer for annual crops). (7-10)<br>• Maintains favorable soil acidity (i.e., pH), which improves the availability of nutrients for plant uptake. (11)<br>• Facilitates immobilization and degradation of soil contaminants (e.g., heavy metals, petroleum products) that can harm water quality, plants, animals and human health. (12,13) |
| Biology | • Increases diversity and abundance of soil organisms, in particular, beneficial microorganisms (e.g., bacteria, fungi) that improve soil fertility and suppress plant disease, up to 2 times more soil microbial activity has been observed. (5, 14-16) |

The extent of the improvements that are realized depends on the characteristics of the soil where compost is applied. For example, compost will improve the water-holding capacity of sandy soils more than clay soils (5, 17, 18), and disturbed or eroded soils will see a bigger boost in organic matter from compost than soils with perennial vegetation (19, 20). Ultimately, the benefits that occur depend on the type of compost, the application rate and timing, and factors such as soil type, site characteristics and project goals (11, 19, 21-23).

Compost use has numerous advantages for a variety of sectors, and scientific research demonstrates that compost use can replace conventional materials and practices (e.g., inorganic fertilizer, grey stormwater management practices) that are typically utilized (24-27). Table ES-II highlights the key benefits of compost use for the five sectors examined in this report: agriculture, horticulture and landscaping, green infrastructure and stormwater management, ecosystem conservation and restoration (e.g., wetlands creation, wildfire rehabilitation), and contaminated site remediation. The benefits provided by compost are related to improved soil health (Table ES-I), which yields co-benefits for surface water and groundwater, vegetation and whole ecosystems. The enhancements are relevant and valuable across different sectors. For example, compost enhances the ability of soil to absorb and retain water, which in turn helps farmers by reducing the need for irrigation, helps public works departments by reducing stormwater runoff into sewer systems, and helps communities cope with extreme drought or flood conditions.

*Table ES-II. Summary of Key Compost Use Benefits by Sector.*

| Benefit | Sector | | | | |
|---|---|---|---|---|---|
| | Agriculture | Horticulture & landscaping | Green infrastructure & stormwater management | Ecosystem conservation & restoration | Contaminated site remediation |
| Decreased stormwater runoff | ✓ | ✓ | ✓ | ✓ | ✓ |
| Decreased soil erosion | ✓ | ✓ | ✓ | ✓ | ✓ |
| Reduced surface water & groundwater pollution | ✓ | ✓ | ✓ | ✓ | ✓ |
| Decreased irrigation requirements | ✓ | ✓ | | | |
| Reduced contamination of crops by human pathogens | ✓ | ✓ | | | |
| Improved plant establishment & growth | ✓ | ✓ | ✓ | ✓ | ✓ |
| Improved crop yield & crop quality | ✓ | ✓ | | | |
| Increased carbon sequestration | ✓ | ✓ | ✓ | ✓ | ✓ |
| Soil fertilization | ✓ | ✓ | ✓ | ✓ | ✓ |
| Immobilization/degradation of soil contaminants | ✓ | ✓ | ✓ | | ✓ |
| Plant disease suppression | ✓ | ✓ | | | |
| Weed suppression | ✓ | ✓ | | | |

By supporting soil health and plant growth, compost benefits water resources and improves climate resilience (18, 22, 28-30) (Figure I). Compost protects water resources when used as media in stormwater (e.g., berms, filter socks, blankets) and green infrastructure practices (e.g., bioretention basins, rain gardens) (24, 31, 32). Compost-based practices help reduce stormwater runoff volumes and protect water quality by preventing contaminants (e.g., nutrients from fertilizers, sediment, pathogens, heavy metals, synthetic chemicals) from entering surface and groundwaters (32-34). Compost reduces soil erosion by providing essential soil nutrients and organic matter to improve vegetation cover and decrease the amount of bare soil exposed to rain and runoff. Compost can hold up to five times its weight in water, helping to increase water infiltration into soils, water retention in soils and groundwater recharge (29, 31, 35).

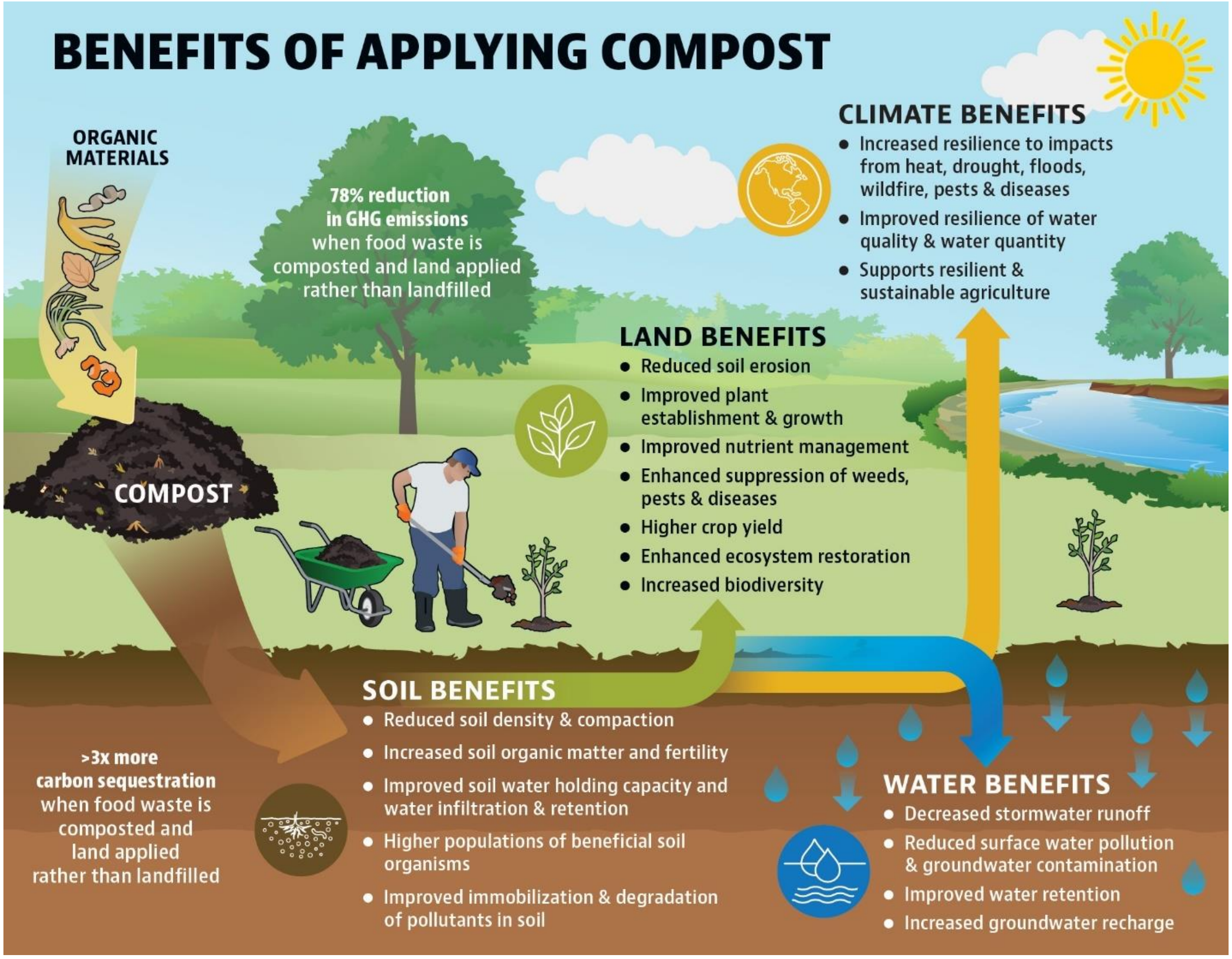


*Figure ES-I. Soil health benefits from compost application, and associated water, land and climate benefits. Source for carbon sequestration increases and GHG emissions reductions: (36)*

These benefits also provide resiliency to climate-driven changes in the water cycle and extreme weather events (22). In the face of increasing air temperatures and changing precipitation patterns, compost use has emerged as a versatile solution that can offset some of the impacts of extreme weather events (22). It is considered an effective and scalable way to contribute to reducing carbon emissions and increasing climate resilience across communities. Compost use has three key climate-related benefits. First, greenhouse gas emissions (carbon dioxide, methane and nitrous oxide) are avoided by composting rather than landfilling organic materials (36), applying composted rather than raw animal manure to fields (37), and substituting compost for conventional materials in various management practices (e.g., substitution for inorganic fertilizers) (37, 38). Second, compost use contributes to soil carbon sequestration; in particular, it results in greater carbon sequestration than landfilling organic materials (36, 39). Finally, compost use can increase the resiliency of rural and urban communities to droughts, by enhancing soil structure, soil water retention and growth of plant roots (17, 41, 42); floods, by increasing water infiltration into soils and reducing runoff (29, 41); wildfire, by reducing surface runoff, soil erosion and pollutant transport (43-45); and urban heat island effects, by improving soil moisture levels and enhancing the growth of trees and other plants that provide shade and evaporative cooling (35, 46).

There are, however, challenges and risks associated with compost use that vary with the feedstock blends used to manufacture compost and how the finished compost is used (e.g., use for large-scale production of edible crops vs. replacement of peat in potting mixes for ornamental plants vs. a compost filter sock used to filter pollutants from stormwater). For example, compost feedstocks may contain undesirable contaminants such as plastic, glass and/or harmful chemicals such as per- and polyfluoroalkyl substances (PFAS) (47), which could be introduced to a site through compost use. Research is active and needed on the transformation and fate of microplastics and PFAS in compost, and a risk assessment for PFAS in soil-like media is yet to be developed. Additionally, research indicates that for some applications, such as stormwater control, it is important to consider levels of nutrients in compost and potential leaching to surface or groundwater (48-50).

The vast quantities of compostable materials (e.g., food waste, yard trimmings, biosolids and animal manure) generated in the U.S. offer significant potential to scale up compost production, compost use and its associated environmental benefits. In the United States, food waste, yard trimmings and wood comprise approximately 40% of landfilled municipal solid waste (MSW) and 38% of the MSW that is incinerated (51). Only 5% of food waste is currently composted (51, 52). Nearly half of the biosolids generated in the United States are landfilled or incinerated (53). Additionally, roughly 2 trillion pounds of compostable livestock manure is generated in U.S. agriculture each year, most of which is applied to agricultural fields in a raw form (54, 55). Although composting manure before application results in similar benefits for crop production, compost provides additional advantages such as decreased risks of nutrient pollution, reduced risks of food crop contamination by human pathogens, and improved suppression of crop disease (17, 19, 56-58).

While the environmental value of compost use has received attention for decades, there is a lack of comprehensive economic evaluations examining changes in net costs and profitability associated with compost use (14). The cost of compost use depends upon multiple factors, such as the type of feedstocks used to make compost, where the compost is used, how it is used, the target benefits and the time span over which benefits are being considered (59, 60). Furthermore, the net change in costs associated with compost use depends on the specific conventional materials (e.g., compost vs. inorganic fertilizer, peat, or plastic mulch) and practices (e.g., seeded compost blankets vs. topsoil placement and hydroseeding for erosion control) that compost is being used to augment or replace (31, 45, 61-63).

Compost production and use currently tend to be localized, largely due to the costs associated with transporting bulky materials with relatively low per-unit monetary value. The measurable benefits also tend to be localized; however, the cumulative effects of compost use across multiple projects and sectors can generate benefits that support regional or national sustainability goals (e.g., carbon neutrality, food sustainability, nutrient circularity, water quality protection) (64-67).

Further research is needed to improve understanding and inform efforts to expand compost use over broader scales. These research needs include:

- Long-term studies to fully understand the effects of compost use over time; most studies in the current scientific literature are short term (< 10 years).
- New research that explores combining both organic and inorganic nutrient sources or other amendments (for example, biochar) to meet crop or plant nutrient demands could help to improve knowledge about optimized compost use.
- More research about acceptable levels of contamination for various purposes (e.g., revegetation of a mine site versus agriculture to produce food) and strategies, methods and technologies to reduce contaminant levels (e.g., soluble salts, PFAS, plastics) in feedstocks and final compost.
- Further economic analysis of compost for different end uses to help distinguish scenarios in which compost use reduces net costs and/or increases net profitability versus circumstances where it is not economical.
- Research on the potential net environmental benefits that might occur if compost is more widely used over broader scales (e.g., regional, national).

# Executive Summary References


1. Mohammadshirazi F, Brown VK, Heitman JL, McLaughlin RA. Effects of tillage and compost amendment on infiltration in compacted soils. Journal of Soil and Water Conservation. 2016;71(6):443-9.
2. Mohammadshirazi F, McLaughlin RA, Heitman JL, Brown VK. A multi-year study of tillage and amendment effects on compacted soils. Journal of Environmental Management. 2017;203:533-41.
3. Cogger C, R. Hummel, J. Hart, and A. Bary. Soil and Redosier Dogwood response to incorporated and surface- applied compost. Hort Sei. 2008;43:2143-50.
4. Ozores-Hampton M. Impact of compost on soil health. Compost Utilization in Production of Horticultural Crops: CRC Press; 2021c. p. 9-26.
5. Brown S, Cotton M. Changes in Soil Properties and Carbon Content Following Compost Application: Results of On-farm Sampling. Compost Science and Utilization. 2011;19(2):87-96.
6. Owen D, Davis AP, Aydilek AH. Understanding the Effects of Slope Ratio, Straw Mulching, and Compost Addition to Topsoil to Establish Permanent Vegetation and Reduce Nutrient Runoff. 2020.
7. Maynard AA, Hill DE. Cumulative Effect of Leaf Compost on Yield And Size Distribution in Onions. Compost Science & Utilization. 2000c;8(1):12-8.
8. Alexander R. Compost Use Applications- A Return on Investment (ROI): Edible Gardens. In: Foundation CRE, editor.: Compost Research & Education Foundation; 2020c.
9. Alexander R. Compost Use Applications- A Return on Investment (ROI): Row Crop Production. In: Foundation CRE, editor.: Compost Research & Education Foundation; 2020i.
10. McCray JM, Ji S, Ulloa M. Influence of compost/sludge application on sugarcane yield and nitrogen requirement on a sand soil. Journal of Plant Nutrition. 2017;40(15):2156-67.
11. Stehouwer R, Cooperband L, Rynk R, Biala J, Bonhotal J, Antler S, et al. Chapter 15 - Compost characteristics and quality. In: Rynk R, editor. The Composting Handbook: Academic Press; 2022. p. 737-75.
12. Brown SL, Chaney RL. Use of Amendments to Restore Ecosystem Function to Metal Mining-Impacted Sites: Tools to Evaluate Efficacy. Current Pollution Reports. 2016;2(2):91-102.
13. Vouillamoz J, Milke M. Effect of compost in phytoremediation of diesel-contaminated soils. Water Science and Technology. 2001;43(2):291-5.
14. Adeleke KA, Atoloye IA, Creech JE, Dai X, Reeve JR. Nutritive and non-nutritive effects of compost on organic dryland wheat in Utah. Agronomy Journal. 2021;113(4):3518-31.
15. Reeve JR, Endelman JB, Miller BE, Hole DJ. Residual effects of compost on soil quality and dryland wheat yield sixteen years after compost application. Soil Science Society of America Journal. 2012;76(1):278-85.
16. Grobe K. Fine-tuning the soil food web. BioCycle. 1998:42-6.
17. Rynk R, Cooperband L, Oshins C, Wescott H, Bonhotal J, Schwarz M, et al. Chapter 1 - Why compost? In: Rynk R, editor. The Composting Handbook: Academic Press; 2022a. p. 1-26.
18. Hill D. Compost utilization in turfgrass and lawn management. Compost Utilization in Production of Horticultural Crops: CRC Press; 2021. p. 85-100.
19. Ozores-Hampton M, Biala J, Evanylo G, Faucette B, Cooperband L, Roe N, et al. Chapter 16 - Compost use. In: Rynk R, editor. The Composting Handbook: Academic Press; 2022. p. 777-846.
20. Brown S, Beecher N. Carbon Accounting for Compost Use in Urban Areas. Compost Science and Utilization. 2019;27(4):227-39.
21. Hurley S, Shrestha P, Cording A. Nutrient Leaching from Compost: Implications for Bioretention and Other Green Stormwater Infrastructure. Journal of Sustainable Water in the Built Environment. 2017;3(3):04017006.
22. Winfield E. Climate-Smart Agriculture: Compost Amendments. 2020.
23. Archuletta R, Faucette B. Compost blankets for runoff and erosion control 2014.
24. Faucette B, Cardoso F, Mulbry W, Millner P. Performance of compost filtration practice for green infrastructure stormwater applications. Water Environment Research. 2013;85(9):806-14.
25. Brown S, Faucette B, Kurtz K. The Compost & Climate Connection: Compost Research and Education Foundation; 2017.
26. Evanylo GK, Porta SN, Li J, Shan D, Goatley JM, Maguire R. Compost practices for improving soil properties and turfgrass establishment and quality on a disturbed urban soil. Compost Science & Utilization. 2016;24(2):136-45.
27. Sullivan D, Bary A, Nartea T, Myrhe E, Cogger C, Fransen S. Nitrogen availability seven years after a high-rate food waste compost application. Compost science & utilization. 2003;11(3):265-75.
28. Gould CM. Compost increases water holding capacity of droughty soils. Michigan State University Extension. 2015.
29. Magdoff F, Van Es H. Building Soils for Better Crops Ecological Management for Healthy Soils. 10 ed: Sustainable Agriculture Research and Education; 2021.
30. IPCC. IPCC Sixth Assessment Report: Impacts, Adaptation and Vulnerability. 2022.
31. Faucette B. Compost in the green infrastructure tool box. Biocycle. 2012a;53(10):33-6.
32. Faucette B, Cardoso-Gendreau FA, Codling E, Sadeghi AM, Pachepsky YA, Shelton DR. Storm Water Pollutant Removal Performance of Compost Filter Socks. J Environ Qual. 2009d;38:1233-9.
33. Alferez F. Compost utilization in fruit production. Compost Utilization in Production of Horticultural Crops. 2021:51-8.
34. Pitt R, Lantrip J, Harrison R, Henry CL, Xue D, O'Connor T. Infiltration through disturbed urban soils and compost-amended soil effects on runoff quality and quantity: National Risk Management Research Laboratory Duluth, GA, USA; 1999.
35. Faucette B. Using Compost BMPs for LEED Green Building Credits. Land and Water. 2009b:41.
36. Brown S. Greenhouse gas accounting for landfill diversion of food scraps and yard waste. Compost Science & Utilization. 2016;24(1):11-9.
37. Nicholson F, Bhogal A, Cardenas L, Chadwick D, Misselbrook T, Rollett A, et al. Nitrogen losses to the environment following food-based digestate and compost applications to agricultural land. Environmental Pollution. 2017;228:504-16.
38. Levis JW, Barlaz MA. What is the most environmentally beneficial way to treat commercial food waste? Environmental Science and Technology. 2011;45(17):7438-44.
39. Brown S, Kruger C, Subler S. Greenhouse Gas Balance for Composting Operations. Journal of Environmental Quality. 2008;37(4):1396-410.

40. Francou C, Poitrenaud M, Houot S. Stabilization of organic matter during composting: Influence of process and feedstocks. Compost science & utilization. 2005;13(1):72-83.
41. Basche A. Turning Soils into Sponges. How Farmers Can Fight Floods and Droughts. Union of Concerned Scientists (UCS); 2017.
42. Kranz CN, McLaughlin RA, Johnson A, Miller G, Heitman JL. The effects of compost incorporation on soil physical properties in urban soils – A concise review. Journal of Environmental Management. 2020;261.
43. McFarland MJ, R B Brobst, G Kester. Restoring fire ravaged land in California with biosolids. water. 2009:39-40.
44. Meyer VF, Redente EF, Barbarick R, Brobst R. Biosolids (compost) Application Affect Runoff Water Quality Following Forest Fire. Journal of Environmental Quality. Journal of Environmental Quality. 2001;30:1528-32.
45. Crohn DM, Chaganti VN, Reddy N. Composts as post-fire erosion control treatments and their effect on runoff water quality. Transactions of the ASABE. 2013;56(2):423-35.
46. Chapman EJ, Small GE, Shrestha P. Investigating potential hydrological ecosystem services in urban gardens through soil amendment experiments and hydrologic models. Urban Ecosystems. 2022;25(3):867-78.
47. Rynk R, Schwarz M, Richard TL, Cotton M, Halbach T, Siebert S. Chapter 4 - Compost feedstocks. In: Rynk R, editor. The Composting Handbook: Academic Press; 2022b. p. 103-57.
48. Heyman H, Bassuk N, Bonhotal J, Walter T. Compost quality recommendations for remediating urban soils. International Journal of Environmental Research and Public Health. 2019;16(17).
49. Davis AP, Aydilek A, Felton GK, Forgione ER. Achieving Highway Runoff Volume and Pollutant Reduction Using Vegetated Compost Blankets: A Guide. National Cooperative Highway Research Program; 2023. Report No.: NCHRP Research Report 1040.
50. Faucette LB, Jordan CF, Risse LM, Cabrera M, Coleman DC, West LT. Evaluation of stormwater from compost and conventional erosion control practices in construction activities. Journal of Soil and Water Conservation. 2005;60(6):288.
51. EPA. Advancing Sustainable Materials Management: 2018 Fact Sheet. Assessing Trends in Materials Generation and Management in the United States. 2020c.
52. EPA. Advancing Sustainable Materials Management: 2018 Tables and Figures Assessing Trends in Materials Generation and Management in the United States. 2020b.
53. NEBRA. National Biosolids Data Project: North East Biosolids & Residuals Association; 2024 [Available from: https://www.biosolidsdata.org/.
54. Zhang H, Schroder J. Animal Manure Production and Utilization in the US. Applied Manure and Nutrient Chemistry for Sustainable Agriculture and Environment. 2014:1-21.
55. Ribaudo MO, Gollehon NR, Agapoff J. Land application of manure by animal feeding operations: Is more land needed? Journal of Soil and Water COnservation. 2003;58(1).
56. Brown S, Goldstein N. The Role of Organic Residuals in Urban Agriculture. In: Brown S, McIvor K, Hodges Snyder E, editors. Sowing Seeds in the City: Ecosystem and Municipal Services. Dordrecht: Springer Netherlands; 2016. p. 93-106.
57. Neher DA, Hoitink HA, Biala J, Rynk R, Black G. Chapter 17 - Compost use for plant disease suppression. In: Rynk R, editor. The Composting Handbook: Academic Press; 2022. p. 847-78.
58. Coker CS. Compost utilization in ornamental and nursery crop production. Compost Utilization in Production of Horticultural Crops: CRC Press; 2021. p. 77-84.
59. Tyler RW. Compost utilization and the economic impact in crop production. In: Ozores-Hampton M, editor. Compost Utilization in Production of Horticultural Crops: CRC Press; 2021. p. 135-56.
60. Endelman JB, Reeve JR, Hole DJ. Economically optimal compost rates for organic crop production. Agronomy Journal. 2010;102(4):1283-9.
61. Julian JW, Strik BC, Larco HO, Bryla DR, Sullivan DM. Costs of establishing organic northern highbush blueberry: Impacts of planting method, fertilization, and mulch type. HortScience. 2012;47(7):866-73.
62. Brown S, Mahoney M, Sprenger M. A comparison of the efficacy and ecosystem impact of residual-based and topsoil-based amendments for restoring historic mine tailings in the Tri-State mining district. Science of the Total Environment. 2014;485:624-32.
63. Faucette B. Economic case for green infrastructure. BioCycle. 2012b;53(8):36-9.
64. Brown S, Miltner E, Cogger C. Carbon sequestration potential in urban soils. Carbon sequestration in urban ecosystems. 2012b:173-96.
65. Bell B, Platt B. Building Healthy Soils with Compost to Protect Watersheds. Institute for Local Self-Reliance; 2014.
66. WORC. Soils for Salmon: Building Soil: Washington Organic Recycling Council; 2023 [Available from: https://www.soilsforsalmon.org/.
67. Harrison BP, Chopra E, Ryals R, Campbell JE. Quantifying the Farmland Application of Compost to Help Meet California's Organic Waste Diversion Law. Environmental Science and Technology. 2020;54(7):4545-53.

# 1. Introduction

## 1.1 Purpose

This Environmental Protection Agency (EPA) Office of Research and Development (ORD) report summarizes the state of the science about the environmental value of compost use in a variety of sectors, including agriculture, horticulture and landscaping, green infrastructure and stormwater management, ecosystem conservation and restoration, and contaminated site remediation. Potential challenges with compost use and areas where further research is needed are also identified. The intended audiences for the findings of the report are policymakers and the current and potential users of compost in both the public (e.g., local and state government agencies) and private (e.g., commercial businesses) sectors.

## 1.2 Need

While compost is commonly used in the agriculture, horticulture and landscaping sectors as a soil amendment to improve soil health, its utility extends to other sectors such as stormwater management and green infrastructure, restoration of disturbed lands (where soils have been depleted of organic matter, have had their structure destroyed and/or have been compacted, including those affected by wildfires), and remediation of contaminated lands (e.g., urban brownfields). EPA seeks to understand the value of compost use in these additional sectors and the potential benefits of increasing the use of compost at scales that better align with the volume of organic materials (e.g., food waste) available for composting.

The vast quantities of compostable materials (e.g., food waste, yard trimmings and animal manure) generated in the U.S. offer significant potential to scale up compost production, compost use and its associated environmental benefits. EPA's National Recycling Goal calls for an increase in the recycling rate to 50% across the United States by 2030, including the recycling of organic waste through composting. In the United States, compostable food waste, yard trimmings and wood comprise approximately 40% of landfilled municipal solid waste (MSW) and 38% of the MSW that is incinerated (EPA, 2020a). Additionally, nearly half of biosolids generated annually in the U.S. are landfilled or incinerated (NEBRA, 2024). Food waste is a particularly underutilized resource, with roughly 5% currently being composted (EPA, 2023a).

## 1.3 Scope

The primary focus of this report is on the use of compost; however, some discussion of the composting process is included to provide background information and, where necessary, to describe the performance and benefits of compost use. More information on composting methods and the environmental impacts of the composting process can be found in EPA's 2023 report From Field to Bin: The Environmental Impacts of U.S. Food Waste Pathways. Additionally, this report focuses on compost produced through conventional thermophilic composting methods. Thermophilic composting methods rely upon the decomposition of organic materials at internal temperatures above 105 degrees Fahrenheit (°F) (NRCS, 2010). The report discusses characteristics of the most commonly composted organic materials (such as food waste and biosolids) but does not address the multitude of organic materials that potentially can be used (such as animal carcasses, aquatic weeds, mollusk shells, paper mill sludge, organic textiles and leather).

It should be noted that although the benefits of compost use are the focus of this report, the challenges associated with compost use are also discussed to provide context, where relevant, about potential adverse impacts. For example, the potential for nutrient leaching from compost is discussed as it relates to soil chemistry (Section 2.2), agricultural use (Section 5.1) and green infrastructure (Section 7.1). Possible risks due to physical and chemical contaminants in compost are also briefly outlined (e.g., potential for per- and polyfluoroalkyl substances [PFAS] in compost feedstock in Chapter 10). More information on potential compost contaminants can be found in EPA's 2021 reports on Plastic Contamination and Persistent Chemical Contaminants as emerging issues in food waste management (EPA, 2021b; EPA, 2021c).

## 1.4 Background on Compost Manufacturing

Compost is a biologically stable soil amendment produced by the aerobic (with oxygen [$O_2$]) decomposition of organic (C-based) materials by microorganisms. A wide variety of materials can be composted, the most common of which include food waste, yard trimmings, biosolids, manure, agricultural residues (e.g., hay and straw), and wood. These materials are referred to as compost feedstocks. Compost is typically manufactured from locally abundant feedstocks. For example, compost produced in agricultural areas predominantly uses crop residues and animal manure/bedding, whereas compost manufactured in urban areas is more likely to use food waste, yard trimmings and biosolids (Kelley et al., 2020). The conventional composting method relies on the biological processes of microorganisms, including bacteria, fungi and actinomycetes to decompose organic materials under continuous aerobic conditions (NRCS, 2010). A continuous aerobic environment, adequate moisture and an appropriate carbon-to-nitrogen ratio (C:N) must be maintained during compost production (Governo et al., 2003). The compost feedstock recipe and composting conditions can be adjusted to manage the composting process and influence the characteristics (e.g., particle size, nutrient levels, pH) of the finished compost (Rynk, Schwarz, et al., 2022).

The collective metabolic activity of microorganisms in a composting pile generates heat, which drives a rapid increase in temperatures from what is known as a mesophilic stage (moderate temperatures between approximately 50 °F and 105 °F) to a period known as the thermophilic stage (temperatures that exceed roughly 105 °F) (NRCS, 2010). This is why conventional composting is also known as thermophilic composting. During the thermophilic stage, temperatures typically peak between 130 °F and 160 °F (NRCS, 2010).

Thermophilic composting can destroy undesirable organisms (such as pathogens and weed seeds) while maintaining viable populations of beneficial microorganisms (Hustvedt et al., 2016; NRCS, 2010). Because livestock manure often contains weed seeds, applying composted manure to crop fields reduces the likelihood of spreading weed seeds. Composting has also been shown to reduce and, in some cases, eliminate chemical contaminants that can occur in the original feedstocks through processes such as microbial decomposition of organic matter, adsorption and volatilization (Governo et al., 2003). For example, composting biosolids, manures, yard trimmings, and crop residues is an effective means to degrade synthetic organic compounds (hormones, antibiotics and pesticides), reducing the susceptibility of loss to the environment (Governo et al., 2003; Stehouwer et al., 2022). However, some herbicides tend to be resistant to degradation during the composting process, such as clopyralid, aminopyralid, aminocyclopyrachlor and picloram (Rynk, Cooperband, et al., 2022; Stehouwer et al., 2022). The application of compost containing these herbicides can cause significant damage to plants, including commercially important species in the nightshade (tomatoes, potatoes), aster (sunflowers), cucurbit (cucumber, squash), and legume families (peas, beans, clover) (Stehouwer et al., 2022).

The thermophilic phase is followed by a gradual decline in biological activity and a return to mesophilic conditions as the readily degradable organic matter supply declines and the remaining organic C is stabilized. This final stage, discussed further below, is maturation or curing (Rynk, Cooperband, et al., 2022), and is critical to achieving a highly stable compost. Adequate curing of compost ensures beneficial microorganisms (such as bacteria and fungi) populate the compost, some of which aid in the suppression of plant diseases (Neher et al., 2022).

*Figure 1. Food scraps and carbon-rich organic materials being prepped for mixing and composting. Photos courtesy of ECO City Farms, Bladensburg, MD.*

Vermicomposting is an alternative method for decomposing organic materials into a product that is similar to compost. Vermicomposting is not considered to be "true" composting (Rynk, Cooperband, et al., 2022). Instead of relying upon microbial decomposition of organic materials under thermophilic conditions, vermicomposting uses worms (e.g., *Eisenia fetida*) to mediate the decomposition of organic materials at moderately low temperatures (generally 55–85 °F) to produce a material called "worm castings" (Ali et al., 2015; Rynk, Cooperband, et al., 2022).

Appropriate compost stability and maturity are important for plant establishment and growth (Aslam, 2009; Brinton, 2010; Stehouwer et al., 2022). Compost maturity describes the degree to which the more readily degraded organic materials have completed their degradation while less readily degradable organic materials remain. Immature compost may contain substances harmful to plant growth (Stehouwer et al., 2022). Compost stability indicates the rate of organic material degradation under existing conditions; the organic matter in a stable compost is resistant to further decomposition. An application of unstable compost will degrade more rapidly and may significantly reduce nitrogen (N) availability for plants due to uptake by microorganisms as they continue to decompose readily degradable organic C. Further information on the physical, chemical and biological processes that occur during composting can be found in the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) National Engineering Handbook (NRCS, 2010).

Best practices for composting need to be followed (particularly for small-scale residential composting) to ensure that the compost does not become a source of pathogens, pests or harmful chemicals. For example, it is commonly recommended that meat and dairy products be excluded from at-home composting operations due to the potential for attracting disease vectors such as flies and rodents. Although somewhat dated, Hoitink et al. (1996) provides an informative overview of the value of compost for plant disease suppression, including an emphasis on the importance of compost stability and maturity for compost performance.

Understanding compost manufacturing methods, stages and key characteristics provides important context for the potential environmental benefits of compost use; adhering to general guidelines at the production stage can help optimize the achievement of benefits. Section 10 provides additional detail on compost feedstocks and manufacturing, while Section 11 discusses compost qualities (e.g., nutrient levels, particle size, stability, maturity) and how variation in compost qualities can affect the environmental performance of compost use.

Finished compost is primarily used as a soil amendment to support plant growth (Brown et al., 2017); however, its value extends beyond improving the health of soils – see Figure 2. For example, it can be used as an alternative to peat in the horticultural sector and as a replacement for materials such as topsoil, straw and wood chips in stormwater management and erosion control practices (Faucette, Governo, et al., 2009; Ozores-Hampton et al., 2022). Compost can also be steeped in water to produce "compost tea"; this product can provide many of the same benefits as compost yet allows for alternative means of application such as distribution through irrigation systems or use as a foliar spray for plants. Subsequent sections of the report explore a variety of uses and benefits of compost in more detail.

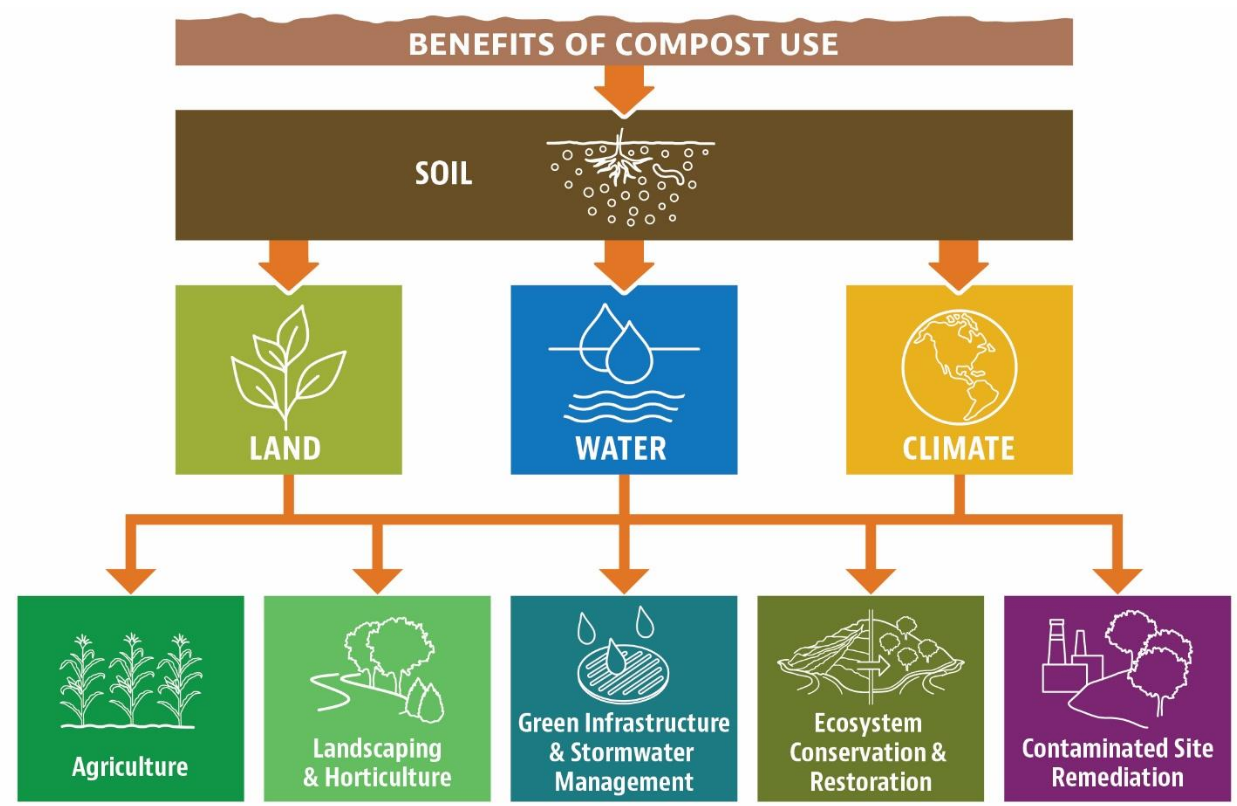


*Figure 2. Compost use directly improves soil health, with cascading benefits for ecosystems and various sectors.*

## 1.5 Report Overview

The report initially summarizes the benefits of compost use for soil health, water resources and climate (Sections 2–4). Sections 5 through 9 offer a sectoral breakdown of environmental benefits for agriculture, landscaping and horticulture, green infrastructure and stormwater management, contaminated land remediation, and ecosystem conservation and restoration. Section 10 describes common compost feedstocks and compost production methods while Section 11 discusses how the environmental functions of compost are influenced by compost characteristics. Section 12 provides an overview of the typical compost application frequencies and rates for different end uses. Section 13 describes how site-specific characteristics (e.g., soil type, climate) can affect compost performance. Section 14 explores the economic value associated with compost production and use. Section 15 explores the benefits and barriers to "compost use at-scale," the term used to examine potential large-scale benefits if compost production and use became better aligned with the available stream of compostable materials. Finally, Section 16 provides conclusions about the benefits of compost use as well as recommendations for future research.

## 1.6 Research Methods

A literature search was initially conducted to identify and collect relevant peer-reviewed publications, reports, book chapters and other publicly available information (e.g., grey literature, online resources) pertinent to the environmental benefits associated with compost use. The literature search was mainly based on literature published after 2010 in order to focus the review on the most up-to-date scientific information, with priority given to publications from the United States. Additional references from outside the original search focus (e.g., pre-2010 references) were used to fill information gaps identified during the report development process. Most sources cited in this report are peer-reviewed publications. Several government reports and data sources are referenced, which may not be peer-reviewed. Additional literature associated with composting industry organizations (such as the U.S. Composting Council, the Compost Research and Education Foundation, and BioCycle) is also referenced to fill miscellaneous gaps in data and information (e.g., compost manufacturing, compost supply and demand, compost quality specifications and application rates/frequencies). It is unknown if such literature was peer-reviewed. The Appendix provides further details about the initial literature search methods, including keywords, literature databases and screening methods.

Compost experts were consulted during two different phases of report development. Three interviews were conducted with experts in the field of compost use to verify that key sources of literature were not excluded and to help ensure the accuracy of the report content. Three additional experts on compost use conducted a full peer review of the report to ensure scientific completeness and accuracy of the content.

# 2. Soil Health Benefits

Compost used as a soil amendment can play an important role in improving and maintaining soil health (Ozores-Hampton, 2021c). The USDA NRCS [defines soil health](#) as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans." Other definitions of soil health expand to include soil's role in water and air quality, nutrient cycling, pollution control and climate change (FAO, 2008; Lehmann et al., 2020).

It is important to note that the magnitude of soil health benefits resulting from compost use will vary based on a soil's characteristics and soil health status at the time of compost use. For example, the effects of compost use will differ based on soil texture (e.g., sandy soils versus clayey soils) (Brown & Cotton, 2011; Hill, 2021; Rynk, Cooperband, et al., 2022) as well as the existing level of soil organic matter (SOM) (Ozores-Hampton et al., 2022). Furthermore, the effects of compost use will be greater for soils that have been degraded by land use activities associated with agriculture, mining and construction or through natural disasters such as wildfire (Brown & Beecher, 2019; Magdoff & Van Es, 2021; McFarland, 2009).

Soil health improvements and maintenance from compost use result in cascading co-benefits for water quality and conservation, including climate change adaptation and resilience. Figure 3 illustrates the soil health benefits and co-benefits associated with compost use. In addition, compost use may have long-term economic benefits; for example, it can increase crop productivity and quality while reducing the cost of inputs such as irrigation and pesticides. These benefits are discussed in upcoming sections. This section summarizes the potential effects and direct benefits of compost applications on soil health in more detail.

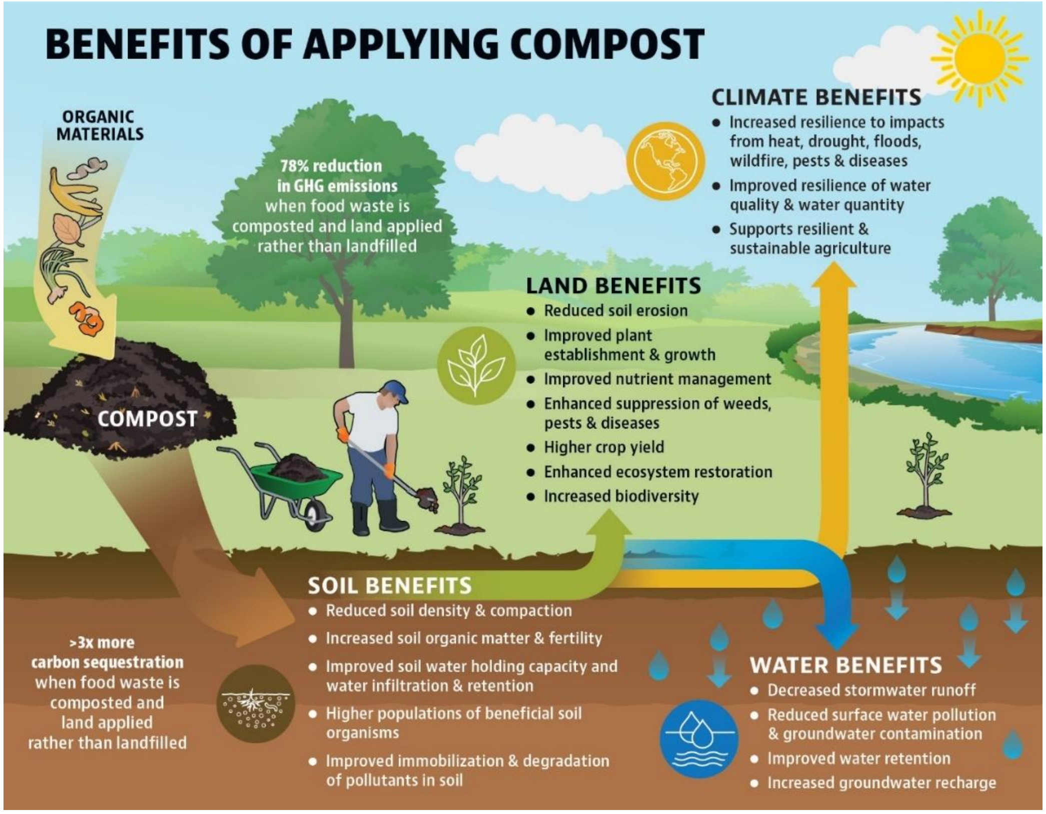


*Figure 3. Soil Health benefits from compost application, and associated water, land and climate benefits. Source for carbon sequestration increases and GHG emissions reductions: Brown (2016)*

## 2.1 Soil Physical Characteristics

The physical characteristics of soils, such as soil texture (i.e., proportions of sand, silt and clay), provide the foundation for all soil functions, such as providing a medium for plant growth, protecting water quality and regulating surface runoff and groundwater recharge. Scientific literature reports that compost modifies the physical characteristics of soils, including structure (e.g., soil particle aggregation), bulk density, porosity and water-holding capacity (Brown & Cotton, 2010, 2011; Brown & Goldstein, 2016; Brown et al., 2011; Dubelko et al., 2022; Dunifon et al., 2011; Evanylo et al., 2016; Imran et al., 2022; Kranz et al., 2020; Long et al., 2017; Readyhough et al., 2021; Wang et al., 2022; Ward et al., 2021).

Changes in soil physical characteristics are directly associated with SOM (Khaleel et al., 1981). SOM consists of live plant and animal tissues, along with dead organisms, in various phases of decomposition, as well as organic C-based secretions and excretions from organisms (Magdoff & Van Es, 2021). It is distinct from the inorganic (e.g., non-C based) fraction of soil, which consists largely of minerals, water and gases (e.g., N gas ($N_2$), carbon dioxide ($CO_2$) and $O_2$), along with lesser amounts of other inorganic molecules such as nitrate ($NO_3$) and phosphate. SOM content in soils is typically less than 5%, although it can be more than 30% for soils formed in wetlands (Biernbaum, 2012).

SOM plays a critical role in developing the soil structure (Ozores-Hampton, 2021d). It promotes the development of stable soil aggregates (clumps of particles), which increases soil porosity, thereby facilitating water infiltration, water percolation and aeration (Rynk, Cooperband, et al., 2022). SOM improves soil aggregation through physicochemical interactions with clay and oxides (e.g., minerals containing silicate, iron, manganese [Mn] and aluminum) and by providing structure and food for microorganisms that help mediate the binding of soil particles through biochemical processes (Hillel et al., 2004). Soil particle aggregates are more resistant to the dispersive forces from wind, rainfall impact and overland flow, thereby inhibiting soil erosion (Owen et al., 2020, 2021). The ability of soil aggregates to resist disintegration is referred to as aggregate stability.

Compost has a high organic matter content (exceeding 25%) (Ozores-Hampton, 2021c) relative to most soils. Increased SOM levels, associated with compost additions, improve soil particle aggregation and increase aggregate stability, which enhances soil health by lowering soil bulk density and increasing soil porosity (Alexander, 2017; Brown & Cotton, 2010; Brown et al., 2011; Gilbert et al., 2020a; Oldfield et al., 2014; Ozores-Hampton, 2019; Stoffella et al., 2016). These effects are referred to as soil structure conditioning, or soil conditioning. Bulk density is inversely related to soil porosity, and both are indicators of the ability of air and water to move into and through soils, as well as the ability of plant roots to extend through the soil profile (Kranz et al., 2020). Porosity is a measure of the void space in soils, which ranges from micropores (usually voids between individual particles within aggregates of particles) to meso- and macropores (usually the inter-aggregate voids). Water and gas exchange with the atmosphere and plant root extension occur primarily and most readily via macropore and mesopore networks. Compost use is, therefore, particularly beneficial where soils are naturally dense or have become compacted, limiting plant growth (Tyler, 2021). The interrelated effects of porosity and soil biology are further discussed in Section 2.3.

In the scientific literature, decreases in soil bulk density following compost addition have been reported ranging from 6% to 35% (Cogger et al., 2008; Evanylo et al., 2016; Mohammadshirazi et al., 2017; Ozores-Hampton, 2019).

Table 1 summarizes results from a selection of studies that evaluated the effect of compost applications on soil bulk density.

*Table 1. Effects of compost use on soil bulk density. Adapted from Kranz et al. (2020).*

| Soil type[b] | Compost feedstock[c] | Approximate compost application rate (t $ac^{-1}$ wet wt.) and (application depth)[d] | Soil incorporation depth (inches)[e] | Time (years)[f] | Change in soil bulk density[g] | Reference[a] |
|---|---|---|---|---|---|---|
| Sandy clay | Yard trimmings | 134 (2 in.) | 12 | 2 | 28% decrease[h] | Mohammadshirazi et al. (2017) |

| Soil type[b] | Compost feedstock[c] | Approximate compost application rate (t ac$^{-1}$ wet wt.) and (application depth)[d] | Soil incorporation depth (inches)[e] | Time (years)[f] | Change in soil bulk density[g] | Reference[a] |
|---|---|---|---|---|---|---|
| Clay loam fill | Yard trimmings | 134 (2 in.) | 12 | 2 | 8% decrease[i] | Mohammadshirazi et al. (2017) |
| Fine sandy loam | Yard trimmings | 134 (2 in.) | 12 | < 1 | 35% decrease[j] | Mohammadshirazi et al. (2016) |
| Sandy loam | Yard trimmings | 201 (3 in.) | 8 | 6 | 15% decrease | Cogger et al. (2008)[k] |
| Sandy loam | Mixed | 67–134 (1–2 in.) | 3.0 – 4.0 | 2 | 6-11% decrease | Evanylo et al. (2016) |

*Notes:* in = inches; t ac$^{-1}$ = tons per acre

[a] All studies are in a non-agricultural setting.

[b] Soil textural class recorded when provided in original source material. When soil taxonomic names or soil series were given in source material, the Web Soil Survey was used to determine the textural class.

[c] Yard trimmings" compost is used to refer to compost feedstock materials derived from plant-based materials, such as lawn clippings, leaves and wood. "Mixed" compost refers to compost made from paper mill sludge, wood, wood ash and food processing waste.

[d] Either the rate or depth are approximations based on reported values in Kranz et al. (2020) and a conversion to depth from mass per unit area, or vice versa, based on an assumed density of 1000 lbs per cubic yard following Table 16.6 in Ozores-Hampton et al. (2022).

[e] Incorporation includes multiple mechanical methods of mixing compost with soil.

[f] Time in years after the initial compost incorporation into the soil. If multiple measurements were taken over time, the longest time span since the initial application.

[g] Ranges for each soil type grouping were taken from the lowest and highest reported values in Table 1 of Kranz et al. (2020); percent changes in Table 1 were based on the last reported measurement in a study.

[h] Percent change for compost + tillage relative to tillage alone; relative to the control, tillage alone decreased bulk density by 16% and tillage + compost decreased bulk density by 40%.

[i] Percent change for compost + tillage relative to tillage alone; relative to the control, tillage alone decreased bulk density by 12% and tillage + compost decreased bulk density by 19%.

[j] For Mohammadshirazi et al. (2016), this is the percent change for compost + tillage relative to tillage alone; relative to the control, tillage alone decreased bulk density by 31% and tillage + compost decreased bulk density by 55%.

[k] The study was performed on soil formerly used for growing annual crops.

Compost applications increase the rate at which water moves into and through soils (Kranz et al., 2020), commonly referred to as infiltration and percolation. As described previously, compost can facilitate an increase in soil porosity, enabling water to infiltrate at a higher rate. The organic matter additions from compost applications may also inhibit soil sealing and crusting, thereby facilitating water infiltration (Gould, 2015). In California, Brown and Cotton (2011) found that compost use on agricultural soils reduced infiltration times from 17.5 minutes to less than 1 minute. Higher infiltration rates decrease surface runoff and can help prevent soil erosion (Rynk, Cooperband, et al., 2022). In general, the effect of compost additions on soil infiltration rate varies with soil texture; infiltration rates tend to increase more in fine-textured soils (e.g., clay soils) than in coarse-textured soils (e.g., sandy soils) (Magdoff & Van Es, 2021; USCC, 2008) due to the effect of compost on soil bulk density. Soils that already have a relatively low bulk density (e.g., many sandy soils) tend to have a relatively high infiltration rate that may not substantially increase through the addition of compost. For multiple sites in California, Brown and Cotton (2011) found infiltration rates to increase significantly in fine-textured soils amended with compost (relative to controls), but infiltration rates did not improve in coarse-textured soils. However, Cogger et al. (2008) observed that compost addition to a fine sandy loam soil previously used for growing annual crops led to a 183% increase in infiltration rate. In this regard, compost may also increase infiltration in coarse-textured soils that have become compacted. Table 2 summarizes observed changes in infiltration rates after compost additions, as reported in the literature. In addition to increasing infiltration, compost application increases saturated hydraulic conductivity, or the rate at which water moves through saturated soils (Kranz et al., 2020). Saturated hydraulic conductivity is important for plant growth since it relates to how quickly a saturated soil can drain.

*Table 2. Effects of compost use on soil infiltration rate. Source: adapted from Kranz et al. (2020).*

| Soil type[b] | Compost feedstock[c] | Approximate compost application rate (t $ac^{-1}$ wet wt.) and (application depth)[d] | Soil incorporation depth (in)[e] | Time (years)[f] | Percent change[g] | Reference[a] |
|---|---|---|---|---|---|---|
| Sandy clay | Yard trimmings | 134 (2 in.) | 12 | 2 | +125%[h] | Mohammadshirazi et al. (2017) |
| Clay loam fill | Yard trimmings | 134 (2 in.) | 12 | 2 | +59%[i] | Mohammadshirazi et al. (2017) |
| Fine sandy loam | Yard trimmings | 134 (2 in.) | 12 | < 1 | +68%[j] | Mohammadshirazi et al. (2016) |
| Sandy loam | Yard trimmings | 201 (3 in.) | 0 | 4 | +183%[k] | Cogger et al. (2008)[l] |

*Notes:* in. = inches; t $ac^{-1}$ = tons per acre

[a] All studies are in a non-agricultural setting and use a compost and soil incorporation method. Infiltration rate is typically measured in in/hr or cm/hr.

[b] Soil textural class recorded when provided in original source material. When soil taxonomic names or soil series were given in source material, the Web Soil Survey was used to determine the textural class.

[c] "Yard trimmings" compost is used to refer to compost feedstock materials derived from plant-based materials, such as lawn clippings, leaves and wood. "Mixed" compost refers to compost that uses a combination of yard trimmings and wastewater solids and/or other MSW.

[d] Either the rate or depth are approximations based on reported values in Kranz et al. (2020) and a conversion to depth from mass per unit area, or vice versa, based on an assumed density of 1000 lbs per cubic yard following Table 16.6 in Ozores-Hampton et al. (2022).

[e] Incorporation includes multiple mechanical methods of mixing compost with soil.

[f] Time in years after the initial compost incorporation to the soil. If multiple measurements were taken over time, the longest time span since the initial application.

[g] The range in percent change for a given soil type grouping was taken from the lowest and highest reported values in Table 2 of Kranz et al. (2020); percent changes in Table 2 based on the last reported measurement in a study.

[h] On a plot with vehicle traffic; percent change for compost + tillage relative to tillage alone; relative to the control, tillage alone increased infiltration by 80% and tillage + compost increased infiltration by 305%.

[i] Percent change for compost + tillage relative to tillage alone; relative to the control, tillage alone increased infiltration by 190% and tillage + compost increased infiltration by 359%.

[j] For Mohammadshirazi et al. (2016), this is the percent change for compost + tillage relative to tillage alone; relative to the control, tillage alone increased infiltration by a factor of 22 and tillage + compost increased infiltration by a factor of 37.

[k] This is the change in infiltration rate observed after compost was added to the soil surface; there was no significant difference between compost applied to the surface and compost incorporated 8 inches into the soil.

[l] The study was performed on soil formerly used for growing annual crops.

The SOM content and texture of soil influence its capacity to store water (Adeleke et al., 2021; Brown & Cotton, 2010; Rynk, Cooperband, et al., 2022). Studies have found substantial increases in soil water-holding capacity following compost applications (Alexander, 2020g; Brown & Cotton, 2011; Brown et al., 2011; Gilbert et al., 2020a; Rynk, Cooperband, et al., 2022). Increases in soil water-holding capacity by 35% to 57% have been reported (Brown & Cotton, 2011; Ozores-Hampton, 2021c); one study reported a 250% increase in soil water-holding capacity for a sandy fill material used to create urban garden plots (Maynard, 2000b). As with water infiltration, the effect on soil water-holding capacity varies by soil texture. For example, compost can substantially increase water-holding capacity in sandy soils but may not increase water-holding capacity of clay soils (Hill, 2021; Rynk, Cooperband, et al., 2022). Improvements in both water infiltration and water storage provide co-benefits for plant growth, water conservation and water quality in various sectors (see Sections 3 and 5 through 9).

Lal (2020) describes how organic matter additions increase the field capacity of soils (i.e., the amount of water held by soils after the large pores are drained) yet do not appreciably increase the amount of water held in the soil at the permanent wilting point (i.e., the point at which there is too little water for plants to uptake). Brown et al. (2011) measured changes in soil water at field capacity following compost additions at multiple long-term agricultural sites in California State. Soils with compost applications displayed a 48%–54% increase in plant-available water (the difference between field capacity and permanent wilting point) at three of seven sites due to increased field capacity. This suggests that compost additions may help increase the amount of water held by soils during moist to wet conditions and may slow the drying of soil during drought conditions, but ultimately, compost cannot prevent soils from drying out under prolonged drought. However, there is inconsistency amongst the scientific literature regarding the magnitude of changes in plant-available water from organic matter additions such as compost. A recent meta-analysis of 60 studies concluded that a 1% increase in soil organic C (SOC) from organic matter additions increased volumetric plant-available water by only 1.2% (Minasny & McBratney, 2018).

Most studies on the physical effects of compost additions are based on short-term changes (post-amendment). However, there is limited information regarding the long-term (e.g., > 10 years) persistence of changes to parameters such as bulk density, infiltration rate and water-holding capacity. Ward et al. (2021) found that improvements in soil water-holding capacity and bulk density were measurable in urban soil plots six years after amendment with compost. Sax et al. (2017) documented increased organic matter and water-holding capacity and decreased bulk density that persisted for at least 12 years; however, the treatment of compacted soils involved soil excavation followed by mixing with compost, which confounds the attribution of decreased bulk density to compost alone. The persistence of benefits to soil physical characteristics is more important at sites where a single application occurs (e.g., during a revegetation effort) than at sites where ongoing compost applications (e.g., periodic applications to agricultural soils) are used to maintain benefits to soils.

**Summary: Key Soil Health Benefits from Compost Use**

Improved soil physical characteristics

- Improved soil structure
- Improved water infiltration
- Enhancement of water-holding capacity

Enhanced soil chemical fertility

- Increased SOC
- Supplemental plant macro- and micro-nutrients
- Enhanced nutrient bioavailability

Enrichment of soil biology

- Increased diversity and abundance of beneficial soil organisms

## 2.2 Soil Chemistry

Soil fertility refers to the ability of a soil to sustain plant growth by providing favorable chemical, physical and biological conditions. Compost increases soil chemical fertility through effects on SOC, cation exchange capacity (CEC: a measure of the ability of soils to retain positively charged plant nutrients), pH, and nutrient levels.

SOM is composed largely of SOC (typically 40% to 60%) (Pluske et al., 2024), with the other components being nutrients and other chemical compounds. SOC levels are controlled by organic C inputs to soils, microbial activity, and the chemical and physical characteristics of the soil matrix (Witzgall et al., 2021). SOC increases the chemical fertility of soils (Ozores-Hampton, 2021d) by providing energy sources for soil organisms and regulating the availability of organically bound nutrients (Billings et al., 2021). In other words, as soil organisms consume SOM over time, it enables a slow, ongoing release of necessary plant nutrients.

Increases in SOC levels are a key benefit of compost applications (Adeleke et al., 2021; Brown & Cotton, 2011; Devine et al., 2022; Kelley et al., 2020; Li et al., 2010; Otuya et al., 2021; Reeve et al., 2012; Tautges et al., 2019). The capacity of soil to store C varies by soil type, with coarser-grained soils reaching capacity (called “C saturation”) with lower SOM levels (and fewer C inputs) than finer-grained soils (Li & Evanylo, 2013). Soils with depleted levels of organic matter generally have more potential to store carbon (Brown et al., 2011). Ryals and Silver (2013) found that a single 0.5-inch application of yard trimmings compost to rangeland soils at two study sites was associated with a 25% to 70% increase in net SOC on plots over a three-year period, excluding the C added from the compost itself. The increase in SOC was attributed to an increase in above-ground primary productivity (78% ± 13% and 42% ± 14% for the two study sites), which offset C losses from greater soil respiration. Yu et al. (2012) reported that eighteen years of compost application to cultivated soils resulted in a 71% to 122% increase in SOC. Table 3 summarizes results from various studies that quantify the effects of compost application on SOC.

*Table 3. Increases in SOC associated with compost application.*

| Study | Increase in SOC (%) | Notes |
|---|---|---|
| Brown and Cotton (2011) | 200% | 2–15 years of application at multiple sites in California; rates of 2.5–15 t $ac^{-1}$ (dry wt.). |
| Brown et al. (2011)[a] | 106% (0–6 in. soil depth)<br><br>75% (6–12 in. soil depth) | 7–16 years of compost application (unspecified compost types) across multiple sites in Washington; cumulative rate of approx. 22.3 t $ac^{-1}$ (dry wt.). |
| Evanylo et al. (2008)[b] | 19%–low rate (0–6 in. soil depth)<br><br>60%–high rate (0–6 in. soil depth) | 3 years of a 2:1 poultry litter and yard trimmings compost mixture applied to vegetable crop fields in Virginia at two different annual rates. The low rate was 3.8–6 t $ac^{-1}$ $yr^{-1}$ (13.8 t $ac^{-1}$, cumulatively; dry wt.) The high rate was 14.7–29.9 t $ac^{-1}$ $yr^{-1}$ (64.2 t $ac^{-1}$, cumulatively; dry wt.). |
| Rath et al. (2022)[c] | 16% (0–39 in. soil depth) | 25 years of poultry manure compost application (1.8 t $ac^{-1}$ $yr^{-1}$) plus cover cropping on corn-tomato rotations in Sacramento Valley, CA[g] |
| Tautges et al. (2019)[d] | 12.6% (0–79 in. soil depth) | 19 years of annual poultry manure compost application at 1.6 t $ac^{-1}$ $yr^{-1}$ plus winter cover cropping to maize/tomato rotations in Sacramento Valley, CA[g] |
| White et al. (2020)[e] | 49.5% (0–12 in. soil depth) | 8 years of urban yard trimmings compost application at a rate of 3.4 t $ac^{-1}$ $yr^{-1}$ (dry wt.), plus differing cover cropping systems on vegetable crop fields in Salinas Valley, CA. |
| Wilson et al. (2018)[f] | 24% (0–12 in. soil depth) | 3 years of compost application at a rate of 20 t $ac^{-1}$ $yr^{-1}$ (dry wt.) on potato fields in New Brunswick, Canada. |

*Notes:* in. = inch; dry wt. = dry weight; t $ac^{-1}$ $yr^{-1}$ = tons per acre per year.

[a] Sites included orchards, landscaping, turfgrass and roadsides in Washington State. The SOC increase is approximate, calculated across all site types. Mean estimated SOC increase was 5.3 t $ac^{-1}$ for orchards and 1.5 tons carbon $ha^{-1}$ for turfgrass. Increases in N, P and water retention were also observed.

[b] SOC in the control was roughly 11.6 to $ac^{-1}$. The SOC increase for the low compost rate was approximately 2.2 t $ac^{-1}$, which was considered insignificant. The SOC increase for the high compost rate was significant at approximately 7 t $ac^{-1}$.

[c] Same sites as in Tautges et al. (2019). The SOC increase was 8.5 t $ac^{-1}$ within the 1m soil profile. The SOC increase is approximate; 26% of the SOC increase was in the top 6 in. The study did not find an increase in SOC from either inorganic fertilizers alone or inorganic fertilizers plus cover crops.

[d] Incorporating cover crops alone into maize/tomato rotations resulted in a net loss of SOC within the 79 in. soil profile.

[e] The intensified soil disturbance and cropping system associated with the experiment led to an initial SOC loss of 13.8 t $ac^{-1}$ in year 1; the cumulative SOC increase was 4.2 t $ac^{-1}$ for years 2-8. Compost use plus cover crops had an SOC increase approximately 2.8 times greater than use of cover crops alone.

[f] The SOC increase is an average among five different types of compost (marine with shells, poultry manure, forestry residues, municipal source separated organic materials and forestry waste + poultry manure); individual compost increased SOC by 9%–27%.

[g] The study did not report whether applications were in wet or dry weight.

Composting organic materials improves the stability of the organic C compounds, which can increase the persistence of SOC post-application (Bernal et al., 1998; Ozores-Hampton et al., 2022). Gilbert et al. (2020a) reported that 11%–45% of the organic C derived from compost remained in the soil as SOC over a period of 4–12 years. Brown et al. (2011) reported a higher SOC content of turfgrass plots 16 years after a single compost application compared to plots that only received inorganic fertilizer. Modeling of compost applications to California rangelands suggests that a single compost application at a rate of 17 tons $ac^{-1}$ (wet wt.) can result in SOC benefits that persist for at least 30 years (Silver et al., 2018).

Higher levels of SOC enhance CEC and result in greater nutrient availability for plants (Rynk, Cooperband, et al., 2022). Numerous sources indicate that compost additions improve soil CEC (Alexander, 2005, 2017, 2020f, 2020k; Hill, 2021; Ozores-Hampton, 2019; USCC, 2008). Improved CEC and water retention, as well as reductions in soil erosivity, help reduce the amount of plant nutrients that may otherwise be lost through leaching or in surface runoff (Alexander, 2005, 2017, 2020k; Oladeji et al., 2019; Shrestha et al., 2020; USCC, 2008). Compost amendments also buffer soil pH (Stehouwer et al., 2022; Wilson et al., 2018), which improves CEC and soil fertility because soil particles will have more negatively charged sites on which to retain cations that are important for plant growth. As soil acidity increases, the availability of N, P and potassium (K) tends to decrease. As soil basicity increases, plant nutrients such as Mn and Fe tend to become immobilized. By buffering soil pH and increasing CEC, compost additions can, therefore, increase the availability of nutrients for plant uptake (Alexander, 2020g; Gilbert et al., 2020a).

In addition to increasing the bioavailability of plant nutrients, periodic applications of compost can replenish soils with the macro-nutrients (N, P, K, magnesium [Mg], calcium [Ca] and sulfur [S]) and micro-nutrients (boron [B], chloride [Cl], Copper [Cu], iron [Fe], Mn, nickel [Ni] and zinc [Zn]) essential for the overall health and growth of plants (Li et al., 2010; Ozores-Hampton, 2019; Rynk, Cooperband, et al., 2022; USCC, 2008; Wilson et al., 2018). Compost is a source of N, P and K inputs; however, the amount of these nutrients in compost is typically lower than in inorganic fertilizers (e.g., mined P and N fertilizer synthesized from natural gas) on a per mass basis (Kelley et al., 2022; Ozores-Hampton, 2019; USCC, 2008). For example, compost generally contains ≤ 6% N and ≤ 3% P, while inorganic fertilizers contain up to 82% N and 75% P (Ozores-Hampton, 2021b; Vitosh, 1996). However, compost applications tend to be on the order of tons per acre rather than pounds per acre (as used for inorganic fertilizers) and can serve as a substantial source of plant nutrients (Kelley et al., 2020; Kelley et al., 2022). In Florida, compost application (including yard trimmings, biosolids and the organic fraction of municipal solid waste (OFMSW)) to a sandy soil used for vegetable production increased P, K, Ca, Mg, Mn, Zn over a 10-year period; this was likely due to concurrent increases in SOM and CEC, which improve nutrient retention and bioavailability in soils (Ozores-Hampton, 2019). Reeve et al. (2012) evaluated soils on a commercial dryland wheat farm in Snowville, Utah, which had been amended with a single application (at a rate of 22 $t^{-1}$ $ac^{-1}$ dry wt.) of dairy manure and bedding compost. Sixteen years post application, soils from compost-amended plots contained greater plant available P, K and Zn in the top 2 inches compared to control plots.

N in compost is mostly in the form of organic N, which must be mineralized (transformed from an organic form to an inorganic form such as $NO_3$) before plants can absorb it (Ozores-Hampton et al., 2022). Compost is seldom used as the primary source of N for annual crop production, which tends to have a relatively high N demand due to compost's low N:P ratio and slow release of N (Ozores-Hampton et al., 2022). In general, a C:N ratio over 25 will inhibit N mineralization; progressively lower C:N ratios facilitate greater mineralization rates and lead to more plant-available N (Busby et al., 2007; Kelley et al., 2022; Ozores-Hampton et al., 2022; Stehouwer et al., 2022). When the C:N ratio is relatively high (e.g., > 25), microorganisms can outcompete plants for the uptake of bioavailable N, resulting in a condition referred to as N immobilization (Coker, 2021; de Gannes et al., 2018; Long et al., 2017). The rate of N mineralization is largely influenced by the N content, C:N ratio and stability of the compost, together with the temperature, moisture, and aeration of the soil (Brown & Goldstein, 2016; Ozores-Hampton et al., 2022; Stehouwer et al., 2022). Stehouwer et al. (2022) suggested the following estimates of N availability from compost use:

- Up to 10% of total N in mature composts is immediately available for plant uptake
- 5%–10% of the organic N is mineralized in the first year
- Mineralization rates decline in subsequent years if no additional compost is added

Raun and Johnson (1999) provided a similar estimate for temperate climates, stating that mineralization rates for compost can range from 0–20% in the first year after application, with 2%–5% of initial organic N per year further mineralized in the following three to five years (Raun and Johnson, 1999).

P in compost is typically in an organic form, which means that most of the P in compost will become available for plants to absorb as the organic matter in compost further degrades (Ozores-Hampton et al., 2022). Animal manure and biosolids compost tend to have higher P content than other types of compost (Ozores-Hampton et al., 2022). P availability for plant uptake in soils is restricted at both low and high soil pH. Compost can shift the pH of soils, increasing the bioavailability of P (USCC, 2008); however, this effect is not entirely straightforward as discussed further in Section 13.1. When using compost for soil fertilization, adjusting the application rate to meet N demand by plants can result in an over-supply of P, particularly for applications involving ongoing compost applications to soils that already have large reserves of P (Heyman et al., 2019; Ozores-Hampton et al., 2022). This is because the ratio of plant-available N:P derived from compost is typically lower than the ratio absorbed by plants (Shrestha et al., 2020). Therefore, it has been recommended that the application rate be adjusted to meet plant P requirements (Ozores-Hampton, 2021b; Ozores-Hampton et al., 2022). Ideally, compost application rates will be based on knowledge of the soil's P content (see Pierzynski (2000) for more information on soil P testing), plant requirements for N and P, and the N and P content of available compost.

## 2.3 Soil Biology

Microorganisms in soils that are important for soil health include actinomycetes, bacteria, fungi and protozoa. Various larger organisms, such as earthworms, insects and nematodes, are also important. These organisms play an important role in organic matter decomposition, which increases nutrient availability and is key to increasing stable SOC stocks in soil (Abbey et al., 2022; Adeleke et al., 2021; Alexander, 2020f; Brown & Cotton, 2010; Dynarski et al., 2020; Oldfield et al., 2014; Reeve et al., 2012).

Following compost addition, an increase in soil porosity and a decrease in bulk density (associated with soil aggregation) improves the ability of both larger and smaller organisms, such as earthworms and microbes, to move within the soil. In turn, the movements of organisms within the soil also increases porosity. Improvements in soil aggregation associated with compost enhance the ability of roots to extend through the soil matrix, benefitting the ability of plants to acquire water and nutrients (Rynk, Cooperband, et al., 2022). As individual roots die and decompose, the space they occupied becomes new pore space, further improving the rate at which water and air move through the soil.

Research indicates that compost additions have positive effects on soil microbial abundance and diversity. Soil microbial abundance is primarily limited by organic C and water availability, which are vital for metabolic functioning (Soong et al., 2020). By increasing SOM, compost increases the diversity of soil biological communities and the abundance of beneficial organisms (Adeleke et al., 2021; Alexander, 2020f; Brown & Cotton, 2010; Oldfield et al., 2014; Reeve et al., 2012). For example, in California, Brown and Cotton (2011) found that amending soil plots with compost increased organic C threefold (compared to control soils) and doubled the soil microbial activity. Similarly, Otuya et al. (2021) documented an increase in microbial abundance (as well as increased SOC, SOM and total N [TN]) following compost addition to pastures in Texas (Otuya et al., 2021). Grobe (1998) reported that the application of compost derived from yard trimmings and cardboard feedstocks was associated with increases in the soil fungal abundance and diversity in orchards and vineyards, resulting in enhanced nutrient uptake, disease suppression and drought tolerance. In Florida, applying compost over a 10-year period to a sandy agricultural soil increased microbial species richness and diversity, particularly more beneficial microbes such as heterotrophic aerobes, actinomycetes and pseudomonads (Ozores-Hampton, 2019). In Manitoba, Canada, Abbey et al. (2022) found that over a 5-year period, approximately 44% of the variation in bacterial community diversity in soil plots could be attributed to compost applications derived from OFMSW.

Increasing soil microbial activity through compost additions can have cascading effects on soil structure, nutrient availability and plant growth. For example, in a six-year field study, Wang (2014) documented how compost applications established a positive feedback loop benefitting soil quality. Ongoing compost applications facilitated the formation of soil aggregates, resulting in improved retention of dissolved SOC. This increased the abundance and stability of microbial food sources, which led to a greater microbial biomass that could exploit different SOC sources. An overall increase in the bioavailable pool of SOC was also reported. Recent understandings of carbon flows in soils highlight the importance of microbial activity for promoting the accumulation and circulation of SOM, which leads to carbon sequestration (more in Section 4.2) (Dynarski et al., 2020). Research is ongoing to optimize the composting process in ways that will increase the populations of beneficial microbes present in compost applications (Li et al., 2021; USCC, 2008).

# 3. Water Resource Benefits

Compost use is gaining increasing recognition as a cost-effective and sustainable solution to help manage runoff and improve water quality (Faucette et al., 2005; Rynk, Cooperband, et al., 2022). Most compost use benefits for water resources are associated with improved soil health and plant productivity. For example, healthy soils infiltrate and hold more water and promote root growth, which reduces runoff, pollutant transport and irrigation needs. Compost use in water resource management is, therefore, a natural solution that also supports adaptation and resilience to climate-driven changes in hydrology and runoff. This section summarizes the benefits of compost use related to water conservation and water quality.

## 3.1 Water Conservation

Water is a vital natural resource used by plants, animals, people and industries. The extent of water resources (their amount and distribution) and their condition (physical, chemical and biological characteristics) are critical to the environmental sustainability of ecosystems and their use by humans.

Whether rain-fed or irrigated, agricultural crops and managed vegetation in urban areas use large quantities of water. Compost use as a soil amendment can support more efficient water use and less frequent watering, improving water conservation. Compost can hold up to five times its weight in water (Faucette, 2012a). It reduces water loss through surface runoff by improving the infiltration and water-holding capacity of soils (Brown & Cotton, 2011; Chapman et al., 2022; Kranz et al., 2022; Kranz et al., 2020). As a mulch, compost helps to retain water in the soil by reducing evaporation (Rynk, Cooperband, et al., 2022; Stoffella et al., 2016). Furthermore, with improved soil structure, roots can penetrate soils and access water more easily, enabling plants to better withstand drought conditions (Rynk, Cooperband, et al., 2022).

Compost can potentially reduce irrigation water use in row crops (Brown et al., 2008), orchards (Ozores-Hampton et al., 2022), gardens (Alexander, 2020b), turfgrass (Hill, 2021), and landscaping (Alexander, 2020d). Although a higher water demand by vegetation could occur due to increased productivity from compost use, irrigation requirements may not necessarily increase. This is because compost improves water infiltration and storage within the soil, increasing water availability to plants. For example, in the city of Devens, MA, compost use improved the growth of turfgrass on the city's 44-acre soccer field complex and also reduced irrigation requirements from roughly 68,000 gallons $ac^{-1}$ $yr^{-1}$ to 11,000 gallons $ac^{-1}$ $yr^{-1}$, an 83% decrease (Hill, 2021).

Compost use may also facilitate groundwater conservation. By increasing water infiltration into soils, compost use helps increase the potential amount of water available to percolate through the soil (Faucette, 2009; Gould, 2015; Magdoff & Van Es, 2021). Because compost also increases soil water-holding capacity, it may concurrently increase water availability to plants while increasing groundwater recharge. This can be important in urban areas with extensive impervious surfaces that prevent the downward movement of water into soils. For example, compost used in green infrastructure (GI) (e.g., rain gardens, bioswales and constructed wetlands) may offset reductions in groundwater recharge associated with impervious surfaces (Lorenz & Lal, 2012).

Reduced energy use is a potential co-benefit of water resource conservation associated with compost use. A large amount of energy is required to supply both potable and non-potable water and treat wastewater. For example, it has been estimated that in the State of California, supplying drinking water and treating wastewater (which may include stormwater in some areas) accounts for 19% of total energy use (Schultze-Allen, 2010). Much of the potable water supply in urban areas is used to water vegetation in residential areas, commercial/recreational areas and public parks. Energy is also required to supply non-potable water for irrigated agriculture. Compost use reduces irrigation requirements and stormwater runoff, thereby saving energy and the costs associated with the supply and treatment of water and the management of wastewater. The water conservation benefits of compost use in agriculture, landscaping and horticulture are discussed further in Sections 5 and 6.

# 3.2 Water Quality

Compost has filtering capabilities that reduce pollutants in surface runoff as well as water draining through soils (Faucette, Cardoso-Gendreau, et al., 2009; Faucette et al., 2013; Faucette, Governo, et al., 2009; Rynk, Cooperband, et al., 2022). Improvements in soil health associated with compost use can also decrease runoff and soil erosion (Faucette, 2009; Gould, 2015), which can reduce sediment transport to aquatic ecosystems. Compost use can, therefore, play a role in watershed conservation efforts by helping to protect the quality of surface water and groundwater (Owen et al., 2020, 2021).

Conventional inorganic fertilizers (containing high concentrations of mineral (inorganic) N and P) are widely used in agriculture, horticulture and landscape management (e.g., residential/municipal/commercial lawns and landscaping, turfgrass in parks, recreational fields, golf courses). Nutrient (N and P) runoff from excess use of inorganic fertilizers contributes to the eutrophication of waterbodies, drinking water toxicity, algal blooms, and fish kills (EPA, 2021d). Compost used as a replacement for conventional inorganic fertilizers can reduce the amount of nutrients lost through surface runoff and leaching to groundwater (Adelman & Kney, 2010). There are two mechanisms through which compost use can reduce nutrient loss from soils. First, nutrients in compost are only slowly available to plants (Adelman & Kney, 2010). Using compost instead of inorganic fertilizers greatly reduces the potential for a flush of nutrients moving through the soil into surface or groundwater. Second, as compost helps soil infiltrate water, the potential for runoff and soil erosion, also associated with nutrient movement, is reduced (Archuletta & Faucette, 2014; Faucette, 2007). Additionally, compost-amended soils may facilitate the biodegradation of pesticides, thereby reducing the amount leached into groundwater (Alferez, 2021). Protecting groundwater benefits drinking water supplies, streams and other aquatic ecosystems with groundwater connections.

Using compost in best management practices (BMPs) can be an effective tool for managing runoff and improving water quality (Bell & Platt, 2014). Compost can also be used to filter pollutants from urban stormwater. For example, compost filter socks effectively trap sediment, nutrients and toxins (Faucette, Cardoso-Gendreau, et al., 2009; Faucette, Governo, et al., 2009; Faucette et al., 2008). Additionally, compost has been found to be effective at removing *E. coli* and *Enterococcus* bacteria from stormwater runoff (Faucette et al., 2013). Sections 5 through 9 further describe how compost use can help protect water quality across multiple sectors.

# 4. Climate Benefits

Climate change is leading to more frequent and severe weather events (such as heavy precipitation events and prolonged heat waves and drought), as well as changes to ecosystems and biodiversity across many parts of the United States (IPCC, 2022; USGCRP, 2018). Impacts include increased air temperature, altered precipitation, reduced ice cover and snowpack, sea level rise, and an increased risk of wildfires and hurricanes (Dupigny-Giroux et al., 2018; Wuebbles, 2017).

Efforts to address and respond to climate change focus on mitigating greenhouse gas (GHG) emissions (climate mitigation), adapting to the potential effects (climate adaptation), and building resilience to cope with and recover from altered conditions (climate resilience) (EPA, 2021a; Grade et al., 2023). Compost use reduces GHG emissions by diverting organic materials from landfills (Brown, 2016), sequestering C in the soil (Brown, Miltner, et al., 2012), reducing emissions from agricultural practices (Walling & Vaneeckhaute, 2020), and replacing C-intensive products like synthesized N fertilizer and peat (Levis & Barlaz, 2011; Morris et al., 2017; Saer et al., 2013). Compost use can also support climate adaptation and resilience; for example, it can improve drought resilience (Winfield, 2020), reduce runoff that contributes to flooding during severe storm events (Faucette, 2009, 2012a; Kranz et al., 2022), and support tree growth to reduce urban heat island effects (Faucette, 2009). The climate benefits of compost production and use are described in Figure 4.

Establishing composting programs and increasing compost use in different sectors can help states, cities and communities work toward climate change goals as well as goals for waste reduction, landfill diversion, soil health, local food systems and economic development. Compost programs and compost use are considered relatively simple, effective and scalable ways to help reduce C in the atmosphere and increase climate resilience across communities. This section summarizes how composting and compost use can support mitigation, adaptation and resiliency. The benefits associated with compost use within different sectors as a method to address climate change are discussed further in Sections 5 through 9.

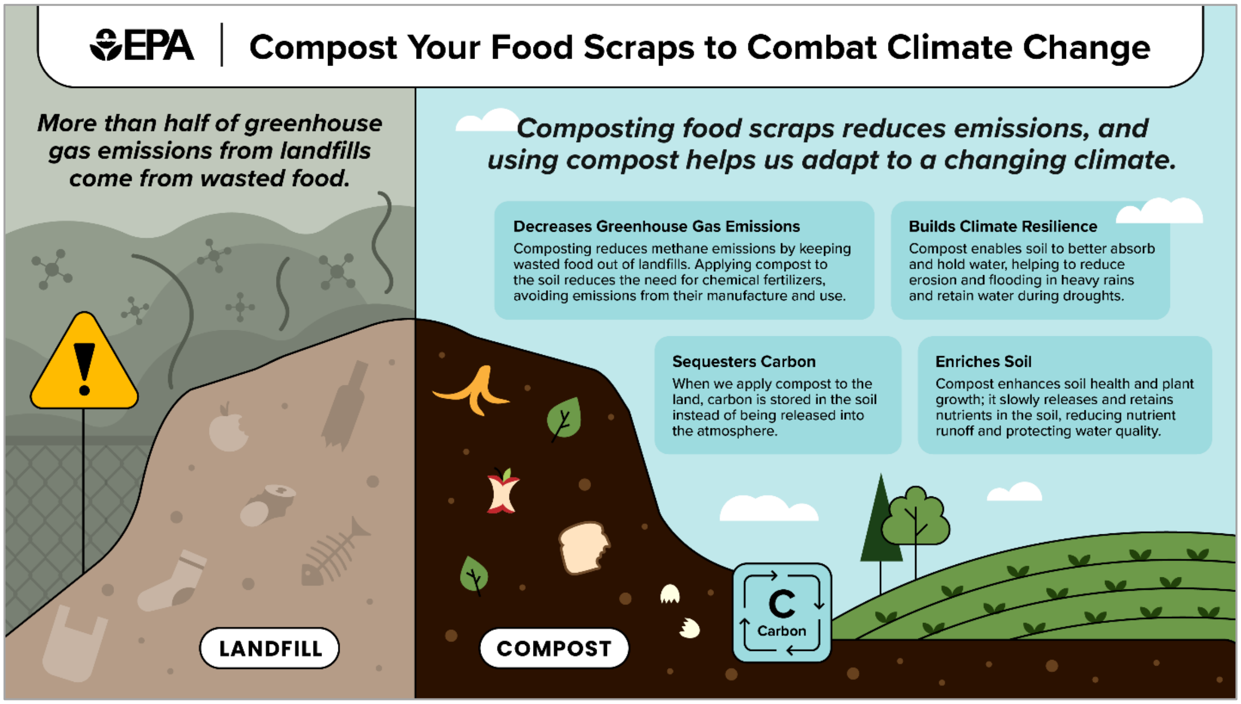


*Figure 4. Climate benefits associated with compost production and use. Source: EPA (2024c).*

# 4.1 Greenhouse Gas Emissions

GHGs, including $CO_2$, methane ($CH_4$), nitrous oxide ($N_2O$), and some synthetic chemicals (such as chlorofluorocarbons), trap some of the earth's outgoing energy, thus retaining heat in the atmosphere (EPA, 2024a). Human activities are increasing the concentrations of GHGs in the atmosphere and are the primary cause of the estimated one-degree Celsius increase in average global air surface temperature observed over the past 115 years (Wuebbles, 2017). In 2019, the total estimated global C emissions from all human activities was 9.55 billion tons (35 billion tons $CO_2$) (MIT, 2023). Mitigating climate change requires a reduction in the flow of heat-trapping GHGs into the atmosphere (Candanosa, 2021; UCAR, 2020), including those sourced from organic materials.

Diversion of organic materials from landfills to composting facilities is an effective strategy for reducing GHG emissions of $CO_2$, $CH_4$ and $N_2O$ (Brown et al., 2017; Rynk, Cooperband, et al., 2022). $CH_4$ is 28 times more potent than $CO_2$ (EPA, 2024b). In 2021, MSW landfills accounted for approximately 17% of human-related $CH_4$ emissions in the United States, making landfills the third-largest source of such emissions in the country (EPA, 2023e). $CH_4$ avoidance from landfill diversion can equate to substantial GHG emission reductions (Brown et al., 2017); the aerobic decomposition processes utilized in compost manufacturing result in less $CH_4$ production than would occur during decomposition under anaerobic conditions within a landfill.

Globally, food loss and waste represent 8% of anthropogenic GHG emissions (EPA, 2021d). In the United States, food waste is a priority for diversion from landfills for the following reasons:

1) A vast amount of food waste can be diverted from landfills to composting facilities; EPA estimates that in 2019, under 4 million tons of food waste out of 106 million tons was diverted from landfills to composting facilities (EPA, 2023a).
2) 61% of $CH_4$ generated from landfilled food waste is not captured by landfill gas collection systems and is released into the atmosphere (EPA, 2023g). Food waste decays more quickly in landfills than many other compostable materials and emits fugitive $CH_4$ before gas capture systems are installed in landfills (EPA, 2023d; Levis & Barlaz, 2011; Levis et al., 2010). Eleazer (1997) found that food waste produces roughly two to ten times more $CH_4$ than an equivalent amount of yard trimmings (grass, leaves and branches), cardboard, or paper in laboratory-scale landfills.
3) 58% of fugitive $CH_4$ emissions from MSW landfills is from landfilled food waste (EPA, 2023g). Food waste produces more GHG emissions than an equivalent amount of other landfilled compostable materials (Eleazer, 1997).
4) Diverting food waste from landfills to produce compost for use in various sectors results in a net C sink when considering GHG emissions and C sequestration (Brown, 2016; Morris et al., 2017).

Studies have reported substantial GHG reductions occur when food waste is diverted from landfills, composted, and applied to soils. A study from Kean University in New Jersey estimated that the University's food waste composting system resulted in 31% less overall cumulative GHG emissions when compared to landfilling (Mu et al., 2017). The study also suggested that compost use can result in lower fossil fuel consumption, surface water eutrophication and smog formation, and improved human respiratory health. This estimate was based on the modeling of fugitive emissions from landfills, avoided $CO_2$ from landfill gas capture, and soil C sequestration.

Brown (2016) estimated that composting food waste and adding it to soils would reduce net $CO_2e$ emissions (i.e., from $CO_2$, $CH_4$ and $N_2O$) by a factor of approximately 4.6 and increase the amount of C sequestration by a factor of 3.5. This equates to a net reduction of 1,918 lbs $CO_2e$ emissions per ton of food waste. The relative balance was +1499 lbs $CO_2e$ emissions per ton when landfilled versus -419 lbs $CO_2e$ per ton when composted and land applied. Given the low volume of organic materials (and only a small fraction of food waste) currently diverted to composting operations in the United States (EPA, 2020a), diversion from landfills may offer a scalable solution to reduce GHG emissions.

Estimates using data from 28 life cycle studies indicated that the manufacture and use of compost derived from food waste would result in net GHG emissions of -0.22 $CO_2e$/lbs per ton versus +0.84 lbs $CO_2e$/lbs per ton for landfill to gas energy production (i.e., approximately 440 pounds of $CO_2e$ reduction per ton of food waste) (Morris et al., 2017). This estimate considered GHG emissions associated with collection/transport, compost production, soil C sequestration, and substitution of food waste compost for fertilizer and peat used in agriculture. However, the current state of the science suggests a need for comprehensive life cycle analysis to evaluate the broader net change in atmospheric C emissions associated with compost production and compost use (Paustian et al., 2016). This is because the ultimate amount of C sequestered depends not only on the net emissions associated with the production and use of compost but also on the emissions that are associated with the practices that are being replaced (e.g., landfilling, incineration, land application of non-composted organic materials and transportation). For example, transporting compost long distances before it is applied to soils may offset the amount of C sequestered in soils, resulting in a net increase in $CO_2$ emissions.

# 4.2 Carbon Sequestration

Soils hold roughly 80% of the world's terrestrial C, and the amount of C in soils is roughly three times as much as in the atmosphere (Ontl & Schulte, 2012). Soils currently display a large C deficit globally due to centuries of soil disturbance associated with development, such as deforestation, soil cultivation, and building and road construction (Lal, 2004b; Lal et al., 2015). For example, since the beginning of agriculture roughly 12,000 years ago, an estimated 121 billion tons of C have been lost from soils used for agriculture, resulting in an ongoing soil C deficit (Sanderman et al., 2017).

Soil carbon sequestration is the avoidance of $CO_2$ emissions to the atmosphere by adding carbon to soils, resulting in a long-term net increase in C within the stable C pool. The mean residence time of carbon within soils is on the order of decades to millennia (USDA, 2024). There is a lack of consensus in the scientific literature regarding the span of time that C must be stored in soil to be considered "sequestered" (Dynarski et al., 2020). The IPCC defines C sequestration as the process of storing carbon in a carbon pool (such as soil), resulting in a net annual increase (IPCC, 2006). Recent research shows the persistence of SOC depends on complex and dynamic interactions between SOM and the soil environment (microbial activity, soil mineralogy, soil particle size, aggregation, etc.) (Dynarski et al., 2020). When organic materials, such as compost, are applied to soils, they augment levels of SOC (Levavasseur et al., 2020; Paustian et al., 2016; Peltre et al., 2012). This happens directly, through the addition of organic matter, and indirectly through plant growth that contributes to SOC through roots and residues. SOC levels constantly fluctuate as C is added and released (i.e., mineralized); carbon sequestration occurs when the rate of carbon added to soil is greater than the rate of carbon released to the atmosphere from soil (e.g., as $CO_2$ or $CH_4$), and a fraction of that SOC is protected from microbial degradation within the soil matrix.

Compost use can increase carbon sequestration in the soils of cropland, rangeland, parks, roadsides, residential yards, disturbed lands (e.g., abandoned surface mines) and contaminated sites (e.g., brownfields) (Brown, Miltner, et al., 2012; EPA, 2011; Ward et al., 2021; Yu et al., 2012). The amount of carbon that can be sequestered in soils depends on a variety of factors, including the organic matter content of the compost (or other amendment) being added, the soil type, soil microbial communities, climate, and management practices (Levavasseur et al., 2020). The capacity of soil to store C varies by soil type, with coarser-grained soils reaching capacity (called "C saturation") with lower SOM levels (and fewer C inputs) than finer-grained soils (Li & Evanylo, 2013). Soils of any type with depleted levels of organic matter generally have more potential to store carbon (Brown et al., 2011).

During composting, a portion of the organic carbon in feedstocks is stabilized, making it resistant to further decay (Francou et al., 2005). EPA has estimated that composting organic materials stabilizes up to 20 percent of the organic carbon that would otherwise be lost to the atmosphere (as $CO_2$ or $CH_4$) or lost through leaching (as dissolved C) if the materials were left to naturally decay (EPA, 2023b). Due to this stabilization, a larger fraction of carbon from compost appears to persist in soils longer compared to carbon from non-composted materials when C inputs from both amendments are comparable (Busby et al., 2007; Nest et al., 2014; Powlson et al., 2012). Not all carbon derived from a compost addition is sequestered, but compost use increases carbon sequestration by driving a long-term carbon accumulation rate that exceeds carbon emissions from soils. It is difficult to compare the net soil carbon sequestration potential of a compost to a non-composted material because some carbon in the raw organic material is lost as $CO_2$ or $CH_4$ during the composting process (Nordahl et al., 2023). However, $CO_2$ and $CH_4$ emissions that occur during composting are considered to be biogenic rather than GHG emissions because the compost feedstocks are part of the short-term carbon cycle (EPA, 2023b). Additionally, some carbon is lost from both compost and raw materials following applications to soils (Busby et al., 2007).

Sequestration potential can be estimated through modeling (e.g., Levavasseur et al. (2020); Peltre et al. (2012)), but more long-term observational studies are needed to better understand the process and longevity of soil carbon sequestration associated with compost application. The longevity of carbon sequestration is reported to increase with ongoing (e.g., annual) applications that build up SOC reserves (Brown & Beecher, 2019; Brown, Miltner, et al., 2012; Dynarski et al., 2020). Once the upper limits of soil carbon stocks approach (i.e., C saturation), SOC increase rates slow and then flatten, with SOC levels showing little or no increase even with the continued addition of C amendments (Li & Evanylo, 2013). Some modeling studies suggest that the rate of carbon sequestration decreases over time despite repeated ongoing applications (Peltre et al., 2012). Levavasseur et al. (2020) and Peltre et al. (2012) report that applications of various types of compost at multiple cropland sites in France increased carbon sequestration by 0 t C $ac^{-1}$ to 11 t C $ac^{-1}$ over time periods ranging from roughly 12 to 20 years. Based on measured rates of soil C, the carbon sequestration rate associated with compost applications (at a rate of 0.89 t C $ac^{-1}$ every two years) was estimated to range from a low rate of 0.08 t $ac^{-1}$ $yr^{-1}$ at sites with a Mediterranean climate to a high rate of 0.30 t C ac $yr^{-1}$ at sites with a Nordic climate; this equates to a soil carbon sequestration rate of 0.18 to 0.67 tons C per ton of C applied (Peltre et al., 2012).

Modeling suggests that C sequestered from a single compost application may persist for a minimum of 10–30 years (EPA, 2011; Paustian et al., 2016), and there is also evidence that C derived from organic amendments may persist for more than a century (Dynarski et al., 2020). Brown et al. (2008) empirically estimated that 8.2% of the C added to a soil from a compost application would persist for longer than 100 years. Based on a literature review, Martínez-Blanco et al. (2013) report that an estimated 2% to 16% of the C derived from a compost application would persist in a soil on a timescale of 10 to 100 years; however, the authors provided a caveat that estimates should be performed on a case-specific basis because differing environmental and management factors can result in large variability in C sequestration potential. Compton and Boone (2000) found that historic cropland soils in Massachusetts that received manure additions in the mid-1800s had 56% more C in the top 9 inches than soils that did not receive manure additions, which may also provide an indication of how long C may persist in soils following additions of other types of organic matter, such as compost.

Increases in above and below-ground plant productivity resulting from compost applications can also contribute to C sequestration (Adeleke et al., 2021; Brown et al., 2011; Dynarski et al., 2020) as well as increased storage of C in the tissues of long-lived plants (i.e., trees) (Brown, Miltner, et al., 2012; Scharenbroch, 2009). Compost applications can initiate a positive feedback loop where increased plant growth leads to more C inputs to soils (e.g., through plant litter, root exudates); this further increases soil C sequestration and plant productivity (DeLonge et al., 2013; Paustian et al., 2016), including at deeper soil depths where sequestration on the scale of hundreds to thousands of years is more likely (Dynarski et al., 2020).

## 4.3 Climate Resilience and Adaptation

In both the natural and built environments, improvements in soil health associated with compost use support adaption and increase resilience to climate change impacts such as flooding, drought and heat waves (Winfield, 2020). Increased SOC improves soil productivity and water conservation, which increases overall ecosystem resilience to altered climate conditions (Brown et al., 2017; IPCC, 2022; Winfield, 2020). Compost holds up to five times its weight in water (Faucette, 2012a) and increases both soil water-holding capacity and water infiltration when incorporated into soil (Kranz et al., 2020; Stoffella et al., 2016). Improvements in water infiltration and soil water retention boost plant productivity and help to reduce surface runoff, soil erosion and the risk of flooding (Chapman et al., 2022). As a mulch, compost reduces evaporation and the potential for drought conditions (Rynk, Cooperband, et al., 2022; Stoffella et al., 2016), which may increase water availability for plants during dry periods.

In urban environments, compost use in GI increases its resilience to climate-related changes in stormwater runoff (Faucette, 2012a). It also supports vegetation that provides shade and evaporative heat transfer, especially around buildings and paved surfaces, thereby helping to reduce urban heat island effects (Chapman et al., 2022; Faucette, 2009). In rural areas, compost use can support water conservation, biodiversity protection and ecosystem functions, helping to build resilience to changing climate conditions (Gonçalves et al., 2019; Habteweld et al., 2018; Magdoff & Van Es, 2021; Ryals & Silver, 2013; Schultze-Allen, 2010; Winfield, 2020).

# 5. Agriculture

Agricultural producers have long recognized the value of organic material as a soil amendment, with the use of composted manures and other agricultural residues dating back to the beginnings of agriculture (Magdoff & Van Es, 2021; Ozores-Hampton, 2019). Compost use improves soil health for agriculture through increased SOC, enhanced fertility, drought resilience, reduced plant disease, improved crop yield/quality, reduced soil erosion and reduced irrigation needs (Brown et al., 2017; Clark & Douds, 2021; Rynk, Cooperband, et al., 2022). Furthermore, it can be a substitute for conventional fertilizers (i.e., raw manure and inorganic fertilizer) and synthetic pesticides, which leads to co-benefits for water quality protection, GHG emissions reductions and C sequestration (Adelman & Kney, 2010; Brown et al., 2008; Martínez-Blanco et al., 2013; Morris et al., 2014; Ozores-Hampton, 2021a). A summary of the main benefits of compost use for agriculture is provided in Figure 5.

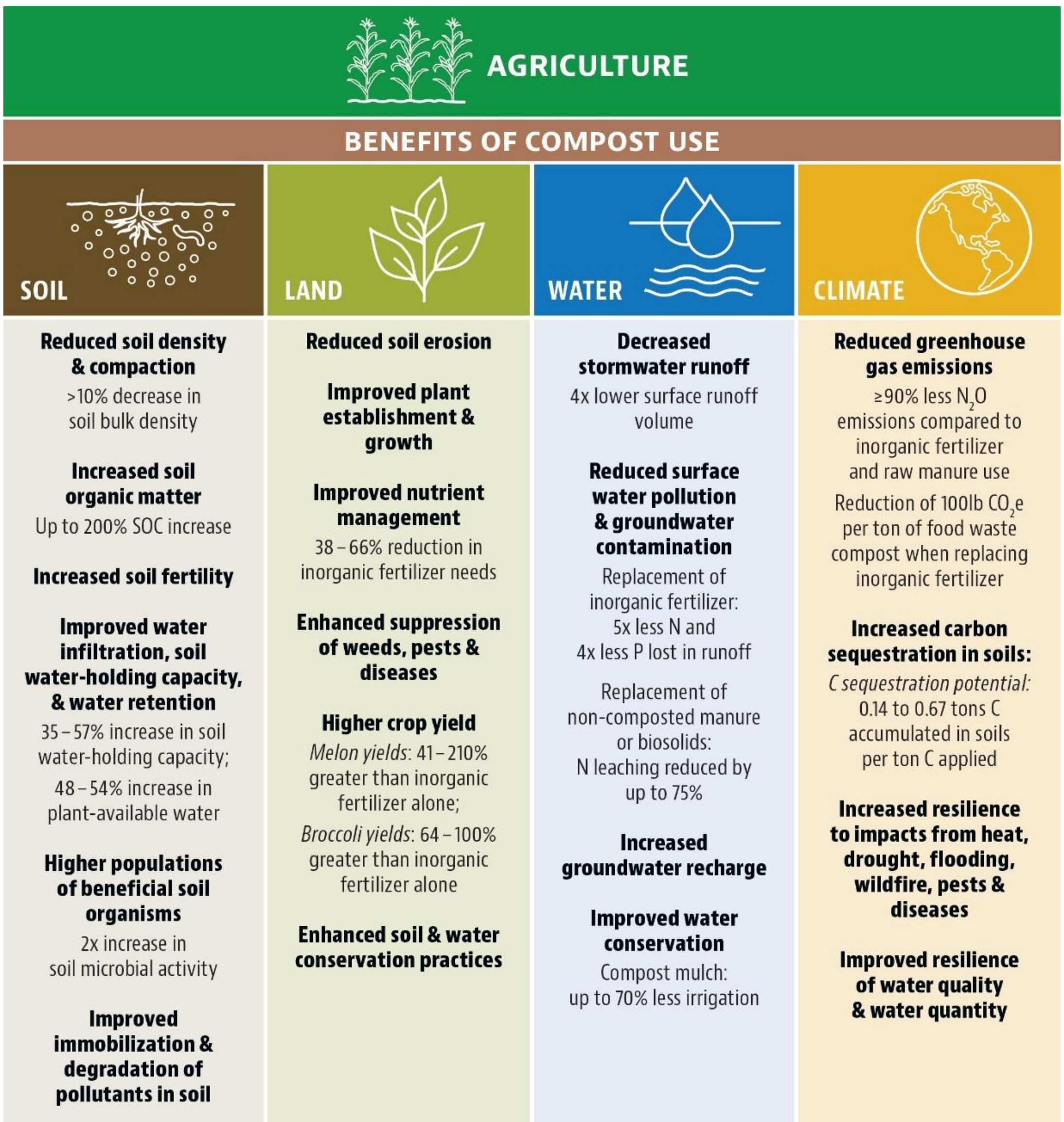


*Figure 5. Summary of key benefits for agriculture from compost use. Sources – Soil: Brown and Cotton (2011); Brown et al. (2008); Evanylo et al. (2008); Maynard (2000b); Ozores-Hampton (2019); Ozores-Hampton (2021c); Rath et al. (2022); Tautges et al. (2019); White*

*et al. (2020); Wilson et al. (2018) Brown et al. (2011); Land: Alexander (2020e); Gilbert et al. (2020b); Morris et al. (2017); Nicholson et al. (2017); Water: Evanylo et al. (2008); Nicholson et al. (2017); Oladeji et al. (2019); Ozores-Hampton et al. (2022); Climate: Gilbert et al. (2020b); Morris et al. (2017); Nicholson et al. (2017); Peltre et al. (2012); Walling and Vaneeckhaute (2020).*

# 5.1 Fertilizer Replacement

Inorganic (e.g., synthetic N, mined P) fertilizers and organic (e.g., compost, livestock manure) fertilizers increase plant growth by adding essential plant nutrients. The three major nutrients in inorganic fertilizer are N, P and K. The type and amount of fertilizer applied to each crop generally varies based on local soil conditions, land management practices, individual crop needs and, in some cases, government regulations. Compost can act as a substitute for conventional fertilizers used for crop production (Beck et al., 2016; Kang et al., 2022; Sullivan et al., 2002), particularly for organic cropping systems in which mineral N fertilizers are not used. Using compost as a substitute for mineral (inorganic) P fertilizer may become increasingly important as the global supply of mined phosphate is estimated to fall short of global demand around 2040, resulting in major implications for food security (Nedelciu et al., 2020).

Substitution of compost for conventional fertilizers also improves nutrient management and reduces GHG emissions. Studies have found an association between compost use and reductions in nutrient losses from agricultural fields through surface runoff or leaching through soils (Evanylo et al., 2008; Nicholson et al., 2017; Oladeji et al., 2019). Compost has been found to directly reduce agricultural GHG emissions from soils in comparison to applications of mineral N fertilizer and livestock manure (Nicholson et al., 2017; Walling & Vaneeckhaute, 2020). Compost may also indirectly reduce GHG emissions through improvements to soil health that lead to reduced fossil fuel usage (Alexander, 2020e; Gilbert et al., 2020a). The following subsections discuss the benefits of using compost as a replacement for conventional fertilizers.

## 5.1.1 Inorganic and Organic Fertilizer

Compost is not usually relied upon as the sole nutrient source for the production of annual crops (Ozores-Hampton et al., 2022). Compost typically contains a substantially lower content of N, P and K than conventional inorganic fertilizers and is, therefore, not considered a true “fertilizer” (Gilbert et al., 2020a). However, the difference in nutrient concentrations can be offset through compost application at higher rates than inorganic fertilizers (on the order of tons per acre rather than pounds per acre as with inorganic fertilizer).

Several studies report the benefits of compost use as a fertilizer. For example, Brown et al. (2011) found that applying compost to cherry orchards and hop fields in Washington State not only reduced the need for inorganic fertilizers, but also improved soil health by increasing SOC levels and improving the water-holding capacity of soils. McCray et al. (2017) observed that in southern Florida, compost made with a mixture of yard trimmings and biosolids lowered the annual N fertilizer requirement for sugarcane by an average of 38%. In another example, annual amendments of a sandy soil in Connecticut with leaf compost reduced fertilizer needs for onion crops by one-third to two-thirds the normal rate (Maynard & Hill, 2000). Some studies indicate that compost may reduce inorganic fertilizer applications by up to 50% in a variety of crops while maintaining crop yields, reducing irrigation requirements and reducing tillage requirements (Alexander, 2020b, 2020e). Another advantage of using compost as a substitute for inorganic fertilizer is that since compost is derived from organic matter it typically contains all of the nutrients essential for plant growth.

In contrast to inorganic fertilizers, nutrient availability from compost occurs over a period of years as the nutrients are slowly released into the soil (Sullivan et al., 2003). Yet periodic applications of compost tend to build up soil nutrient reserves (Abbey et al., 2022; McCray et al., 2017; Ozores-Hampton, 2019). One challenge to substituting compost for conventional fertilizer is that the cost of compost applications targeted to meet the N demands of annual crops may not be economical (Ozores-Hampton, 2021a). Additionally, compost application rates targeted to meet the N demand of annual crops may result in an oversupply of P (Moinard et al., 2021; van der Wiel et al., 2021). For this reason, Ozores-Hampton et al. (2022) suggested using compost as a base fertilizer, mainly targeting P and K supply.

## 5.1.2 Nutrient Losses

Compost use can reduce nutrient losses to water (through leaching and runoff) when substituted for application of raw manures and inorganic fertilizer (Faucette et al., 2005; Ozores-Hampton, 2021c; Stoffella et al., 2014; Tyler, 2021). This improves agricultural nutrient management for crop production while helping protect waterbodies from eutrophication (Bell & Platt, 2014; Eghball, 2003). N in most conventional inorganic fertilizers consists of a water-soluble mineral form to facilitate quicker uptake by plants. Furthermore, crops may only utilize 50% or less of the N derived from inorganic fertilizer applications, creating a substantial risk of N being transported in surface runoff to waterbodies or being leached into groundwater Govindasamy et al. (2023); (Ladha et al., 2005). Most of the N in compost is in a more stable organic form that is gradually released into the soil solution over time (Oladeji et al., 2019). Similarly, composted manures have a higher proportion of stable organic compounds in comparison to raw manure, providing a slower release of N (Brown & Goldstein, 2016; Ozores-Hampton et al., 2022). As with N, P in inorganic fertilizers is primarily in a water-soluble mineral form. In contrast, most of the P in compost is in an organic form that is slowly released over time through biological soil processes. Because P tends to bind to soil particles and organic matter, most P loss from soils is associated with soil erosion induced by surface runoff (Magdoff & Van Es, 2021). Following compost applications, the P loss through soil erosion is reduced by improvements in soil health, such as increases in soil aggregate stability, water infiltration and soil water-holding capacity (Stoffella et al., 2014). Stoffella et al. (2014) report that compost has been used to partially substitute for chemical P fertilizers on sandy agricultural soils to reduce the amount of P that leaches into groundwater or is transferred off-site by surface water runoff.

Improved soil health following compost application can also help reduce N loss. Evanylo et al. (2008) found that poultry litter/yard trimmings compost applications designed to meet crop N demand were associated with a significantly lower runoff volume and lower N loads in runoff relative to applications of non-composted poultry litter or mineral N fertilizer. Multiple studies have investigated nutrient leaching from compost (Heyman et al., 2019; Hurley et al., 2017; Nicholson et al., 2017; Oladeji et al., 2019; Owen et al., 2020, 2021). Heyman et al. (2019) found that $NO_3$ leaching from soils was weakly correlated to the $NO_3$ content of compost applied. Oladeji et al. (2019) compared N leaching potential in clay and sandy loam soils from composted versus non-composted biosolids to evaluate if composting stabilizes the N in biosolids. N leaching from composted biosolids (6% to 11% of added organic N leached) during the two-year study period was less than from non-composted biosolids (14% to 21% of added organic N leached). Nicholson et al. (2017) compared N losses to the environment from agricultural applications of yard trimming/food waste compost, solid livestock (cattle or swine) manure and livestock manure slurry at three sites in England and Wales. At one site, N leaching was evaluated following fall applications of compost and manures, with the amount of N applied from compost being equal to or greater than from solid manure or slurry. The amount of N leached through the soil profile was significantly lower for compost than for livestock slurry but no different relative to solid manure. Less than 5% of the total amount of N applied from compost or solid manure was leached, while roughly 14%–20% of the N applied from broadcast swine manure slurry was leached.

Although most P loss is through surface runoff, leaching of P from soils can occur (Pan et al., 2023); however, it is important to note that P is much less susceptible to leaching than N (Evanylo et al., 2008). P leaching is influenced by factors including the amount of P in the soil, the capacity of the soil minerals to adsorb P, the rate of vertical movement of water through the soil, the depth to groundwater, and tillage practices (Djodjic et al., 2004; Pan et al., 2023). Research shows mixed results on P leaching when compost is used as a replacement for inorganic fertilizers and raw manure. Some evidence indicates that P leaching from compost is lower than from raw animal manures (Nest et al., 2016; Nest et al., 2014). McDowell and Sharpley (2004) found that P leaching was greater from dairy manure compost than from mineral P fertilizer. Another study found no difference in P leaching between compost and mineral P fertilizer (Nest et al., 2014). Heyman et al. (2019) reported that compost with a higher content of plant-available P was correlated with greater leaching of soluble reactive P. Manure-based composts were associated with the highest rates of P leaching, followed by compost from yard trimmings, and then food waste-based compost.

Overall, research indicates that N and P losses from compost are often less than those from inorganic fertilizers and non-composted organic materials (such as biosolids and manure) (Hill, 2021; McDowell & Sharpley, 2004; Oladeji et al., 2019; Shrestha et al., 2020). Site-specific factors that determine whether compost use will reduce N and P losses relative to raw manure and inorganic fertilizers include compost N and P content, application rates (Evanylo et al., 2008; Shrestha et al., 2020), soil hydrologic conditions (Hurley et al., 2017; McDowell & Sharpley, 2004), and lag times between compost applications and vegetation growth (Evanylo et al., 2008; Faucette et al., 2005). Substantial leaching of N and P can occur when compost is saturated for prolonged periods of time (Hurley et al., 2017) or when large volumes of water drain through large volumes of recently applied, non-vegetated compost (Owen et al., 2020, 2021). Compost application rates to meet crop N demand may also lead to an oversupply of P (Eghball, 2003; Evanylo et al., 2008; Pan et al., 2023). These findings highlight the importance of testing soil before fertilization to assess N and P levels and develop appropriate fertilization strategies. (The potential for N and P losses as it pertains to urban stormwater is discussed in Section 7)

**Key Advantages When Compost Replaces Conventional Materials in Agriculture**

Replacement of inorganic fertilizer:

- Improved soil health[1]
- Improved crop productivity
- Increased carbon sequestration
- Improved water conservation[2]
- Reduced soil erosion
- Reduced water pollution (N, P)
- Reduced GHG emissions

Synthetic pesticide replacement:

- Improved soil health[1]
- Reduced environmental pollution
- Reduced pollinator mortality

Plastic mulch replacement:

- Improved soil health[1]
- Reduced fertilizer requirements
- Pest and disease suppression
- Reduced plastic waste

[1]See Section 2 on Soil Health Benefits
[2]See Section 3 on Water Resource Benefits

### 5.1.3 GHG Emissions

When inorganic or organic fertilizers are applied to soils, the biological activity of microorganisms produces GHG emissions (e.g., $CO_2$, $N_2O$, $CH_4$). Substituting compost for inorganic fertilizer (such as N fertilizer made from natural gas) or raw manure may reduce GHG emissions from soils (Brown et al., 2009; Brown et al., 2008; Kim et al., 2014; Walling & Vaneeckhaute, 2020). Evaluating GHG emissions from inorganic and organic fertilizers is an ongoing area of research as the processes and causes of variability in net emissions are not well understood (Lazcano et al., 2021; Walling & Vaneeckhaute, 2020). For example, Kim et al. (2014) found that applications of composted manure to rice paddies can result in a roughly 50% reduction in $CH_4$ emissions compared to air-dried manure, but other studies suggest that compost use may increase $CH_4$ emissions from soils in comparison to inorganic fertilizers due to the addition of C (Walling & Vaneeckhaute, 2020). Overall, however, $N_2O$ emissions are of greater significance than $CH_4$ emissions because $CH_4$ tends to be a relatively minor component of total GHG emissions from agricultural soils (Walling & Vaneeckhaute, 2020).

Atmospheric emissions of N often occur after the application of manures and mineral N fertilizer to agricultural lands. Nicholson et al. (2017) reported compost applications can reduce $N_2O$ emissions to air compared to manure slurry. Ammonia ($NH_3$) emissions from compost were lower than from manure slurry but were similar to solid manure. Relative to the total amount of N applied, respective $NH_3$ and $N_2O$ losses to air were 3.3% and < 0.01% from compost, 4.5% and 0.28% from solid livestock manure, and 24%–31% and 0.35%–0.55% for two livestock slurry application methods. Walling and Vaneeckhaute (2020) reported that compost application to soils tends to result in lower $N_2O$ emissions factors (range: 0.11%–1.55% of applied N) in comparison to mineral N fertilizers (range: 0.03%–12.9% of applied N), raw manure (range: 0.05%–13.9% of applied N), and digestates (range: 0–5.1% of applied N). The primary factor leading to reduced atmospheric emissions of N associated with compost use is that compost typically has a much lower content of mineral N ($NH_3$ and $NO_3$) relative to mineral N fertilizers and manure slurries (Nicholson et al., 2017).

Substantial GHG emissions are also associated with soil tillage and irrigation (Lal, 2004a)) and compost use can indirectly contribute to reductions in these emissions. When soil compaction is alleviated through compost use, less fuel may be needed to prepare the seedbed for crops (Gilbert et al., 2020a). For example, improved soil structure in fields that are tilled may reduce tractor fuel requirements for maintaining soil tilth (Alexander, 2020e). By improving water retention in soils, compost applications can also reduce GHG emissions associated with fossil fuels used to generate energy for operating irrigation pumps. Compost can also contribute to fossil fuel reductions when it replaces the use of plastic mulch. These reductions are important; however, studies examining the indirect effects of compost use on GHG emissions are lacking.

## 5.2 Carbon Sequestration

Clearing lands for agriculture and ongoing soil tillage has resulted in the release of an estimated 121 billion tons of C into the atmosphere since the advent of agriculture roughly 12,000 years ago (Sanderman et al., 2017). This loss of C has occurred at a faster rate than it is being replenished, resulting in a global soil C deficit (Lal, 2004b; Lal et al., 2015) with far-ranging consequences for soil health, climate stability, water resources, ecosystem resilience and human civilization. Additional discussion of C sequestration can be found in Section 4.

Studies suggest that compost use on agricultural soils facilitates C sequestration, sometimes after only a single application (Gonçalves et al., 2019; Habteweld et al., 2018; Magdoff & Van Es, 2021; Ryals & Silver, 2013; Schultze-Allen, 2010; Winfield, 2020). Peltre et al. (2012) estimated carbon sequestration rates from compost applications to European cropland sites (at a rate of 0.89 t C $ac^{-1}$ every two years) to range from a low rate of 0.08 t $ac^{-1}$ $yr^{-1}$ at sites with a Mediterranean climate to a high rate of 0.30 t C ac $yr^{-1}$ at sites with a Nordic climate; this equates to a soil carbon sequestration rate of 0.18 to 0.67 tons C per ton of C applied. A study conducted over a 19-year period in California on a maize-tomato cropping system compared the change in C sequestered under inorganic fertilizer use with no winter cover crops, inorganic fertilizer use with winter cover crops, and poultry manure compost (1.8 $t^{-1}$ $ac^{-1}$ $yr^{-1}$ application rate) with winter cover crops (Tautges et al., 2019). In year 19, the cropping system using compost was associated with a net increase in C sequestration of roughly 10 t $ac^{-1}$ (a 12.6% increase), whereas the other two treatments displayed a net loss in soil C. The study found that the greatest increase in soil C with the compost treatment occurred at a depth of 39–79 inches, which was the deepest layer of soil examined. In another study, Yu et al. (2012) found that eighteen years of compost application to cultivated soils increased C sequestration by 71%–122%, whereas C sequestration in soils with inorganic fertilizers increased by 5.5%–25.5%. C sequestration in the compost treatment was found to be associated with greater stability of C in microaggregate and silt + clay fractions.

Modeling studies have estimated the potential magnitude of C sequestration resulting from compost applications at large scales. One study concluded that C sequestration from a one-time application of composted manure to 5% of California rangelands has the potential to offset roughly 31 million tons of $CO_2$e (DeLonge et al., 2013). Similarly, Silver et al. (2018) estimated that a single one-quarter inch application of compost to 6% of Californian rangelands would sequester an amount of C equal to approximately one-half of the California goal to decrease 16.5–22 million tons of $CO_2$e emissions by 2030 and that the C would be sequestered for up to 30 years. However, these studies do not appear to account for $CO_2$ emissions that would occur in transporting and applying compost to vast areas of rangeland. Additionally, the compost application rate (equivalent to 223 lbs N $ac^{-1}$) in the DeLonge et al. (2013) study is at the upper end of typical N rates applied for annual crops with a high N demand, such as corn; it is unclear whether this application rate would be appropriate or realistic for compost applications to rangeland settings.

## 5.3 Crop Yield and Health

Traditional soil amendments, such as inorganic fertilizer, typically target short-term improvements in a single type of soil property (e.g., nutrient levels, pH) to support crop production. As a result, a reliance on in organic fertilizer and traditional soil amendments to maintain soil fertility does not provide long-term soil health benefits (Brown et al., 2017). In contrast, compost use results in numerous soil health benefits, as described in Section 2 (Brown & Cotton, 2011; Governo et al., 2003; Kranz et al., 2020; Long et al., 2017; Ozores-Hampton, 2021c; Reeve et al., 2012; Rynk, Cooperband, et al., 2022; Wang et al., 2022). These soil health benefits enhance the production of agricultural crops through improvements in plant health and crop yields beyond what is attained with conventional inorganic fertilizers (Governo et al., 2003; Li et al., 2010).

## 5.3.1 Crop Yield

Reeve et al. (2012) estimated that a single application of compost (at 22 t $ac^{-1}$ dry wt.) to dryland wheat plots in Utah in 1995 increased the two-year average yield by 1.0 t $ac^{-1}$ in the two years immediately following application. The increase in wheat yield was observable sixteen years later when the two-year average from plots receiving compost was found to be 0.2 t $ac^{-1}$ greater than yields from control plots. In California, compost use has been found to increase yields of almonds by 10% while decreasing the use of inorganic fertilizers, water and pesticides (Goldstein, 2020a). In an Italian olive grove, compost applications improved vegetative growth and olive production while increasing soil C sequestration (Regni et al., 2017). Ozores-Hampton (2021a) identifies numerous studies that report improved vegetable crop quality and yields resulting from the use of mature, stable compost. However, other studies have noted that using compost and inorganic fertilizers together may increase crop productivity more than using either individually (Ozores-Hampton et al., 2022). Table 4 summarizes the benefits associated with compost use for specific crops and other plant types; the benefits outlined are compared to the use of various conventional practices (e.g., inorganic fertilizers, non-composted manure, no soil amendment).

*Table 4. Examples of benefits to crop production with compost use. Source: adapted from Governo et al. (2003).*

| Benefits | Crops and plants | Reference | Location |
|---|---|---|---|
| • Increased yields | Corn, cotton (seed), peppers, ryegrass | (Granberry et al., 2001; Khalilian et al., 1998; Mamo et al., 2000; Stratton & Rechcigl, 1998) | FL, GA, MN, SC |
| • Increased growth and yield | Broccoli, melon | (Roe & Cornforth, 2000) | FL |
| • Yields equal to fertilizer, manure use | Peppers | (Reider et al., 2000) | PA |
| • Decreased root disease<br>• Increased water uptake efficiency<br>• Increased root mass<br>• Increased nutrient uptake efficiency<br>• Increased yield and fruit size | Citrus tree | (Graham, 1998) | FL |
| • Reduced fertilizer use<br>• Reduced blossom end rot | Tomato | (Maynard, 2000a) | CT |
| • Increased growth | Christmas tree | (Peregrin & Hinesley, 2011) | NC |

## 5.3.2 Crop Health

In addition to inorganic fertilizers, pesticides (including herbicides, insecticides and fungicides) are commonly applied to soils and crops to protect against yield loss and crop damage. Compost use can decrease the incidence of disease, pests and weeds, which can help reduce the use of pesticides (Alexander, 2020b, 2020f; Governo et al., 2003; Larkin, 2022; Rynk, Cooperband, et al., 2022). Consequently, reduced pesticide use can be credited as an environmental co-benefit of compost use (Martínez-Blanco et al., 2013; Ozores-Hampton et al., 2022). Compost use can also reduce the presence of pathogens in soils, resulting in food safety benefits.

### *5.3.2.1 Disease and Pests*

Numerous studies indicate that compost use can support plant health by helping to suppress disease (e.g., root, foliar) and pests in a wide variety of crops (Coker, 2021; Gilbert et al., 2020a; Li et al., 2010; Neher et al., 2022; Winfield, 2020). For example, following compost applications, increased populations of beneficial microorganisms have been associated with the suppression of disease-causing organisms such as pythium and fusarium, as well as pests such as nematodes (Gilbert et al., 2020a; Li et al., 2010; USCC, 2008). The potential for pathogen suppression is greatest for fully mature compost and is least for either immature compost or compost that is excessively stable or fully decomposed in soil (Neher et al., 2022). For citrus crops, there is interest in using compost to improve soil quality, especially in areas with poor soils and where the disease Huanglongbing (HLB, or citrus greening) is present. In Florida, virtually all citrus acreage is affected by HLB, which causes trees to lose as much as 80% of their root system, resulting in a marked decrease in fruit yield and quality. Organic acids derived from compost have been shown to increase root health and fibrous root density when applied to HLB-infected trees (Ozores-Hampton, 2021a). Other studies suggest that compost application can inhibit diseases in apple and cherry orchards (Brown & Tworkowski, 2004; Dupont & Granatstein, 2018). Neher et al. (2022) reported that applying compost made from the organic fraction of MSW or yard trimmings to cropland soil reduced the severity of bacterial spot (Xanthomonas) and early blight (Alternaria) of tomatoes. Reductions in several foliar diseases of beans and cucumbers have been achieved by incorporating composted paper mill sludge into a sandy Wisconsin soil (Neher et al., 2022). Neher et al. (2022) contains a list of compost feedstocks that have been associated with the suppression of specific soilborne pathogens of various crops. Similarly, this reference also contains a list of beneficial microorganisms found in compost that have been found to suppress specific diseases and pathogens of various crops.

Compost tea (i.e., a liquid made from steeping compost in water) has value for the suppression of some plant foliar or root pathogens (e.g., powdery mildew and potato scab), which are conventionally controlled through the use of synthetic pesticides (Alferez, 2021; Coker & Ozores-Hampton, 2021). Coker and Ozores-Hampton (2021) cite several studies that found compost tea suppressed or decreased the severity of disease in fruit and vegetable crops, including beans, melons, onions, potatoes, peppers, cucumbers and tomatoes. The pathogen suppression is believed to be due to antagonistic interactions between microorganisms in the compost tea and plant pathogens following the application of a tea to plant foliage or soils.

When compost is used instead of synthetic pesticides, it reduces environmental impacts (e.g., pollinator mortality, water pollution) and human health risks associated with pesticide exposure (Rynk, Cooperband, et al., 2022). These effects are particularly beneficial for organic agriculture, where compost tea provides an acceptable alternative means of disease control to the prohibited use of synthetic pesticides (Coker & Ozores-Hampton, 2021). Additionally, adding compost to soil can promote the biodegradation of pesticides. Freshly applied compost can absorb and degrade pesticides due to greater C sources for microorganisms to metabolize as they remove chemicals (Alferez, 2021).

The full extent of the value of compost in plant disease and pest management has not yet been fully realized (Rynk, 2022). Efforts are underway to optimize the composting process to increase the population of beneficial microbes (USCC, 2008). The degree to which compost feedstock influences disease and pest-suppression qualities is not yet fully understood, but this may prove to be an important aspect given that certain species of plants contain chemicals known to help control disease and pests (e.g., cedar, chrysanthemum, marigold, neem, oregano, thyme).

#### *5.3.2.2 Weeds*

Compost use can play an important role in weed control for crop production. Compost used as a mulch can also serve as a physical barrier to inhibit weed growth (Ozores-Hampton et al., 2022). Therefore, compost has potential as an alternative to plastic mulches for weed control (Stoffella et al., 2014; USCC, 2008). Also, some immature composts contain substances (volatile fatty acids and/or $NH_3$) that act as a mild herbicide (Stoffella et al., 2014). A reduction in weed abundance can lessen the need for herbicide applications.

#### *5.3.2.3 Pathogens*

Replacing conventional manure applications on crop fields with compost applications can benefit food safety. When composting processes are conducted appropriately, temperatures achieved during the thermophilic phase are highly effective in killing pathogens sourced to animals (Governo et al., 2003; Schwarz et al., 2010; Stehouwer et al., 2022). In addition, the variable composition of C sources in finished compost promotes diversity in bacteria and fungi species, some of which suppress animal pathogens (Hadar & Papadopoulou, 2012; Neher et al., 2022). The effects of composting on pathogen destruction have been reported for pathogenic viruses (e.g., avian influenza), bacteria (e.g., *Salmonella*, *E. coli*), fungi and protozoa (e.g., *Giardia* and *Cryptosporidium parvum*) (Rynk, Cooperband, et al., 2022). For example, research has shown that applying composted poultry litter can enhance bacterial communities that may suppress the pathogens *Salmonella enterica* and *Listeria monocytogenes*. One study found that within 30 days of application, soils amended with compost had a four-fold to five-fold lower abundance of *Salmonella* compared to soils that were not treated with compost (Devarajan et al., 2021). Composting can even provide an effective and inexpensive alternative for managing dead animals (e.g., on-farm livestock mortality, road-killed wildlife), butcher waste and other biological residuals (Schwarz et al., 2010).

## 5.4 Soil and Water Conservation

Irrigation accounts for 42% of all freshwater withdrawals from surface water and groundwater in the United States (Dieter et al., 2018). When incorporated into soils or used as a mulch, compost may increase water availability for crops, thereby reducing irrigation requirements and providing resilience to drought stress (Adeleke et al., 2021). One modeling study indicated that compost applied to cotton fields (at an application rate of 5.4 t $ac^{-1}$) could reduce irrigation requirements by approximately 14,000 to 17,000 gallons $ac^{-1}$ $yr^{-1}$ (Brown et al., 2008). The same study suggested that compost used as a mulch in vineyards (at an application rate of 33.5 t $ac^{-1}$ every 3 years) could increase the soil water-holding capacity by around 10%, leading to total water savings of roughly 102,000 gallons $ac^{-1}$ $yr^{-1}$ (Brown et al., 2008). Improved water conservation also supports climate resilience by improving the ability of crops to withstand droughts and reducing irrigation demands on water supplies that may become more limited with climate change (IPCC, 2022).

Compost can also enhance the effectiveness of conservation practices designed to reduce soil erosion, surface runoff and pollutant transport. For example, compost supports practices such as conservation tillage and no-till (Whalen et al., 2003), cover cropping (Beck et al., 2016; Clark, 2011), integrated pest management (Penha et al., 2012) and nutrient management (Maltais-Landry et al., 2019; Maltais-Landry et al., 2015). A study conducted in Virginia found that compost use decreased surface runoff volumes from cropland by a factor of four, resulting in five times less N and four times less P lost compared to the use of inorganic fertilizer (Evanylo et al., 2008). In recognition of the value of compost use for soil and water conservation, NRCS recently established the application of organic amendments, which includes compost, as a formal conservation practice (NRCS Practice Standard 336: Soil Carbon Amendment) for cropland, pasture, range, forest and associated agricultural lands (NRCS, 2022). The stated purpose of the practice is to improve or maintain SOM, sequester C and enhance SOC stocks, improve soil aggregate stability, and improve habitat for soil organisms. Establishing this practice is an important step towards improving soil health and increasing soil C sequestration at a national scale.

# 6. Landscaping and Horticulture

Many of the soil, water and plant growth benefits of compost use for agriculture also apply to landscaping and horticulture (i.e., ornamental plants or gardens, residential food gardens and urban agriculture) (see Figure 7). In urban areas, compost is common in residential uses (such as gardens, lawns, horticulture and landscaping) and for maintaining landscaping on commercial and public sites (e.g., recreational turfgrass, tree plantings, street trees). In horticultural applications, compost is used as a soil amendment, a mulch, or in growing media for containerized plants. For example, compost blended with other materials can be substituted for growing media and mulches, such as peat, a product associated with significant environmental impacts. This section summarizes the benefits of compost for plant productivity, urban agriculture, water conservation and use as a substitute for peat (in horticulture).

*Figure 6. Topdressing a golf course with compost. Photo courtesy of Agresource.*

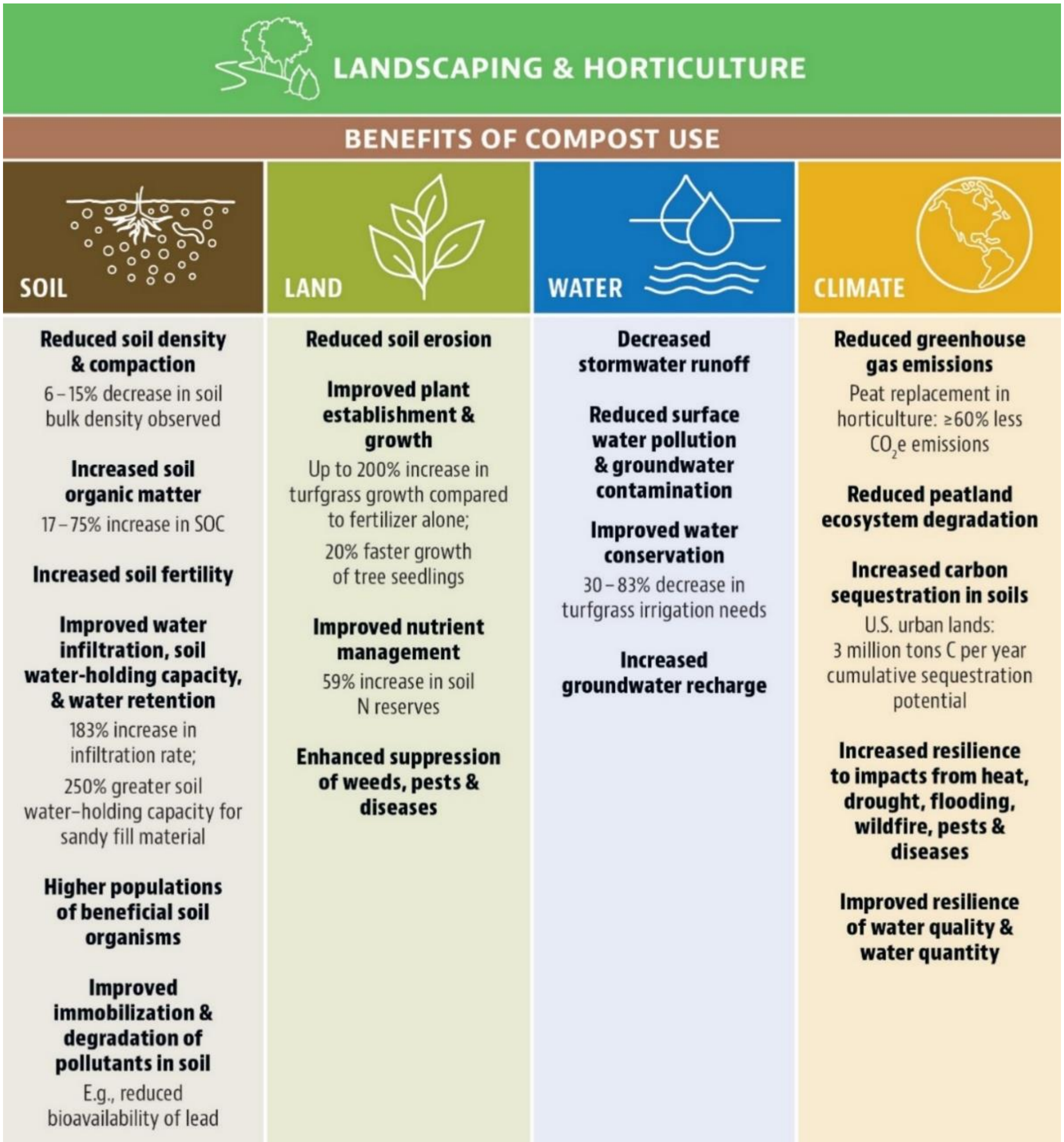


*Figure 7. Summary of key benefits for landscaping and horticulture from compost use. Sources – Soil: Alexander (2020d, 2020h, 2020i); Evanylo et al. (2016); Linde and Hepner (2005); Loschinkohl and Boehm (2001); Mandal et al. (2013); Land: Alexander (2020d, 2020h, 2020i); Evanylo et al. (2016); Linde and Hepner (2005); Loschinkohl and Boehm (2001); Mandal et al. (2013); Water: Hill (2021); Ozores-Hampton et al. (2022); Climate: Brown, Miltner, et al. (2012); Saer et al. (2013)*

## 6.1 Urban Agriculture

Compost is commonly added to the soils of urban farms and gardens and can play an important role in local food production (Kranz et al., 2020). For example, compost is often added to raised beds, a common feature of urban farms and gardens. Additionally, in urban agriculture settings, soils are often degraded (e.g., compacted and/or depleted of organic matter) due to previous land use (Cogger et al., 2016). Compost boosts organic matter, enhances soil organism populations and improves the overall health of soils for urban agriculture (Cogger et al., 2016; Kranz et al., 2020; Rollins & Koenig, 2010).

Biosolids and food waste compost are reported to improve soil health and plant yield in degraded urban soils (e.g., soils with low levels of organic matter, physical disturbance and/or compaction) relative to additions of fertilizer alone (Una et al., 2022). Improvements in water infiltration and retention in amended soils and raised garden beds can also support engineered green stormwater infrastructure in urban settings (Chapman et al., 2022) (see also Section 7).

*Figure 8. Vegetable beds amended with compost. Photo courtesy of ECO City Farms, Bladensburg, MD.*

### 6.1.1 Nutrient Circularity

Substituting compost for inorganic fertilizers in urban agriculture supports the concept of localized "nutrient circularity" (Harder et al., 2021). Nutrient circularity represents a balanced system with equal imports and exports of nutrients to avoid nutrient overloads and associated impacts to local waters while supporting soil health and agricultural productivity. The concept assesses the flow of nutrients (e.g., N and P) in a given area's food production system (Harder et al., 2021; Moinard et al., 2021; van der Wiel et al., 2021). Through compost production and use, local food production can recycle valuable nutrients from organic "wastes" generated within an urban area (e.g., food waste, yard trimmings) (Brown & Beecher, 2019; Brown & Goldstein, 2016; Shrestha et al., 2020).

Using locally sourced, organic residuals on soils for growing crops may improve food security by replenishing soils with nutrients and C (Harder et al., 2021; van der Wiel et al., 2021). Local recycling of nutrients through composting also improves the efficiency of nutrient use on a global scale by reducing the reliance upon nutrients (in fertilizers and animal feeds) sourced long distances from their point of use and by reducing losses of essential agricultural nutrients (e.g., into the atmosphere, water bodies, landfills) (Harder et al., 2021; van der Wiel et al., 2021). For example, biosolids and food waste compost derived from urban areas can be used in urban agriculture, improving nutrient circularity and reducing reliance on inorganic fertilizers imported from far away (Brown et al., 2023b). One caveat to the concept of nutrient circularity in urban agriculture is that only a portion of the nutrients recycled from an urban area will be derived from that local area because it is likely that the vast majority of food consumed in that urban area was not produced locally.

### 6.1.2 Soil Remediation

Urban soils used for agriculture are sometimes contaminated with harmful substances like lead, arsenic and polycyclic aromatic hydrocarbons (PAHs) that can accumulate in crops or vegetables (Attanayake et al., 2015; Brown, 2023). Compost use may reduce the risk of contaminant bioavailability in soils and/or uptake by crops. For example, research has shown that compost use can reduce the amount of lead taken up by plants (Attanayake et al., 2014; Brown et al., 2016). However, not all studies report a decrease in contaminant bioavailability or uptake by crops following compost additions (Attanayake et al., 2021). Due to site-specific variations in soil conditions, urban soil samples should be analyzed for contaminants before amending with compost or planting (Carroll, 2016) (See Section 8 for more on soil remediation).

**Key Advantages When Compost Replaces Conventional Materials in Landscaping and Horticulture**

Inorganic fertilizer replacement[1]:

- Improved soil health[2]
- Improved nutrient circularity
- Improved plant growth
- Increased carbon sequestration[3]
- Improved water conservation[4]
- Reduced runoff and nutrient pollution (N and P)
- Reduced soil erosion
- Reduced GHG emissions
- Disease and weed suppression

Synthetic pesticide replacement[1]:

- Improved soil health[2]
- Reduced environmental pollution
- Reduced pollinator mortality

Replacement of bark, wood and plastic mulch[1]:

- Improved soil health[2]
- Reduced fertilizer requirements
- Pest and disease suppression
- Reduced plastic waste

Replacement of peat:

- Improved peatland conservation
- Reduced GHG emissions

[1]See also Section 5 on Agricultural Benefits
[2]See Section 2 on Soil Health Benefits
[3]See Section 4 on Climate Benefits
[4]See Section 3 on Water Resource Benefits

## 6.2 Plant Productivity

Compost use improves plant growth in multiple landscaping and horticulture applications (Dudka et al., 1998; Evanylo et al., 2016; Ward et al., 2021). Much of the evidence of improved plant growth comes from studies of compost use for turfgrass management. Many studies have concluded that compost use enhances turfgrass establishment and maintenance beyond what is achieved through conventional practices involving topsoil, straw and inorganic fertilizers (Dudka et al., 1998; Evanylo et al., 2016; Ward et al., 2021). Sullivan et al. (2003) found that a one-time application of compost incorporated into soils before seeding ryegrass, followed by periodic mineral N fertilizer applications after grass cuttings, resulted in a 13% to 23% cumulative increase in grass yield over seven years in comparison to plots that received the same N fertilization but no compost. Evanylo et al. (2016) found that after roughly two years, one to two inches of compost incorporated into soils before turfgrass establishment resulted in turfgrass biomass more than two times greater than either using straw mats with fertilizer or using fertilizer alone. In Devens, Massachusetts, compost topdressing on recreational turfgrass reduced re-seeding needs by roughly 66% over a three-year period (Hill, 2021). Additionally, compost can help enhance turfgrass productivity by contributing to the control of both weeds and turfgrass disease (Block, 2000; Nelson, 1996). Nelson provides an overview of the potential disease-suppressing characteristics of compost used in turfgrass management and its potential to help reduce the environmental risks of synthetic pesticides. The key benefits of compost use to enhance turfgrass productivity can be summarized as follows (Alexander, 2020h, 2020i; Hill, 2021; Loschinkohl & Boehm, 2001):

- Enhanced rate of grass establishment, growth and overall appearance
- Reduced inorganic fertilizer needs (e.g., a potential 50% or more reduction in fertilizer needed for the first year of grass establishment, and with up to 75% of the N and P for two years of turfgrass growth)
- Enhanced degradation of grass thatch
- Potential suppression of soil-borne diseases, reducing the need to apply pesticides

Figure 9 below illustrates the effect of using compost for establishing turfgrass on disturbed (e.g., physical destruction of soil structure and/or compaction) glacial till soil. Compost was incorporated into soils at a rate of 30% by volume. Four years after establishment, turfgrass quality on plots with compost remained greater than plots without compost and surface runoff was decreased by up to 50%.

**Turfgrass growth without compost** **Turfgrass growth with compost**

*Figure 9. Comparison of turfgrass established on disturbed soils, with and without compost. Photo courtesy of Seattle Public Utilities.*

Other use cases also highlight the benefits of compost use for plant productivity in horticulture. For example, Ward et al. (2021) found that after six years, compost additions to urban forest plots increased SOC and N stocks by 17% and 59%, respectively, relative to the initial conditions and was associated with a 20% increase in the growth (basal area) of planted tree seedlings; in contrast, the control plots displayed declines in SOC. Substituting conventional materials with compost in potting media can also improve plant growth (Stoffella et al., 2016; Traversa et al., 2014). Dudka et al. (1998) found that blends of composted biosolids and bottom ash from power plants improved the biomass and visual appearance of marigolds when used as an alternative to a conventional potting mix made from pine bark, sphagnum moss, peat, perlite and charcoal. Traversa et al. (2014) observed that replacing 5% to 20% (by volume) of a peat seed germination media with compost improved the growth of switchgrass (*Panicum virgatum L.)* seedlings.

# 6.3 Water Conservation

As discussed in Sections 2, 3 and 5 organic matter added to soils from compost applications can increase water infiltration and soil water-holding capacity and reduce irrigation needs in landscaping and horticulture. Compost used as a mulch for annual and perennial plants can reduce irrigation needs by up to 70% (Ozores-Hampton et al., 2022). Using compost to establish and maintain turfgrass offers large-scale potential for improving water conservation and can reduce irrigation requirements by up to 30% (Ozores-Hampton et al., 2022). As an example of potential water savings, in south Texas, it has been estimated that maintenance of sports fields and golf courses requires 20 to 30 in. of irrigation water per year; in arid west Texas, the amount increases to 40 to 50 in. In these settings, compost use may reduce irrigation requirements by roughly 160,000 to 400,000 gallons of water $ac^{-1}$ $yr^{-1}$ (Duble, n.d.).

Furthermore, the total acreage of irrigated turfgrass in the United States rivals that of irrigated cropland, covering roughly 40 million acres (± 9 million acres) (Brown & Beecher, 2019). At a national scale, using compost for turfgrass management could result in annual irrigation water savings on the order of quadrillions of gallons per year (Duble, n.d.). Given that the turfgrass in urban areas is often irrigated with potable water, there is also vast potential to use compost to reduce the demand on municipal water resources and the energy required for water treatment (Schultze-Allen, 2010).

## 6.4 Peatland Conservation

Peat is widely used in a variety of horticultural activities, such as the cultivation of flowers, vegetable and fruit plants, and other landscaping plants (Levis & Barlaz, 2011; Saer et al., 2013). However, peatlands are highly important in the global C cycle (they contain ~33% of the SOC on Earth). Harvesting peat for commercial uses can lead to GHG emissions, as the C contained in peatlands is released into the atmosphere. Compost can serve as a substitute for much of the peat used in activities such as landscaping, nursery and greenhouse production, gardening, potting indoor house plants, and erosion control (Saer et al., 2013; USGS, 2023).

Both peat and compost are often mixed with other materials for use in growing media. Pure compost is not used as a plant-growing medium because most compost formulations are too porous and do not have a sufficient water-holding capacity; plus, some composts have elevated levels of soluble salts that can harm plants (Ozores-Hampton et al., 2022). Instead, the amount used for container growing typically ranges from 5%–60% depending on the specific application (e.g., seed mix, potted plants, nursery stock) and plant species. Other components of a mixture may include materials such as perlite, vermiculite, wood chips, bark, peanut hulls and/or coconut coir, which have minimal salt levels and increase water-holding capacity and can decrease the bulk density of the media (Coker, 2021; Ozores-Hampton et al., 2022).

### The Importance of Peatland Conservation

Peatlands cover less than 3% of the Earth's landmass yet contain roughly 33% of its soil carbon (Nelson et al., 2021). Peatland draining and mining currently affects roughly 10% of global peatlands (Leifield & Menichetti, 2018). Globally, most of the 200 million tons of peat mined in 2022 was used as a heating fuel; however, an estimated 1.7 million tons used in the United States was for horticultural purposes (USGS, 2023). Whereas ecologically intact peatlands serve as sinks for atmospheric carbon, peat extraction undermines carbon sequestration while also generating significant GHG emissions (Leifield & Menichetti, 2018). Draining and mining peatlands generates N2O and CO2 emissions as the peat dries out and decomposes, accelerates dissolved carbon leaching, and leads to CO2, CO (carbon monoxide), and CH4 emissions from wildfires and burning of mined peat. Substituting compost for peat in horticulture can help conserve peatland ecosystems and support climate mitigation efforts (Leifield & Menichetti, 2018; Saer et al., 2013).

Levis and Barlaz (2011) concluded that substituting commercial food waste compost for peat has greater GHG emissions and energy usage offsets than using compost for soil fertilization. In a unique study, Saer et al. (2013) performed a life-cycle assessment of GHG emissions for peat products compared to substitution with compost. The study evaluated the substitution of peat used on The Pennsylvania State University grounds for horticultural activities with compost produced from food waste on the campus. The authors conservatively estimated (i.e., a minimum emissions scenario) that this substitution would result in a reduction of net $CO_2$e emissions by 59.5%.

# 7. Green Infrastructure and Stormwater Management

Compost use enhances the ability of stormwater management and GI practices to control the volume of stormwater runoff and prevent pollutants from reaching lakes, streams and rivers. Compost-based practices reduce storm runoff volumes and associated soil erosion by increasing the amount of water infiltrated into soils, increasing the water-holding capacity of soils, and decreasing the impact of erosive forces upon soils (Archuletta & Faucette, 2014; Faucette, 2012a; Mohammadshirazi et al., 2016; Mohammadshirazi et al., 2017). Compost-based practices help protect water quality through physical filtration of particulate contaminants, binding of chemical contaminants to organic matter, and facilitating microbial degradation of contaminants such as petroleum products (Faucette, Cardoso-Gendreau, et al., 2009; Faucette, Governo, et al., 2009; Faucette et al., 2008; Obrycki et al., 2017; Semple et al., 2001; Vouillamoz & Milke, 2001). Practices such as compost blankets and compost filter socks are applicable to various settings in which soils have become disturbed, compacted, stripped of vegetation, or otherwise degraded, such as construction sites, roadsides and vacant lots. Furthermore, most of the stormwater management challenges in urban areas can be traced back to the cumulative extent of surfaces (e.g., asphalt, concrete) that are impervious to precipitation and stormwater runoff. In this regard, stormwater management strategies seeking to increase the extent of permeable ground surfaces in urban areas increasingly rely on compost use. Compost use also supports the development of climate-resilient practices with a focus on nature-based solutions. This section summarizes scientific research about compost use in stormwater management and GI, with an emphasis on research examining the substitution of conventional stormwater management materials with compost.

*Figure 10. Green infrastructure for filtering stormwater coming off a bridge in Seattle, WA. Photo courtesy of Seattle Public Utilities.*

# 7.1 Green Infrastructure and Stormwater Best Management Practices

Uncontrolled stormwater runoff is one of the biggest contributors to water pollution in urban areas and can cause overflows of combined sewer systems. Stormwater management aims to prevent or reduce flooding and water quality problems associated with storm runoff from rooftops, roadways, parking lots and physically disturbed or compacted soils (e.g., from the construction of roadways and buildings). Many conventional urban stormwater management practices (e.g., retention basins, stormwater conveyances) do not involve any natural filtration or treatment of stormwater runoff. This results in repeated delivery of pollutants to water bodies.

Compost can be used in a variety of GI and stormwater BMPs, including incorporation into soils or use in compost blankets, compost berms, bioretention media and compost filter socks. The EPA's menu of stormwater BMPs for the National Pollutant Discharge Elimination System includes various compost-based practices (EPA, 2022b; Tyler et al., 2011):

- Compost blankets
- Soil amendment for vegetated filter strips
- Engineered soils within stormwater filtration devices
- Bioswale soil amendments
- Rain gardens
- Green roof systems
- Compost socks for channel protection, streambank stabilization, slope stabilization, level spreaders, vegetated gabions and biofiltration systems
- Compost for vegetated retaining walls
- Compost grout

Figure 12 summarizes the main benefits of compost use in stormwater management and GI practices. Compost use helps to "keep rain where it falls" by improving the water-holding capacity and infiltration rate of GI, such as bioswales and rain gardens (Chapman et al., 2022; Kong et al., 2015). For example, the City of Seattle's Street Edge Alternative Project infiltrated street runoff into vegetated bioretention cells with soils enhanced by compost; this reduced stormwater runoff from a street by 99% and improved water quality protection.

*Figure 11. Street-side bioretention swales with compost-amended soils, across an area of 34 city blocks in Seattle, WA. Photo courtesy of Seattle Public Utilities.*

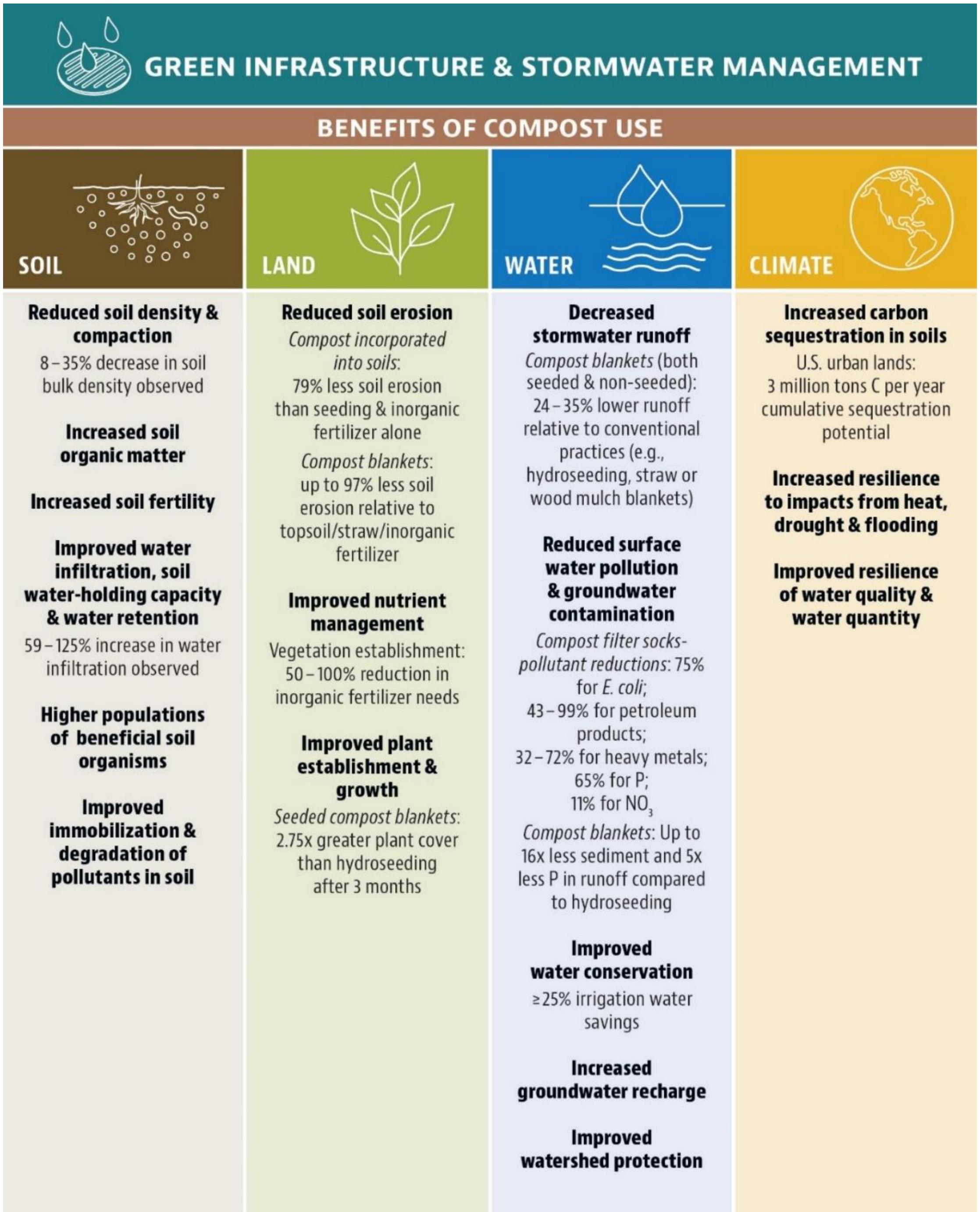


*Figure 12. Summary of key benefits for stormwater management and GI from compost use. Sources – Soil: Mohammadshirazi et al. (2016); Mohammadshirazi et al. (2017); Land: Faucette, Cardoso-Gendreau, et al. (2009); Faucette (2007); Faucette et al. (2005); Logsdon et al. (2017); Pitt et al. (1999); Water: Faucette, Cardoso-Gendreau, et al. (2009); Faucette (2007); Faucette et al. (2005); Mukhtar et al. (2004); Climate: Brown, Miltner, et al. (2012).*

Compost-based practices can be more effective than conventional practices at reducing stormwater runoff volumes and filtering pollutants (Alexander, 2005, 2017, 2020k; Brown et al., 2017; Faucette et al., 2013; Governo et al., 2003; Ozores-Hampton et al., 2022). Table 5 summarizes observations about compost-based BMPs and effects on pollutants in urban stormwater.

*Table 5. Effects of compost use on pollutant reductions in urban environments. Source: adapted from Kranz et al. (2020).*[a]

| Soil type[b] | Compost feedstock[c] | Compost practice (incorporation depth)[d] | Compost application rate and (application depth) | Time (years)[f] | Effects[g] | Reference |
|---|---|---|---|---|---|---|
| N/A | Unknown | Compost filter sock, with anionic polymers | N/A | N/A | *E. coli*: 75% reduction; petroleum products*:* 43%–99% reduction; heavy metals: 32%–72% reduction; P: 65% reduction; $NO_3$: 11% reduction; ammonium $(NH_4)+$: 17% reduction | Faucette, Cardoso-Gendreau, et al. (2009) |
| Sandy loam | Mixed | Compost incorporated into soil, seeded with grass species (no data) | 2:1 soil: compost by volume | < 1 | Surface flow: decreases in mass export of TN (31%), TP (50%), Al, Ca, Cl, Cu, Fe, K, Mg, Mn, Si, Zn<br><br>Subsurface flow: increases in mass export of TN (50%), TP (50%), Cu (20%); decreases in export of Al, Fe, Zn | Pitt et al. (1999) |
| Glacial till soils | Yard trimmings | Compost tilled 2–4 in. into soil, seeded with grass species, plus 0.5 in topdressing of compost in year 3 | Year 1: 134 t $ac^{-1}$ wet wt. (2 in)[e]<br><br>Year 3: 34 t $ac^{-1}$ wet wt. (0.5 in) | 4 | Relative to seeding and inorganic fertilizer use: 79% decrease in sediment loads: 86% decrease in ortho-P loads in runoff | Logsdon et al. (2017) |

*Notes:* N/A = not applicable; $NO^3$ = nitrate; in. = inches; t $ac^{-1}$wet wt.= tons per acre wet weight; TN = total nitrogen; TP = total phosphorus.

[a] All studies are in a non-agricultural setting.

[b] Soil textural class recorded when provided in original source material. When soil taxonomic names or soil series were given in source material, the Web Soil Survey was used to determine the textural class.

[c] "Yard trimmings" compost is used here to refer to compost derived from lawn clippings, leaves and potentially wood. "Mixed" compost is used here to refer to compost derived from either sawdust and MSW (organic fraction) or yard trimmings.

[d] Incorporation includes multiple mechanical methods of mixing compost with soil.

[e] The application rate (wet wt.) is an approximation based on a conversion from application depth to mass per unit area, based on an assumed density of 1000 pounds per cubic yard following Table 16.6 in Ozores-Hampton et al. (2022).

[f] Time in years after the initial compost incorporation into the soil. If multiple measurements were taken over time, the longest time span since the initial application was used.

[g] For Pitt et al. (1999), represents paired site comparisons to a no-compost control. For Logsdon et al. (2017), represents comparison to seeding and a 10-20-10 inorganic fertilizer applied in years 1 and 3 at a rate of 152 lbs $ac^{-1}$. Statistics were taken from the papers, and the percent changes were calculated from the data presented in the papers. The percent changes were calculated from the last time point available, which is reported in the preceding column.

## 7.2 Common Compost-Based Practices

As noted previously, a number of green infrastructure and stormwater practices use compost to reduce runoff and filter pollutants. The following subsections summarize research comparing the performance of three common practices (compost blankets, bioretention systems, and compost filter socks) utilizing compost as a replacement for conventional materials used in stormwater control and water quality protection.

## 7.2.1 Compost Blankets

Compost blankets consist of a thin layer (e.g., 1-2 inches) of compost applied to a soil surface to reduce stormwater runoff and soil erosion. Studies indicate that compost blankets (and compost incorporated into soils) are effective at reducing stormwater runoff volumes and offer advantages over conventional practices. Faucette et al. (2005) compared the effectiveness of compost blankets with compost filter berms to that of hydroseeding and either silt fence or mulch filter berms on construction sites in Georgia. The seeded[1] compost blankets with filter berm treatments displayed reductions in runoff of up to 3.5 times less during the first storm and up to 16 times less during the second storm relative to the hydroseed and silt fence practice. Additionally, cumulative peak stormwater runoff rates for all compost treatments were 25% lower relative to the two conventional hydroseeding practices. Beighley et al. (2010) reported that 1- and 2-inch thick non-seeded compost blankets on slopes underlain by netting or a wood ("excelsior") fiber blanket (to inhibit compost sliding downslope) were effective at reducing surface runoff relative to other techniques, including the control (bare soil), thinner (0.5 in.) compost blankets, compost blankets without netting or fiber blankets, coconut fiber blankets, and straw-net blankets. Faucette (2007) reported that soil on a Georgia construction site treated with seeded compost blankets (1.5 inches deep) absorbed 80% of a 4-inch simulated rainfall event and reduced runoff stormwater volume by 60%; in contrast, wood mulch blankets reduced runoff by 34%. Research conducted at Texas A&M for the Texas Commission of Environmental Quality indicated that 2-inch non-seeded compost blankets on clay soils subjected to 3.6 inches of rainfall reduced the mean stormwater volume by 35% (and as much as 67%) (Mukhtar et al., 2004).

**Key Advantages When Compost Replaces Conventional Materials in GI and Stormwater Control Practices**

- Improved soil health[1]
- Improved water infiltration
- Improved water quality
- Improved plant growth
- Increased carbon sequestration[2]
- Reduced stormwater runoff
- Reduced soil erosion
- Reduced need for inorganic fertilizers

[1] See Section 2 on Soil Health Benefits
[2] See Section 4 on Climate Benefits

Compost blankets are also reported to be more effective at reducing soil erosion and facilitating vegetation establishment than conventional erosion control practices such as hydroseeding and straw/seed/fertilizer treatments (Bakr et al., 2012; Evanylo et al., 2016; Faucette, 2007; Faucette et al., 2006). In a simulated rainfall experiment in Georgia, Faucette et al. (2005) found that total suspended solids loads in runoff from seeded compost blankets with compost filter berms were up to 3.5 times less during the first storm and up to 16 times less during the second storm relative to a conventional practice of hydroseeding and silt fence. One key advantage is that compost blankets allow for plant growth and can remain in place along roadways (or other sites), while practices like woodchip blankets may need to be removed once construction projects are complete.

The establishment of vegetative cover is important to prevent erosion and help control sediment losses in runoff. Faucette et al. (2006) found that seeded compost blankets enabled faster vegetation growth on soils that had been construction sites compared to hydroseeding. Compost blankets provided an average of 2.75 times more vegetative cover than hydroseed after three months, and they led to a substantial decrease in weeds. A three-year field study compared the effects of various one-time compost applications on soil properties and revegetation of a degraded urban soil site (stripped of topsoil and compacted by construction) in Virginia. The compost-treated soil maintained a higher C, N, K, Ca and Mg, a reduced bulk density, and better turfgrass growth than the fertilizer-treated controls, demonstrating that compost improves soil properties and vegetative growth. The benefits increased with time and were

---

[1] Seed can be incorporated into the compost before application (seeded compost blankets) or broadcast on the compost blanket after installation (non-seeded compost blankets). Typically, seeded compost blankets are used to ensure even distribution of the seed throughout the compost and to reduce the risk of the seed being washed from the surface of the compost blanket by stormwater runoff CWC. (n.d.). *Compost Blankets*. Crow Wing County. Retrieved August 1, 2023 from https://www.crowwing.gov/DocumentCenter/View/739/Compost_Blankets1?bidId=. Also, seed germination may be quicker in seeded blankets, which may result in a shorter time period until: vegetation cover reduces exposure of the compost blanket to precipitation and runoff; plant roots can help stabilize the soil; and plants can uptake water and nutrients.

associated with application rate: a higher compost application rate maintained a higher soil N and C concentration (Evanylo et al., 2016).

Studies show mixed results when comparing nutrient retention by compost blankets to conventional practices such as topsoil placement, straw mulch and hydroseeding. Mukhtar et al. (2004) found that non-seeded compost blankets made from dairy manure compost reduced total Kjeldahl N and P losses by 69% and 71%, respectively, relative to a conventional practice of applying inorganic fertilizer to bare soil. Faucette et al. (2005) compared TN, $NO_3$, TP and dissolved reactive P (DRP) loads in runoff among seeded compost blankets derived from different materials and hydroseeding (containing inorganic fertilizer) with either a silt fence or a mulch berm after one day, three months and twelve months. The compost blankets were derived from either poultry litter, biosolids, OFMSW, or yard trimmings. Runoff was produced by simulating rainfall at a rate of 3.1 in. $hr^{-1}$ for a duration of one hour, which is equivalent to a one-hour storm event with a 50-year return period for the study site in Georgia. Immediately following placement, but before vegetation establishment, the four compost blankets showed lower TP and DRP export, except for the biosolids compost blanket, which showed no differences compared to hydroseeding with silt fence (likely because biosolids tend to contain more P than other composts, unless blended with feedstocks having low levels of P (Stehouwer et al., 2022)). Results for TN and $NO_3$ were mixed, with yard trimming compost consistently showing lower N export and biosolids compost showing consistently greater N export. Results for three and twelve months after installation showed no differences in nutrient loads among treatments, except after twelve months when the poultry litter compost blanket showed a significantly lower $NO_3$ load than hydroseeding with a berm, and the biosolids compost blanket showed a significantly greater DRP load than either hydroseeding treatment. Table 6 below summarizes the relative differences in average nutrient loads from the compost blankets relative to hydroseeding with a mulch berm and hydroseeding with a silt fence immediately following the practice installation.

*Table 6. Comparison of TN and TP loads in runoff from different types of compost blankets relative to hydroseeding treatments.* [1,2]

| Compost Blanket Type | Nutrients in Runoff Prior to Vegetation Establishment | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | TN | | $NO_3$ | | TP | | DRP | |
| | A | B | A | B | A | B | A | B |
| Poultry litter compost[3] | NS | NS | NS | NS | L | L | L | L |
| Wastewater solids compost[3] | H | H | H | H | L | NS | L | NS |
| OFMSW compost | NS | H | L | L | L | L | L | L |
| Yard trimmings compost | L | L | L | L | L | L | L | L |

*Notes:* TN = total nitrogen; $NO_3$ = nitrate; TP = total phosphorus; DRP = dissolved reactive phosphorus; OFMSW = organic fraction of municipal solid waste

[1] Columns marked with “A” indicate comparisons to hydroseeding with a mulch berm; Columns marked with “B” indicate comparisons to hydroseeding with a silt fence.

[2] “NS” represents no statistically significant difference; H indicates that loads from compost blanket were significantly greater than loads from a hydroseeding treatment; L indicates that loads from compost blanket were significantly less than loads from a hydroseeding treatment. The statistical significance of comparisons is likely to have been influenced by a low number of replicates and high variability in N and P loads.

[3] Poultry litter compost blankets and wastewater solids compost blankets were blended with wood mulch on a 1:1 volumetric basis; gypsum (CaSO4) was mixed with the poultry litter compost on a 1:20 volumetric basis to reduce P losses.

Owen et al. (2020) found that most compost-containing treatments (produced from either biosolids or yard trimmings) reduced N and P export relative to the standard topsoil with straw mulch treatment, which received inorganic fertilizer (N:P:K ratio of 20:16:12) at a rate of 2000lbs $ac^{-1}$ N/K/P. The most effective treatments were 1:2 compost-topsoil blends and pure compost with straw mulch, with export reductions ranging up to 92% for N and 76% for P. The exception was a 2:1 biosolids compost-topsoil blend with straw mulch, which displayed a 36% increase in N export and a 15% increase in P export; it was recommended that this treatment not be used to replace the standard topsoil treatment for slope stabilization along highways. Biosolids compost tends to contain a higher level of inorganic nutrients than other composts, such as yard trimmings compost, which may explain the increase in nutrient export (Faucette et al., 2005); note that for applications such as stormwater control, biosolids and other feedstocks with relatively high nutrient levels (e.g., food waste) can be blended with low nutrient feedstocks to reduce the risk of nutrient loss in runoff.

Owen et al. (2021) examined nutrients in runoff from various compost and compost-topsoil blends compared to a conventional topsoil treatment on a highway construction site with steep slopes (71% ± 20%). There was an initial flush of N and P in runoff from all sites, with compost treatments displaying higher concentrations than the conventional topsoil treatment. Relative to the conventional topsoil treatment, only the biosolids compost produced a lower runoff volume. The reduced volume of runoff associated with the biosolids compost treatment resulted in an overall reduction in P export and no difference in N export relative to the conventional topsoil treatment. The biosolids compost treatment had the coarsest particle size among all treatments (median diameter = 0.09 in. versus 0.07 in. for the conventional topsoil treatment). Greater N and P concentrations in runoff combined with increases in runoff volume for all other compost-containing treatments resulted in greater nutrient export compared to both the conventional topsoil and biosolids compost treatments.

*Figure 13. Erosion control study in Upper Marlboro, MD that compare the effects of compost blankets composed of various biosolids and yard waste compost mixtures on grass cover and sediment retention on steep slopes. Photo by Dylan Owen. Research sponsored by Maryland Department of Transportation - State Highway Administration.*

## 7.2.2 Bioretention Systems

A [bioretention system] is a landscaped depression in the soil surface that collects and filters stormwater runoff from impervious surfaces such as roadways and parking lots. When used as a filter medium in bioretention systems, compost improves the treatment of stormwater runoff, removing sediment and increasing the CEC of bioretention media, thereby increasing the binding of contaminants (Alexander, 2020a; Davis et al., 2022). Jay et al. (2019) reported that bioretention media containing compost and other materials (including biosolids, sawdust and oyster shells) removed 84% to 100% of petroleum hydrocarbons from highway runoff. Such uses have also been found to decrease the leaching of pesticides and facilitate microbial-mediated degradation of petroleum hydrocarbons (Alexander, 2020a; USCC, 2008). These examples highlight compost use as a key component of GI that helps to protect surface and groundwater from a variety of pollutants associated with runoff from roadways and other impervious surfaces such a parking lots (Governo et al., 2003; USCC, 2008, 2022a).

*Figure 14. Compost-amended bioretention cascade along a residential street in Seattle, WA, with mulch, compost, plants and trees to support stormwater capture and filtration.*

### 7.2.3 Filter Socks

A compost filter sock is a tubular mesh bag that is filled with compost and placed on the ground to intercept and filter stormwater runoff. Numerous studies report that compost filter socks are effective at removing pollutants such as nutrients, sediment, heavy metals, *E. coli* and oil from urban stormwater runoff (Faucette et al., 2013, Faucette et al., 2009c, Faucette et al., 2009d). They can be placed in various locations to intercept runoff and trap sediment and have been found to be more effective at trapping sediment than conventional mulch filter berms and straw bales. In a controlled experiment using simulated runoff, Faucette, Governo, et al. (2009) reported that compost filter socks removed 84% to 88% of total solids loads and performed better than mulch filter berms (63.5% removal) and straw bales (71.3% removal).

## 7.3 Revegetation

Compost-based practices also have substantial value for controlling soil erosion and enhancing vegetation establishment for long-term soil stabilization on construction sites, along roadways and at former industrial sites (Basta et al., 2016; Brown, 2020; Kranz et al., 2020). The key compost-based practices for revegetation efforts are soil incorporation and compost blankets.

Compost use is particularly valuable for revegetation of areas with extensive disturbance, such as highway construction projects (Brown et al., 2009). Compost alleviates associated poor soil conditions (e.g., high bulk density, low porosity, low organic matter), promoting vegetation establishment and growth (Evanylo et al., 2016). Often, these sites are revegetated through conventional techniques, such as tillage or topsoil placement, mulching with straw, and applying hydroseeding formulas containing inorganic fertilizers. Incorporating compost into soils that have been physically disturbed (e.g., topsoil removed and/or compacted) can improve the health of soils and the success of revegetation efforts beyond the results achieved through conventional practices to reduce potential erosion and sediment losses.(Evanylo et al., 2016). Often, these sites are revegetated through conventional techniques, such as tillage or topsoil placement, mulching with straw, and applying hydroseeding formulas containing inorganic fertilizers. Incorporating compost into soils that have been physically disturbed (e.g., topsoil removed and/or compacted) can improve the health of soils and the success of revegetation efforts beyond the results achieved through conventional practices to reduce potential erosion and sediment losses.

Owen et al. (2020) conducted a greenhouse experiment comparing the standard topsoil/straw/fertilizer treatments for revegetating and stabilizing highway embankments with alternative treatments containing various blends of compost and topsoil with straw mulch. Compared to the standard topsoil treatment, compost and topsoil-compost blends reduced average sediment mass export by 73.2% to 97.0%. There was no significant difference in vegetative cover among the treatments, with all displaying cover greater than 95% after 60 days. Owen et al. (2021) suggested that a layer of straw mulch can improve erosion control when using compost treatments, particularly on sites with greater soil slopes. In clay loam soils along a highway outside of Detroit, Michigan, Dubelko et al. (2022) compared vegetation establishment following treatments of tillage only, a 3 in. application of municipal yard trimmings compost, and 3 in. of compost tilled into the soil; all plots also received 3 in. of fine hardwood mulch. Tillage had no significant effect on plant establishment. The addition of compost decreased bulk density by roughly 30%, improved the soil pH, and was associated with increased plant survival, cover, height and plant foliar nutrient content. In a similar study examining the effects of compost on revegetation and runoff water quality at an urban construction site in North Carolina, compost made from yard trimmings improved vegetation establishment relative to a control treated only with soil tillage and did not alter the amount of nutrients in runoff water (Kranz et al., 2022).

## 7.4 Nutrient Losses

Compost-based practices prevent nutrient losses by reducing runoff volumes, but when the water-holding and/or infiltration capacity of the compost-amended soil is exceeded, substantial leaching of soluble nutrients from compost can occur in the short term (Davis et al., 2023). Studies such as Owen et al. (2021) indicate that factors such as the compost texture, site soil slope and precipitation patterns may influence how much runoff occurs, thereby influencing the potential for nutrient export. In addition, when considering substituting compost for a conventional practice that would introduce lower amounts of nutrients onto a site, a number of other factors should also be considered, including the N and P content of compost, the C:N ratio of the compost, soil characteristics, compost application methods, revegetation methods and the susceptibility of the watershed to nutrient pollution (Davis et al., 2023).

Nutrient leaching from compost blankets is usually a minor concern because the reduction in stormwater runoff volumes results in more nutrients being retained on-site relative to conventional stormwater and erosion control practices that use inorganic fertilizers (Faucette, 2023). The growth of plants seeded in the compost blankets will also further reduce runoff and will uptake N and P from the compost blankets, thereby reducing the pool available for transport (Faucette et al., 2005). However, to help minimize N and P losses from compost blankets, it is recommended to use composts that have a high proportion of organic C and a low proportion of inorganic N, as well as high levels of organic C, organic matter and Ca (e.g., added gypsum) (Faucette et al., 2005).

Compost used as a media in stormwater bioretention systems and green roofs can also be a source of nutrient leaching (Brown et al., 2015; Jay et al., 2017; Jay et al., 2019; Owen et al., 2021). However, sorbents added to compost used as a media in stormwater filtration practices can increase N and P capture and retention (Brown et al., 2015; Faucette et al., 2013). For example, water treatment residuals containing iron can substantially reduce the amount of P leached from GI (Jay et al., 2017). Additional research is needed to improve the understanding of compost’s role in nutrient cycling in green roof systems and the associated potential for leaching (Buffam & Mitchell, 2015).

# 8. Contaminated Site Remediation

Through its ability to bind contaminants and reduce their mobility within the soil, compost enhances the remediation of sites contaminated by harmful substances, including heavy metals, petroleum products and salts (Alexander, 2005, 2020j; Ugarte & Taylor, 2020; USCC, 2008). Compost can, therefore, increase the success of revegetation efforts on sites where contaminated soils inhibit plant establishment and growth (Brown et al., 2005; Solís-Domínguez et al., 2011). Figure 16 summarizes the main benefits of compost use for contaminated site remediation.

This section provides a brief overview of scientific findings on how compost can be used to support contaminated site remediation. In 2007, EPA published a report entitled *The Use of Soil Amendments for Remediation, Revitalization, and Reuse* which serves as a guide on using compost and other soil amendments to remediate a variety of types of soil contamination (EPA, 2007).


*Figure 15. Differences in vegetation growth across test plots for remediating mine tailings at Henry's Knob Superfund site in South Carolina. Left: ridge and furrow test plot, a conventional remediation practice. Right: vendor test plot with vendor-supplied amendments (right). Middle: Standard farming test plot, which used leaf compost and raw manure to add organic matter and showed the best results.*

## 8.1 Heavy Metals

Compost use can help reduce the bioavailability of heavy metals in soils (Brown, Clausen, et al., 2012; EPA, 1997). For example, aluminum is precipitated at soil pH levels of five or above; below a pH of five, toxic aluminum ions dissolve into the soil solution. Compost incorporation can shift soil pH toward neutral, binding aluminum ions to the organic matter provided by the compost, thereby reducing aluminum mobilization (Ho et al., 2022).

Compost use has been observed to reduce the toxicity of urban soils contaminated by heavy metals, such as lead (Pb) paint and emissions from smelting facilities (EPA, 1997). Compost containing a high iron content (e.g., due to the addition of water treatment residuals) has been found to enhance the immobilization of Pb and arsenic in contaminated soils (Brown, Clausen, et al., 2012; Brown et al., 2005; Solís-Domínguez et al., 2011).

**Key Advantages when Compost Replaces the Conventional Remediation Technique of Capping Soil with Topsoil**

- Reduced soil toxicity
- Reduced surface runoff
- Reduced pollutant transport
- Reduced soil erosion
- Improved soil health[1]
- Improved vegetation establishment and growth
- Improved water conservation[2]
- Increased carbon sequestration[3]

[1]See Section 2 on Soil Health Benefits
[2]See Section 3 on Water Resource Benefits
[3]See Section 4 on Climate Benefits

Brown et al. (2014) found that a mixture of biosolids, mushroom and biosolids composts, and limestone could be used as an effective replacement for topsoil in revegetating and remediating Pb and Zn mine wastes in Missouri. Not only did the amendment perform similarly to topsoil in terms of increasing nutrient availability and soil physical properties, but there was evidence that it ameliorated the toxicity of metals. Recent research indicates that compost-biochar mixtures perform better at ameliorating metals' toxicity in soils than either material alone (Qian et al., 2023). Brown and Chaney (2016) report various studies in which compost has been used to reduce metal bioavailability and reestablish ecosystem functions in soils degraded by the mining of metals (e.g., soils with low levels of organic matter, physical disturbance, compaction and/or contamination). Using compost to amend soils with low levels of contamination can be a more cost-effective remediation strategy than conventional approaches, such as removing and replacing contaminated topsoil (Ugarte & Taylor, 2020). Substituting compost for topsoil used in mine waste remediation may also have broader ecosystem and climate benefits. The previously mentioned Brown et al. (2014) study concluded that the use of a biosolids, compost and limestone amendment was more sustainable than the use of harvested topsoil due to the slow rate of natural topsoil formation. It was also estimated that using the amendment could result in a substantial reduction in GHG emissions largely because the convention in Missouri at the time was to incinerate the majority of biosolids produced.

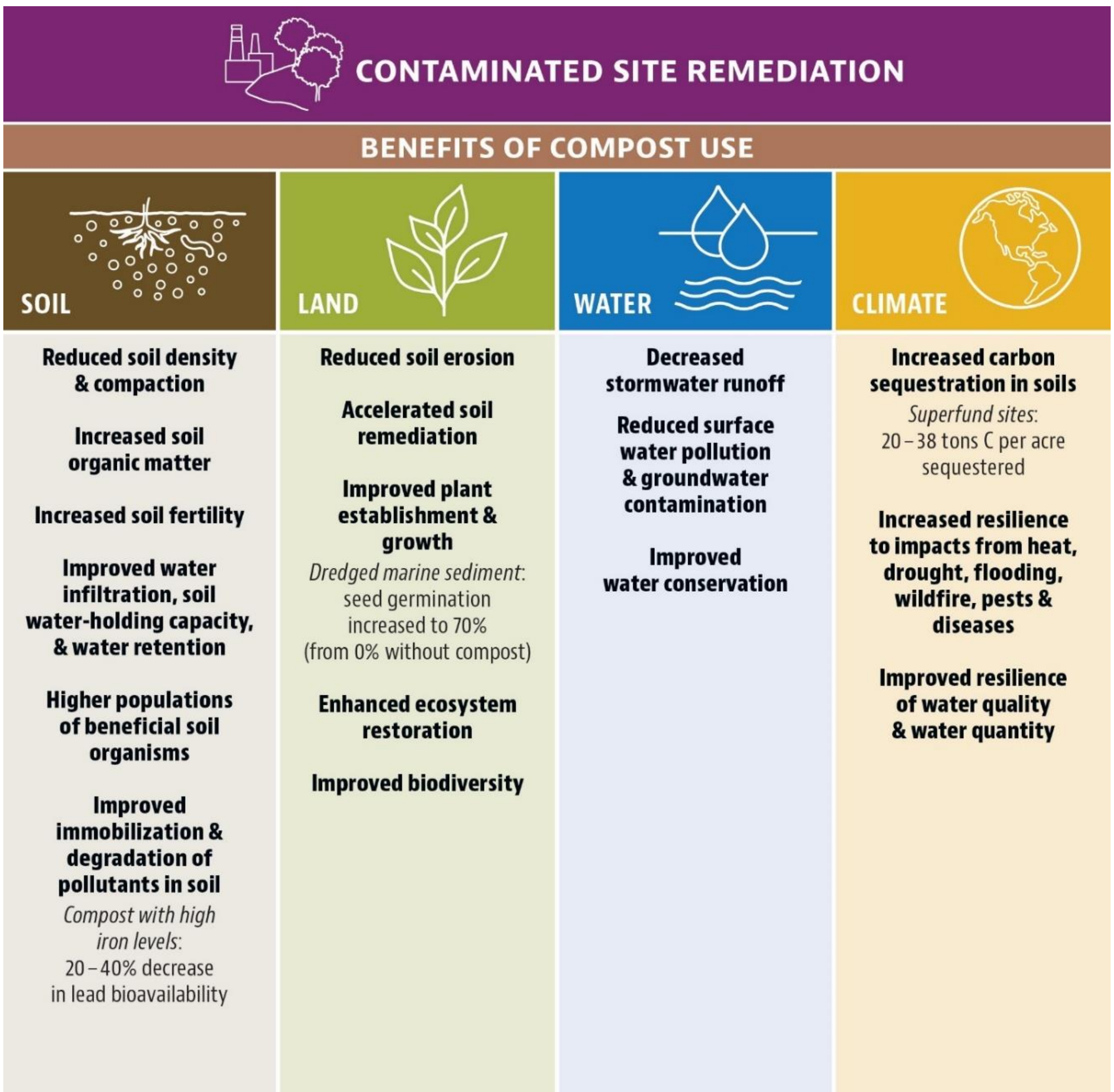


*Figure 16. Summary of key benefits contaminated site remediation from compost use. Sources – Soil: Brown, Clausen, et al. (2012); Land: Stoffella et al. (2016); Climate: EPA (2011).*

## 8.2 Bio- and Phytoremediation

Compost supports a wide range of microorganisms, including bacteria, fungi and actinomycetes, some of which can degrade toxic organic contaminants (such as pesticides, petroleum products and polychlorinated biphenyls [PCBs]) in the soil (Semple et al., 2001). Adding compost to soils contaminated by toxic organic compounds accelerates the remediation process by enhancing the biological communities capable of degrading the organic pollutants (Coker, 2006; Obrycki et al., 2017; USCC, 2008; Vouillamoz & Milke, 2001). In Ohio, incorporating compost and dredged lake sediments into residential soil contaminated with PAHs (at a 1:1:1 ratio) was found to reduce the concentration of benzo(a)pyrene in the soil (Obrycki et al., 2017). Mixtures of compost and woodchips incorporated into soil have been observed to accelerate the degradation of Dicamba, a pesticide used to control weeds (EPA, 1997). As an alternative remediation technique, soils contaminated with organic compounds are sometimes excavated and mixed with compost feedstocks to accelerate the degradation of the contaminants through the composting process (Coker, 2006). For example, at the Seymour Johnson Air Force Base in North Carolina, compost has been mixed with excavated soils contaminated by aircraft fuel spills and leaking underground petroleum product storage tanks to accelerate the remediation process. The compost-based remediation technique replaced a more expensive process of hauling the contaminated soils to a facility where the soil was incinerated to remove the petroleum products (EPA, 1997).

Compost applications to contaminated soils also facilitates the establishment and growth of plants that support remediation efforts. This includes plants that are capable of absorbing and accumulating contaminants such as heavy metals from the soil, a process called phytoremediation, which can then be removed from the site (Ducey et al., 2021; González et al., 2019). However, research on the value of compost-supported phytoremediation is ongoing, and its practicality has yet to be proven.

## 8.3 Marine Sediments

Compost has also been used to mitigate the salinity of marine sediment associated with dredging, making it more suitable for land application and vegetation establishment. Such sediments have a high salt content, which adversely affects seed germination and subsequent plant growth. Stofella et al. (2016) evaluated the effects on plant establishment when compost was mixed with dredged marine sediments in South Florida. A biosolids and yard trimmings compost mixture (ratio of 20:80) was used to amend the dredged sediment. The sediment contained < 5% total C, 0.3% TN and a large concentration of salts (> 2%). Not only did the incorporation of compost into the sediments dilute the salt content, but it also shifted the pH towards neutral and substantially increased the organic matter, nutrient content and water-holding capacity. The study also found that a thin compost layer (0.5 in) on top of the sediment mixtures significantly improved seed germination with a germination rate of > 70% in mixtures with 80% or less marine sediment.

# 9. Ecosystem Conservation and Restoration

The health of ecosystems such as forests, grasslands and wetlands depends on soil health. Compost is well-suited to support conservation and restoration activities due to its proven ability to improve soil health (Magdoff & Van Es, 2021). When compost is manufactured from residual organic materials (such as forest harvest residues) derived from within the region in which it will be used, it promotes nutrient circularity, as described in Section 6. Figure 17 summarizes the main benefits of compost use for ecosystem conservation and restoration.

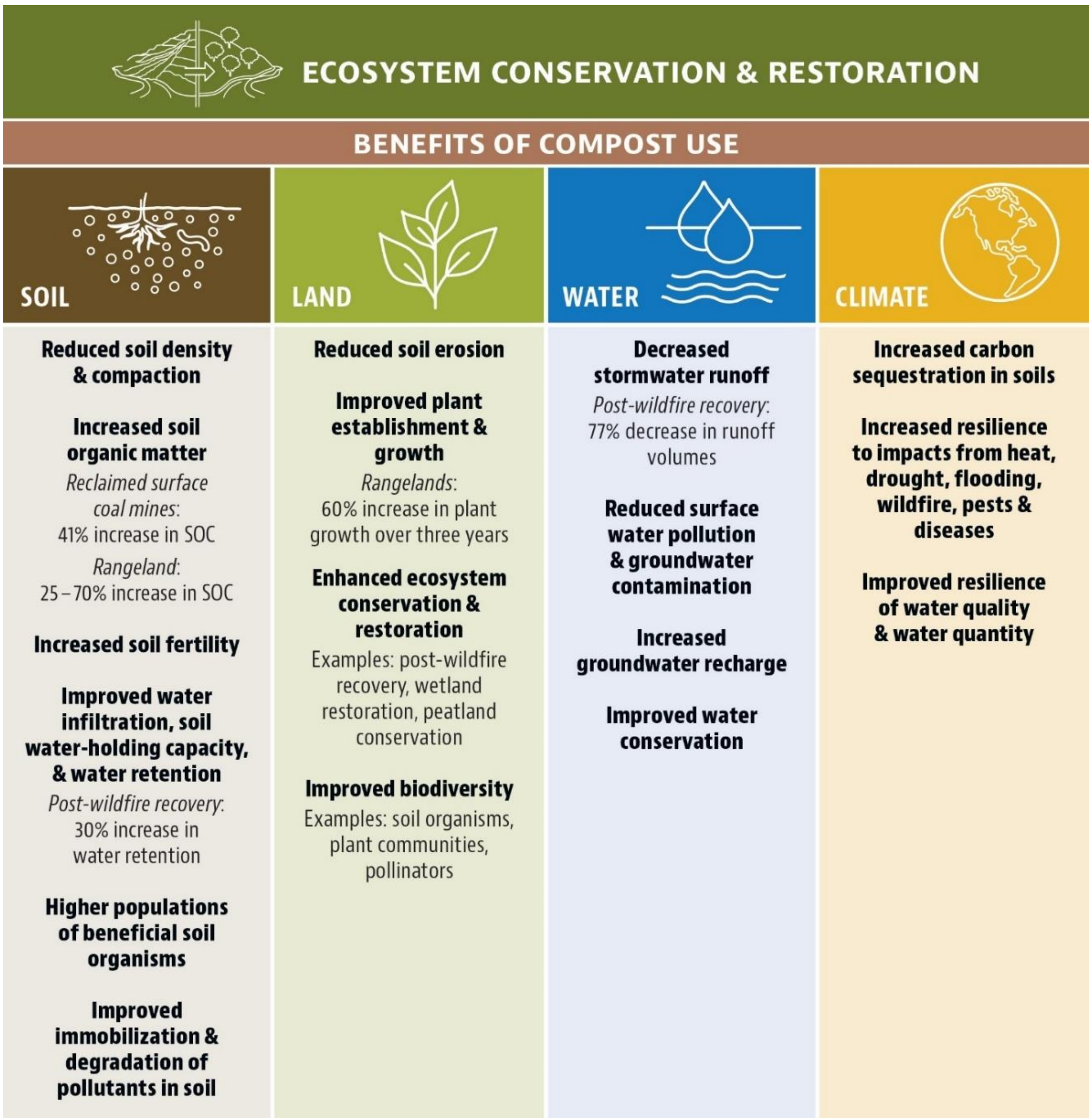


*Figure 17. Summary of key benefits for ecosystem conservation and restoration from compost use. Sources – Soil: Meyer et al. (2001); Ryals and Silver (2013); Trlica and Brown (2013); Land: Crohn et al. (2013); Leifield and Menichetti (2018); Meyer et al. (2001); Ryals and Silver (2013); USCC (2008); Water: Meyer et al. (2001).*

# 9.1 Ecosystem Restoration

Compost has utility for a variety of ecological restoration projects. It has been used to improve soil health in semi-arid grasslands (Otuya et al., 2021; Ryals & Silver, 2013) and to facilitate the reclamation of former coal mining sites (Brown et al., 2009). At surface coal mines in Pennsylvania, the use of composted biosolids was found to increase C storage in the upper 6 inches of soil by 41% while also resulting in an equivalent content of soil N relative to reclamation that used only topsoil and inorganic fertilizer (Trlica & Brown, 2013). The authors suggested that this enhancement of soil health can accelerate the reforestation of reclaimed mines, which will contribute to the provision of ecosystem services such as climate regulation, water quality protection and recreational activities.

**Key Advantages of Compost Use for Ecosystem Conservation and Restoration**

- Improved soil health[1]
- Improved water conservation[2]
- Improved water quality protection
- Increased carbon sequestration[3]
- Improved plant growth
- Enhanced habitat and biodiversity
- Reduced surface runoff
- Reduced soil erosion

[1] See also Section 2 on Soil Health Benefits
[2] See also Section 3 on Water Resource Benefits
[3] See also Section 4 on Climate Benefits

Of particular significance, compost assists in activities related to protecting, reclaiming, or creating wetlands, which are commonly affected by transportation corridors. Rich in organic matter and microbial populations, compost and soil/compost blends closely simulate the characteristics of wetland soils, thereby encouraging the re-establishment of native plant species (USCC, 2008). Compost use also facilitates vegetation re-establishment and growth in riparian buffers along streams, helping to stabilize streambanks and reduce streambank erosion (Faucette, 2009). The restored vegetation (and compost) filters pollutants from runoff, provides shade that inhibits water temperature increases, and improves aquatic habitat for fish and other aquatic organisms by providing wood and detritus inputs (Dosskey et al., 2010; Gregory et al., 1991; Naiman & Décamps, 1997). Additionally, compost products do not disrupt wildlife migration patterns or trap wildlife, as observed with some conventional ecological restoration materials, such as fiber netting-based materials used in soil stabilization (Faucette, 2009).

# 9.2 Ecosystem Services

Through improving soil health, compost use promotes a variety of “ecosystem services” (Potschin & Haines-Young, 2016). Compost use supports *Provisioning Services* by enhancing the production of food, forage, fiber and freshwater from ecosystems. It supports *Regulating Services* by enhancing ecosystem processes that affect air quality, soil quality, C sequestration and hydrologic cycles. For example, healthier soils have less surface runoff contributing to flooding and erosion (Basche, 2017) and water quality impacts (Lewandowski & Cates, 2023). Also, compost use that increases C sequestration in the soils supports ecosystem sustainability and climate mitigation (Gravuer et al., 2019). Compost contributes to *Supporting Services* by facilitating the development and maintenance of habitat for soil organisms, plants and wildlife and associated biological diversity (Faucette, 2009; Magdoff & Van Es, 2021). In turn, biodiverse soil and plant communities improve habitat for a wide range of wildlife species, which notably includes important pollinators such as native bees, moths and butterflies (Magdoff & Van Es, 2021). By supporting these ecosystem services, compost use can also enhance *Cultural Services* such as opportunities for recreation and aesthetic appreciation.

# 9.3 Wildfire Resilience

Compost supports ecosystem recovery following wildfires. The risk of wildfire, particularly in the western United States, is increasing with the changing climate. Where wildfires have damaged soils, compost use improves soil health and vegetation establishment, supporting the restoration of the natural ecosystem (Crohn et al., 2013; McFarland, 2009; Meyer et al., 2004). This helps accelerate the recovery of fire-damaged lands by providing essential nutrients to vegetation and reducing runoff and soil erosion. Meyer et al. (2001) found that after seven simulated rainfall events with 2-inch accumulations on plots within a burned area in Colorado, compost incorporated at 18 t $ac^{-1}$ in gravely clay loam and gravely sandy loam soils reduced the mean stormwater runoff by 77%, while the percent of total rainfall retained was increased to 94% from an initial 64%. Crohn et al. (2013) measured the effects of compost treatments on runoff and water quality using soil plots within an area where a controlled burn had been recently conducted. Treatments consisted of 1- or 2-inch depths of either biosolids/livestock bedding or yard trimmings compost that applied as a surface mulch or incorporated into the soil. Averaged across all compost treatments, compost reduced surface runoff by 86% and total suspended solids by 80% relative to the untreated control plots. Compost treatment reduced suspended metals (Cadmium [Cd], Chromium [Cr], Cu, Ni, Pb and Zn) loads in runoff by 93% to 95%, although dissolved metals losses were not significantly different than the control plots. For nutrients, compost treatments reduced average dissolved P, suspended P, and $NO_3$ losses by approximately 72%, 98%, and 73%. These results suggest that compost may have utility for protecting aquatic ecosystems and reducing the risk of contamination to drinking water supplies from pollutants following wildfires.

On a global scale, wildfires in boreal peatlands can potentially result in large GHG emissions (Nelson et al., 2021). Hydrologically intact peatlands have less risk of wildfire than those that have been fragmented or physically disturbed, particularly through drainage and subsequent mining (Granath et al., 2016; Nelson et al., 2021). Relying on peat as a resource for agricultural and horticultural production, therefore, increases the risk of wildfires and their associated GHG emissions (See Section 6.4 for further discussion on the importance of peatland conservation). Substitution of compost use for peat use is a practical means for decreasing this risk and can play a role in restoring soil health following wildfires.

# 10. Compost Feedstocks and Manufacturing

Feedstocks are the raw materials used to manufacture compost, and they can include a wide variety of organic materials. Each feedstock has its own unique chemical and physical properties that influence the final compost product and can affect its utility for subsequent uses. This section provides an overview of common feedstock types and their influence on compost characteristics. A brief overview of composting methods is provided, although a comprehensive review of composting processes and considerations is beyond the scope of this report. The compatibility of different feedstocks for specific environmental functions is also discussed.

## 10.1 Compost Production Methods

Commercial compost is typically produced in under moderately high "thermophilic" temperatures (generally 130–160 °F) (NRCS, 2010). Thermophilic compost can be produced using slightly different methods, as described below (EPA, 2023f; NRCS, 2010). Choosing a thermophilic composting method depends on type, characteristics and volume of feedstocks together with available equipment and space, economic/technical feasibility, the composting period length, and the target compost quality (EPA, 2023f, 2023h; Le Pera et al., 2022). Regardless of the thermophilic method used, a final curing phase is necessary to ensure that a compost has adequate stability. See Section 11.1 for more information on the importance of compost stability.

### 10.1.1 Thermophilic Methods

The following subsections summarize three common methods of thermophilic compost manufacturing—in-vessel, static pile, and windrow composting. Differences between these methods are related to the volume and dimensions of the feedstock piles, and sometimes, the method in which the piles are aerated.

#### *10.1.1.1 In-Vessel Composting*

This method uses a container (e.g., drums, bins, concrete-lined trenches, silos), which range in capacity from tens to hundreds of cubic yards for commercial composting units, although in-vessel composting is best-suited for relatively small volumes of materials (Schwarz et al., 2010). The materials are aerated by turning or mixing them. In-vessel composting is appropriate for the widest variety of feedstocks and produces compost at a relatively rapid rate, but it also tends to be more expensive than other methods. Although in-vessel composting may produce compost in as short as a few weeks, there is an elevated risk that such compost will be immature and/or unstable (see Section 11 for more information on the importance of compost maturity).

#### *10.1.1.2 Static Pile (ASP) Composting*

This method works well for large volumes of yard trimmings, food waste and paper products and can produce compost in a minimum of 3–6 months. Large piles of feedstock are amassed, which typically have bulky materials such as wood chips or paper added to help improve aeration. Many ASP systems include a form of active aeration, such as pipes underlying the piles attached to air blower motors that are used to help aerate the pile and collect nuisance odors (EPA, 2023f). Commercial aerated piles are typically 8–12 feet wide and 6–8 feet tall (Schwarz et al., 2010).

#### *10.1.1.3 Windrow Composting*

The windrow method is very similar to the static pile method, but the materials are instead elongated into rows. Diverse materials can be composted with this method, which is suitable for large volumes and requires more space than other methods. It can produce compost in as little as 2–4 months. The optimal height is 4–8 feet, and the optimal width is 14–16 feet, and commercially produced piles may extend for one hundred feet. Materials may be turned for aeration using manual or mechanical means or may include air blowers as described for aerated static pile composting. As with static piles, bulking agents such as wood chips are often added to improve aeration. The large volume of materials tends to create significant amounts of leachate that must be collected and treated to protect surface water and groundwater.

## 10.1.2 Alternatives to Conventional Composting

Two alternatives to traditional composting are vermicomposting and anaerobic digestion. They are each discussed here to distinguish their processes and environmental effects from those of traditional composting.

### *10.1.2.1 Vermicomposting*

Vermicomposting is a process that relies on earthworms (*Eisenia fetida*, most commonly) and microorganisms to break down organic matter and transform its biological, physical and chemical characteristics into a stable product that can be used as a valuable soil amendment and source of plant nutrients (Sherman, 2018). The mixture of worm castings and uneaten bedding and feedstock is called vermicast. Vermicomposting feedstocks can include leaves, manure, food scraps, shredded paper or cardboard, coffee grounds, spent mushroom waste, brewery residuals, agricultural crop residues, grains and food processing waste (Sherman, 2018). In contrast to traditional composting, during vermicomposting, worms and microorganisms biologically mediate the decomposition of organic materials at moderately low temperatures (generally 55–85 °F) (Ali et al., 2015; Rynk, Cooperband, et al., 2022), and the process does not undergo microbial decomposition under thermophilic conditions (Rynk, Cooperband, et al., 2022). With temperatures remaining in the psychrophilic or mesophilic range during vermicomposting, there is a greater diversity and higher numbers of microorganisms than in conventional composting (Sherman, 2018).

Vermicast often yields a higher price than conventional compost when sold, due to its larger and more diverse microbial population. It contains higher nutrient concentrations than conventional compost, while its soluble salts are lower, and its cation exchange capacity is higher. Vermicast also typically retains higher nitrogen levels than conventional compost and has significantly lower carbon-to-nitrogen ratios, which makes nutrients more available to plants (Sherman, 2018).

Vermicomposting can take place at small-scale (small bins in homes and classrooms), mid- or medium-scale (multiple or large bins at small farms, schools, businesses or institutions) or in large-scale operations (similar to mid-scale but often requiring monetary investment and a business plan and producing greater quantities of product for sale). There are various types of vermi-systems, including windrows, wedge systems, pits or trenches, bins, batch systems, continuous flow-through bins, and stacked bins on pallet racking (Sherman, 2018). The number of worms in a system should be scaled to the system's surface area and the volume of compost feedstocks, with at least one pound of worms per square foot of surface area. One pound of worms can consume up to two pounds of materials per week, and therefore, vermicomposting can take as little as half the time of the thermophilic composting process. Maintaining a healthy worm population requires attention to the biological requirements of the worms, including temperature range, moisture levels, food supply and light conditions. As such, vermicomposting is similar to animal husbandry. Vermicomposting accounts for a relatively minor volume of organic material recycling in comparison to thermophilic composting.

### *10.1.2.2 Anaerobic Digestion*

Anaerobic digestion is used to process organic materials into biogas and creates a slurry known as digestate that can be separated into liquid and solid components (EPA, 2022a). Anaerobic digestion is not composting because it relies on the decomposition of organic materials under anaerobic (i.e., without $O_2$) processes rather than the aerobic processes used in composting. Digestates are not considered to be as biologically stable as compost because organic compounds cannot be decomposed as thoroughly under anaerobic conditions (Alexander, 2023). However, anaerobic digestates can be composted to increase their stability. Anaerobic digestate is often considered a fertilizer because it typically contains moderate levels of N, P and K in mineral (inorganic) form rather than as components of organic matter (Gilbert et al., 2020a). Some research has compared digestates and compost produced from similar feedstocks in terms of their value for providing agricultural benefits. For example, Morris et al. (2017)

performed a life-cycle assessment that compared the benefits to soil health and crop yields from aerobically produced food waste compost and anaerobically produced food waste digestate. Overall, both products were deemed to have equal value for increasing crop yields. Anaerobic digestate was determined to have greater fertilizer replacement benefits than compost because, during the composting process, food waste is often mixed with feedstocks with lower nutrient levels (such as wood chips), which dilutes the nutrients from the food waste. Compost ranked higher than digestate for water conservation and C sequestration potential than anaerobic food waste digestate. This is because digestates, with a higher nutrient content, are often applied at lower rates than compost, resulting in lower C additions. However, over long periods of time, the benefits of continued digestate applications are likely to be similar to those of compost (Brown, 2024).

## 10.2 Feedstock Characteristics

Feedstocks carry many of their original qualities to finished compost, including relative levels of organic C, nutrients, minerals, soluble salts, and chemical or physical contaminants. Moisture content and the C:N ratio are the characteristics of greatest concern to the process (Rynk, Schwarz, et al., 2022). For example, manure (especially poultry manure), biosolids and food waste tend to have lower C:N ratios, whereas wood (and often yard trimmings) has a high C:N ratio. Concentrations of chemical constituents tend to increase from start to finish of the composting process, although there may be an overall reduction in mass due to leaching of soluble molecules or biologically mediated transformation of organic matter (Rynk, Cooperband, et al., 2022; Rynk, Schwarz, et al., 2022).

Optimal feedstock characteristics for the composting process are presented in Table 7. Compost producers can manipulate the characteristics to an extent; for example, adding moisture to a compost pile is relatively easy. However, altering feedstock particle size (e.g., through mechanical processing) to achieve a target compost texture might require considerable effort and may not be economically feasible for certain feedstock types, such as larger woody materials (Alexander et al., 2022).

*Table 7. Optimal feedstock characteristics for rapid composting. Source: Rynk, Schwarz, et al. (2022).*

| Condition | Acceptable | Ideal |
|---|---|---|
| Moisture content | 40%–65% | 50%–60% by weight |
| C:N ratio of combined feedstocks | 20:1–60:1 | 25–40:1 |
| Feedstock particle size | < 2 in. | Variable |
| Bulk density | < 1200 lbs/yd$^3$ | 700–1900 lbs/yd$^3$ |
| pH | 5.5–9.0 | 6.5–8.0 |

*Notes:* in. = inches; lbs/yd$^3$ = pounds per cubic yard.

The characteristics of a compost (e.g., particle size range, organic matter content, pH, C:N ratio) affect its compatibility with the performance of different environmental functions (e.g., C sequestration, soil fertilization, water retention). Understanding the variability in compost characteristics can, therefore, help inform decisions about its use and application. For example, feedstocks with a low C:N ratio also tend to possess higher levels of soluble salts than other common feedstocks, which may carry into the final compost (Stehouwer et al., 2022). Higher levels of salts can be detrimental to plant growth if they build up in soils or other growing media, such as soil-less media used for potted plants (Ozores-Hampton, 2021a). An excessive level of soluble salts is considered to be the most limiting factor in the production of container crops (Ozores-Hampton, 2021a).

Common compost feedstocks and some of their unique characteristics are described below. Compost can be manufactured from a single feedstock, such as leaves or livestock bedding. However, it is common for feedstocks to be combined, whether to improve the composting process, to alter the characteristics of the finished compost, and/or because multiple feedstocks are readily available. A feedstock with a low bulk density may be combined with feedstocks of higher bulk density to improve aeration during the composting process (Rynk, Schwarz, et al., 2022). Feedstocks may be blended to create compost characteristics that support specific functions such as larger particle sizes for soil erosion control or higher nutrient content for soil fertilization. Similarly, a feedstock added to a recipe to deliberately complement the processing of another feedstock is called an “amendment” (Rynk, Schwarz, et al., 2022). For example, alkaline amendments with a higher pH, such as wood ash or lime (e.g., lime-treated biosolids), can be used to raise the pH of a compost being produced with low-pH feedstocks (Ekinci, 2013). Table 8 illustrates some of the variations in characteristics that can occur when compost is manufactured from different feedstocks.

*Table 8. Typical (median) characteristics of compost from select feedstocks. Source: Stehouwer et al. (2022).[a]*

| Compost type | pH | Soluble salts (dS/m) | Organic C (%) | C:N ratio | TN (%) | P (%) | K (%) |
|---|---|---|---|---|---|---|---|
| Yard trimmings | 7.5 | 1.76 | 27.1 | 15.5 | 1.5 | 0.24 | 0.53 |
| Food waste (with various co-feedstocks, e.g., yard trimmings) | 8.0 | 1.86 | 19.6 | 15.1 | 1.1 | 0.20 | 0.68 |
| Manure | 7.7 | 2.64 | 29.8 | 16.1 | 1.6 | 0.37 | 1.0 |
| Biosolids | 7.1 | 2.68 | 29.0 | 13.4 | 2.2 | 0.95 | 0.37 |

*Notes*: dS/m = deciSiemens/meter.

[a] These are general values that may vary depending on the specific type of materials used as a feedstock (e.g., poultry manure feedstock may produce compost with differing characteristics than cattle manure).

Decisions around feedstock type can also depend on the potential for contaminants to enter the composting system. Possible contaminants in compost feedstocks include physical contaminants that detract from the appearance and value of the compost (e.g., plastic), hazardous materials (e.g., glass shards), synthetic chemicals that might compromise compost use, and biological materials (such as bacteria and viruses) that present health concerns at elevated concentrations (Rynk, Schwarz, et al., 2022). Plastics have been found to compose up to 85% of the volume of physical contamination (CLP, 2024). Rynk, Schwarz, et al. (2022) note that most pesticides present in compost feedstocks are at insignificant levels or degrade during the composting process. However, commercial composters have faced problems with one class of pesticides referred to as pyridines since the early 2000s. Even at low levels (e.g., less than 10 parts per billion), these pesticides are known to cause harm to a variety of crops, including tomatoes, peppers, potatoes, cucumbers, peas, beans, clover and sunflowers. Pyridines can be present in a variety of feedstock, including yard trimmings, agricultural crop residues, hay, straw and animal manures (Rynk, Schwarz, et al., 2022).

Recent attention has been given to the potential presence of PFAS in compost (Rynk, Schwarz, et al., 2022). PFAS are a group of chemicals that pose significant health risks to humans, fish, wildlife and other organisms and degrade very slowly in the environment (EPA, 2023f). PFAS are present in a wide variety of products and wastes, some of which include compost feedstocks such as food waste, biosolids, yard waste and paper mill residuals (Biek et al., 2024; Rynk, Schwarz, et al., 2022; Saha et al., 2024). EPA (2021d) found that PFAS levels were highest in biosolids compost, intermediate in food waste compost, and lowest in other compost, such as yard trimmings compost. A major source of PFAS in food waste is thought to be food-contact materials, including food packaging (e.g., microwave popcorn bags and food wrappers) and compostable plates and bowls (Timshina et al., 2024). The potential for biological breakdown through composting is unclear; in response to this emerging issue, the U.S. Composting Council released a position paper in 2022 calling for a ban on the intentional addition of PFAS to potential compost feedstocks, such as food packaging (USCC, 2022b). The human and environmental risks of PFAS associated with compost application are not well understood (Beecher & Brown, 2018). This is an active area of research based on concerns about the leaching of PFAS into groundwater or being taken up by vegetation, including edible crops (Johnson, 2022; Levine et al., 2023; Pozzebon & Seifert, 2023; Saha et al., 2024). Careful choice of feedstocks and monitoring of contamination levels in compost can help reduce the risk of contamination in soil and leachate.

## 10.3 Compost Feedstocks

Compost is usually made from locally available feedstocks. The availability of organic materials often depends on economic factors, such as the cost of transporting large volumes of low-value materials. For example, compost produced in agricultural areas predominantly uses crop residues and animal manure/bedding, whereas compost manufactured in urban areas is more likely to use food waste, yard trimmings and biosolids (Kelley et al., 2020). Common feedstocks include:

- Food waste
- Yard trimmings
- Animal manure and bedding
- Crop residues
- Biosolids/wastewater solids
- Wood (e.g., untreated wood scraps, chips, shavings, sawdust)
- Paper and cardboard products
- Anaerobic digestates of organic materials such as food waste

It should be noted that there are other materials that may be composted, such as paper, cardboard, certain food packaging and food service materials, and a variety of organic industrial wastes (e.g., pulp and paper mill byproducts). A more comprehensive list of over 100 potential feedstocks is provided in *The Composting Handbook – Chapter 4: Compost Feedstocks* (Rynk, Schwarz, et al., 2022). Descriptions of more commonly used feedstocks and use suitability is given in subsequent subsections. Note that the discussion of use suitability below is not definitive but is rather largely based on interpretations of the literature (in particular, Ozores-Hampton et al. (2022); Rynk, Schwarz, et al. (2022); Stehouwer et al. (2022)) addressing variability in feedstock characteristics and challenges (including contamination), compost qualities, and compost end uses.

*Figure 18. Compostable materials before processing at a commercial composting facility near Seattle, WA. Photo courtesy of Seattle Public Utilities.*

## 10.3.1 Food Waste

Food waste is an under-used but excellent feedstock for compost production (Brown & Goldstein, 2016). It can come from a wide variety of sources, and its characteristics as a feedstock vary according to the source. The term "food waste" encompasses two broad categories of waste:

i. **General food waste** consists of varied mixtures of raw and processed foods from households, restaurants, grocery stores, etc., that were consumable but, for some reason, were not consumed. This waste also contains inedible food parts, such as bones and shells.
ii. **Food and beverage processing wastes** that are not suitable for human consumption unless upcycled into edible products, such as dairy whey from cheese making; spent grain from breweries; and fruits, nuts and vegetables or portions thereof.

In general, mixed food waste is highly degradable, has a low-to-moderate bulk density and a fair-to-poor structure, and contains a low-to-moderate amount of moisture (Rynk, Schwarz, et al., 2022). Food waste is rarely used as a sole feedstock and is usually composted with bulkier feedstocks (i.e., those with higher C:N ratios) like yard trimmings or chipped wood. The C:N ratio of food waste is typically less than 20 but ranges up to 40 or greater for some types of food/beverage processing waste such as apple pomace (Rynk, Schwarz, et al., 2022); see Section 2 for information about the importance of C:N ratio. Food waste is suitable to combine with feedstocks that have a higher C:N ratio (e.g., bulkier feedstocks such as wood chips or yard trimmings) to achieve an optimal C:N ratio of 25 to 40, increase aeration and add structure (Fernandez-Bayo et al., 2018; Rynk, Schwarz, et al., 2022).

**Challenges:** General food waste often contains a relatively high level of physical contaminants, including plastic, glass and metal; such contaminants increase manufacturing costs and lower the quality of the compost if not removed. The primary source of plastic contamination in food waste streams appears to be physical contaminants like packaging and containers, but microplastics have been detected in food (EPA, 2021c). While composters typically screen feedstocks for physical contaminants, some food waste streams (e.g., unsold food from manufacturers, distributors, or grocers) can require intensive, expensive labor or specialized de-packaging equipment to make them suitable for composting.

Food waste can also contain PFAS (Choi et al., 2019). Higher levels of PFAS have been observed in food contact materials (e.g., packaging, plates or utensils) — which are typical physical contaminants in the food waste stream — than in food itself, with exceptions for food sourced from areas with known PFAS releases (e.g., farms adjacent to military airfields or PFAS manufacturing plants). In food waste streams that contain both food waste and food contact materials, the latter may contribute more to overall PFAS levels on a per weight basis. In comparison to other common feedstocks, such as biosolids and animal manure, food waste typically contains lower amounts of PFAS and other contaminants, such as pathogens and heavy metals (EPA, 2023d). However, compost made from food waste contains more PFAS than compost made from yard trimmings (EPA, 2021b, 2023d; Goossen et al., 2023). In addition, food waste can present odor and pest challenges to composters.

**Use Suitability:** Food waste is a nitrogenous feedstock that contains moderate levels of N (< 3%), P (< 1%) and K (< 1%) and is a source of all required plant micronutrients (Brown & Goldstein, 2016; Kelley et al., 2020; Kelley et al., 2022; Rynk, Schwarz, et al., 2022; Stehouwer et al., 2022). Food waste feedstock is suitable for soil fertilization because it has a relatively high content of plant nutrients and a low C-to-N (C:N) ratio. Food waste is also compatible with soil structure conditioning, soil water retention and plant disease suppression functions. The organic matter in food waste is highly degradable and, therefore, it may have a lower value for C sequestration relative to other feedstocks that have a higher C:N ratio (Rynk, Schwarz, et al., 2022). To maximize utility, care needs to be taken to minimize the level of soluble salts, chemical contaminants (e.g., PFAS from food packaging) and physical contaminants (e.g., glass, plastic, metal) in food waste feedstock.

Compost blends containing variable amounts of food waste are suitable for agricultural uses, horticultural and landscaping uses, gardening, and improving degraded soils (e.g., soils with low levels of organic matter, physical disturbance and/or compaction). When food waste is a minor component of a blend, it is also compatible for growing media for GI as well as in revegetation applications (e.g., seeded compost blankets) for stormwater and erosion control. The texture of the blended compost will influence its value for different purposes. For example, a coarser texture compost (e.g., 25% to 100% of particles having a diameter between 1/4 inch and 3 inches) containing food waste would be suitable for mulch and erosion control, while a fine-textured compost could be used as a topdressing for turfgrass.

The most practical use of composted food waste may be as a soil amendment in urban areas (Brown & Goldstein, 2016) because large supplies of food waste feedstock can be efficiently obtained in urban areas, and, if compost is produced in the same area, lower C emissions would occur during distribution of the finished product.

## 10.3.2 Yard Trimmings

Yard trimmings include materials such as fresh or dried leaves, branches, and grass clippings. They can be used alone as compost feedstock or combined with other feedstocks, such as food waste or biosolids, which are typically high in moisture and less structured. The composition of this feedstock varies seasonally, with greater amounts of woody material available outside of the growing season. The C:N ratio varies by the type of material (e.g., grass, shrub trimmings, woody branches) and its freshness. Fresh yard trimmings have a lower C:N ratio than dried yard trimmings. Due to the variability in C:N ratios, yard trimmings may either be a nitrogenous (C:N ratio < 40) or carbonaceous (C:N ratio > 40) feedstock. Both green and dry wood have a C:N ratio of 80 or more (Rynk, Schwarz, et al., 2022). Shrub trimmings and dry leaves have a C:N ratio between 50 and 60. Fresh grass clippings have a C:N ratio of around 20; because of their relatively high N content, low C content and high moisture level, grass clippings tend to decompose more rapidly than other yard trimmings.

**Challenges:** Lower levels of PFAS have been detected in yard trimmings than in food waste or biosolids (EPA, 2021b; Saha et al., 2024). However, yard trimmings can contain other contaminants, such as persistent herbicides that may harm sensitive plants (EPA, 2021b; Rynk, Schwarz, et al., 2022).

**Use Suitability:** Yard trimmings support C sequestration, soil structure conditioning and erosion control functions due to the moderate to high C:N ratio, high levels of organic matter, and coarser texture (Neher et al., 2022; Ozores-Hampton et al., 2022; Rynk, Schwarz, et al., 2022; Stehouwer et al., 2022). Yard trimmings-based compost is commonly used in horticulture, landscaping, erosion control and remediation of soils. When the C:N ratio is high (e.g., > 25), yard trimmings compost is best used as a surface-applied mulch or, if used as a soil conditioner, may require additional fertilization to prevent N immobilization. In stormwater practices, use in compost berms and filter socks is common, provided levels of N and P are low. Compost derived from yard trimmings is most practical in or near urban areas, where it may be more efficient to collect the feedstock and have a lower C footprint associated with product distribution if the compost is also processed locally.

## 10.3.3 Animal manure

Animal manure feedstock is usually sourced from agricultural operations involving livestock. It is relatively high in N and C and is a nitrogenous feedstock. It may be composted as a sole feedstock but is more commonly composted with other bulkier agricultural materials, such as animal bedding, that have a greater C:N ratio. Liquid manure (e.g., manure washed from dairy barn floors) must be squeezed and screened to separate solids from liquids before composting unless used to add moisture to another feedstock mixture (Rynk, Schwarz, et al., 2022).

**Challenges:** Animal manure often contains potentially harmful bacteria such as *E. coli* and *Salmonella,* as well as parasites, animal pharmaceuticals and pesticides, some of which may persist through the composting process. Proper composting processes can greatly reduce or eliminate levels of these pathogens and substances in compost. This feedstock also tends to contain relatively high levels of soluble salts, which may be harmful to plants in some situations; salt levels can be reduced during the composting process by leaching out or by mixing with feedstocks of lower salt content (Rynk, Schwarz, et al., 2022). Like yard trimmings, animal manure can also contain persistent herbicides.

**Use Suitability:** In general, manure-based compost improves soil water retention and fertilizer functions due to its high organic matter content, plant nutrient content and finer texture (Ozores-Hampton et al., 2022; Rynk, Schwarz, et al., 2022; Stehouwer et al., 2022). Using it for soil conditioning and fertilizer in the long term can lead to elevated levels of soluble salts that may be harmful to plants if they accumulate in soils (Ozores-Hampton et al., 2022; Rynk, Schwarz, et al., 2022). Manure-based compost use is most practical in agricultural areas where the feedstocks originate, and costs associated with collection and distribution can be minimized. A potential constraint for agricultural use is the potential for manure compost to contain residual herbicides (e.g., pyridines) (Rynk, Schwarz, et al., 2022), as discussed in Section 10.2.

## 10.3.4 Biosolids

Biosolids are generated from the treatment of sewage and wastewater and tend to have a relatively high content of N and P (Stehouwer et al., 2022). They are typically combined with other bulkier feedstocks, such as wood chips or yard trimmings, to add structure and improve aeration.

**Challenges:** In the United States, this is the only feedstock that has national regulatory standards (U.S. Environmental Protection Agency 40 CFR Part 503) for pathogen reduction and heavy metals content (Stehouwer et al., 2022). Compost quality specifications often require compost made from biosolids to be treated by a Process to Further Reduce Pathogens (PFRP) to help prevent the spread of pathogenic microorganisms. Because biosolids contain residues of substances used in daily life (through sinks, showers, washing machines, toilets and commercial/industrial discharges), compost made from biosolids may also contain those residues, including heavy metals, PFAS and PCBs (Bernal et al., 2017; EPA, 2023d). Researchers have concluded that the risk of exposure to chemicals derived from pharmaceuticals and personal care products from biosolids compost use is low (Brown et al., 2019), while the significance of contaminants such as PFAS introduced to soils, groundwater and food crops from biosolids and biosolids compost applications is an ongoing area of research (Johnson, 2022; Levine et al., 2023; Pozzebon & Seifert, 2023). EPA considers biosolids and biosolids compost that meet federal standards for Class A Exceptional Quality to be safe for use in any application, including growing food. However, biosolids compost is prohibited for use in organic agriculture due to the potential presence of synthetic chemicals (USDA, 2019). A full risk assessment for PFAS in biosolids is not yet available.

**Use Suitability:** Biosolids-based compost is suited for soil fertilization and water retention due to its organic matter content, fine texture and nutrient content (Ozores-Hampton et al., 2022; Rynk, Schwarz, et al., 2022; Stehouwer et al., 2022). Biosolids are usually co-composted with other bulkier feedstocks like yard trimmings or wood and are generally suitable for a variety of uses, including agriculture, horticultural, landscaping, turfgrass establishment/management and the improvement of degraded soils (e.g., soils with low levels of organic matter, physical disturbance, compaction and/or contamination). Biosolids' nutrient levels are typically consistent over time, and biosolids also have no physical contaminants, providing some advantages over food scraps and yard trimmings. As a higher-nutrient feedstock (relative to other urban residuals), it can be used to make compost that can meet the nutrient demands of turf, ornamentals and crops (Alvarez-Campos et al., 2018; Badzmierowski et al., 2020; Batjiaka & Brown, 2019; Brown et al., 2023b; Cogger et al., 2008; Cogger et al., 2013; McIvor et al., 2012).

Biosolid-based composts may also be suitable for use in GI and compost blankets for stormwater and erosion control projects (assuming N, P, K and contaminant levels are low). In addition, biosolids-based composts have been shown to be highly effective at reducing both metal concentrations and bioaccessibility in contaminated urban soils (Brown et al., 2004; Brown et al., 2003).

## 10.3.5 Wood

This feedstock consists of small woody materials such as chips, shavings, bark and sawdust, as well as large materials such as tree branches, trunks, clean/untreated pallets and lumber. These materials are very high in C and low in N, with a C:N ratio typically greater than 250:1 (Rynk, Schwarz, et al., 2022). Therefore, wood is seldom used as a sole feedstock but instead is typically combined with feedstocks having a low C:N ratio, such as food waste, biosolids and manure. When combined, it adds C and increases structure, aeration and sometimes the water-holding capacity (Rynk, Schwarz, et al., 2022).

**Challenges:** Larger woody materials require specialized equipment for pre-processing (e.g., chipping or grinding) before being added to composting systems to facilitate breakdown. Painted wood and wood that has been treated with chemicals to resist rotting are not suitable for composting; if present, these should be removed from the feedstock.

**Use Suitability:** Wood feedstock supports C sequestration, soil structure conditioning, erosion control, pollutant removal, disease suppression and weed suppression due to its high C:N ratio, low levels of salts, coarse texture and relatively low content of nutrients, metals and other chemical contaminants (Neher et al., 2022; Ozores-Hampton et al., 2022; Rynk, Schwarz, et al., 2022; Stehouwer et al., 2022). Compost mixes with wood are typically used as mulch for landscaping and horticulture, stormwater and erosion control (e.g., seeded compost blankets, compost berms and compost filter socks), GI, and remediating degraded soils (e.g., soils with low levels of organic matter, physical disturbance, compaction and/or contamination).

### 10.3.6 Chemical and Physical Contaminants in Feedstocks

Chemical and physical contaminants pose challenges for using various feedstocks to manufacture compost, and the risks presented by these contaminants may vary depending on how the compost is used. For example, more contamination may be acceptable when applying compost to restore a disturbed mine site than when applying compost to an agricultural field growing edible crops.

High levels of physical contaminants may increase operating costs by requiring additional manual screening/sorting or specialized equipment for de-packaging, and these approaches cannot remove all physical contaminants. Visible physical contamination can lower the value of compost to potential customers, while less discernible micro- and nano-plastics may also pose risks to human health and the environment. While the available literature does not provide substantial evidence of environmental or human health effects that are occurring because of plastic contamination in finished compost, much remains uncharacterized about the environmental fate of and exposure to plastic particles in compost, making it challenging to evaluate risks to human health and the environment. It is also unclear how the risks associated with compost compare to those of background levels of plastic contamination and other sources of plastic contamination in the environment, such as other soil amendments (synthetic or made from wastewater sludge and biosolids) (EPA, 2021c).

Some chemical contamination is present in physical contaminants (e.g., PFAS in food packaging) and may be partially removed through screening or de-packaging. However, PFAS has been detected in finished compost. Available evidence indicates PFAS concentrations are highest in compost made from biosolids, followed by food waste compost and then yard trimmings compost (EPA, 2021b; Goossen et al., 2023). Typically, these feedstocks are mixed when manufacturing compost, resulting in more complex rankings. Given the limited data available, general conclusions cannot be made with confidence about human health and environmental risks associated with land application of PFAS-contaminated compost. There is a need to determine with confidence the exposure levels and risks associated with using PFAS-contaminated compost in various compost uses, from agriculture to stormwater management and disturbed site restoration.

Persistent herbicides may be found in animal manure and yard trimmings and cannot be removed during composting. The presence of these herbicides in compost can damage sensitive plants, thus limiting the compost's potential uses. For more information, see EPA's 2021 reports on Plastic Contamination and Persistent Chemical Contaminants as emerging issues in food waste management (EPA, 2021b, 2021c).

# 11. Compost Qualities and Environmental Performance

Compost qualities can vary considerably due to differences in compost feedstocks, amendments and manufacturing processes. The key characteristics affecting compost performance for different environmental functions are:

- Organic matter
- Particle size
- Maturity
- Stability
- Nutrient levels
- C:N ratio
- pH
- Soluble salts
- Microbial content
- Pathogen levels

It is important to ensure these characteristics align with the intended environmental uses or functions (e.g., soil fertilization, disease suppression, water retention). Some characteristics, including organic matter content, nutrient levels, C:N ratio, pH and soluble salts, largely reflect the feedstocks used. Differing proportions of feedstocks can be used in the manufacturing process to adjust the levels of these characteristics. The compost manufacturing process influences other characteristics, such as particle size, maturity, stability, microbial content and pathogen levels. For example, feedstocks such as wood and yard trimmings can be ground or shredded before composting to facilitate more efficient composting, and finished compost can be screened to achieve a desired range in particle size.

*Figure 19. Compost screening at a municipal yard trimmings composting facility. Photo by Doug Pinkerton, courtesy of BioCycle.*

Generally, the feedstock used to make a compost is not critically important if the qualities of the finished compost align with the intended use. For example, if the primary intended environmental function is C sequestration, any compost that has a high stability and high organic matter content is suitable. In contrast, if the primary environmental function is soil fertilization, it is important to select a compost made from one or more feedstocks having a relatively high nutrient content and low level of contamination, such as food waste or poultry manure, instead of one derived primarily from a feedstock with low nutrient levels (e.g., yard trimmings consisting of dead leaves). Table 9 summarizes the relative importance of these characteristics for contributing to specific end-use functions.

*Table 9. Relative importance of compost characteristics to various environmental functions. Source: adapted from Ozores-Hampton et al. (2022) based on Alexander (2020e); Stehouwer et al. (2022), Alexander (2023), Neher et al. (2022); Ozores-Hampton (2021c); Stoffella et al. (2016), NRCS (2010).*

| Function | Stability[a] | Maturity | Organic matter | Nutrient levels | C:N ratio | pH | Soluble salts | Microbial content | Particle size | PFRP[b] |
|---|---|---|---|---|---|---|---|---|---|---|
| Soil structure conditioning | M | M | VH | M | L | M | H | H | L | L |
| Runoff and erosion control | H | H | H | L | M | L | M | M | H | H |
| Pollutant removal[c] | H | M | H | H | H | M | H | L | H | M |
| Soil fertilization | H | H | H | VH | H | M | M | M | M | M |
| Carbon sequestration | H | M | VH | M | M | L | M | M | M | M |
| Water retention[d] | H | M | VH | L | L | L | L | M | H | M |
| Disease suppression | H | H | H | M | H | M | H | H | L | VH |
| Weed suppression | VH | H | M | M | L | L | L | L | M | H |

*Notes:*
VH: very high importance; H: high importance; M: moderate importance; L: low importance
[a] Relative importance of stability for different functions was based on multiple sources (Neher et al., 2022; NRCS, 2010; Ozores-Hampton et al., 2022; Stehouwer et al., 2022).
[b] Processed to Further Reduce Pathogens (PRFP).
[c] Relative importance of compost characteristics for pollutant removal was surmised using a combination of information sources (Archuletta & Faucette, 2014; Davis et al., 2023; Heyman et al., 2019; Ozores-Hampton et al., 2022; Stehouwer et al., 2022).
[d] Relative importance of particle size for water retention was modified based on Heyman et al. (2019).

Maturity and stability are two key characteristics of compost. Compost maturity refers to the degree to which the fast-degrading materials have completed their degradation and only slow-degrading materials remain. It is an indication of the completion of the composting process, in particular, the extent to which substances that are toxic to plants have been degraded (Ozores-Hampton, 2021a; Stehouwer et al., 2022). Such substances include $NH_3$, volatile fatty acids and other soluble compounds that can impede seed germination, seedling survival and vigor or cause nuisance odors (Stehouwer et al., 2022).

Compost that meets sufficiently high temperatures for a prescribed time period and number of turns to destroy human pathogens is referred to as Processed to Further Reduce Pathogen (PRFP) (Ozores-Hampton et al., 2022). This process is also used to destroy weed seeds. To ensure the destruction of pathogens and weeds, it has been recommended that the composting process maintain a temperature between 131 °F and 171 °F for at least 15 days and that the compost be turned a minimum of five times (Neher et al., 2015).

Stability is an indication of the rate of organic matter degradation through microbial activity (Stehouwer et al., 2022). A compost with high stability has a low rate of continued degradation. A more stable compost will have greater N availability following application to a soil, while a less stable compost may result in N immobilization (NRCS, 2010; Stehouwer et al., 2022). Also, a stable compost will have a lower loss of volume post-application (Stehouwer et al., 2022). The curing phase of compost manufacturing (which occurs as temperatures decline from the thermophilic phase) is critical to achieving compost stability.

A compost can be stable but not be mature. For most purposes, it is important for compost to be both stable and mature (Risse & Faucette, 2023). However, compost of moderate maturity may have more value for suppressing weeds (Stoffella et al., 2016), and compost that is moderately stable may suppress disease more than highly stable compost (Neher et al., 2022).

## 11.1 Compost Quality Recommendations

Specific uses of compost have recommended ranges in characteristics. For some characteristics, such as pH, a single range may confer suitability for a variety of end uses. For others, such as organic matter content and soluble salt concentrations, the recommended ranges vary by end use. This is why standardized testing of finished compost and compost quality standards are important (Bernal et al., 2017; Stehouwer et al., 2022).

Recommended ranges for key parameters of finished compost for select uses are summarized in Table 10. Based on site-specific considerations and concerns, more specific recommendations may be applicable. For example, Heyman et al. (2019) recommended that when incorporating up to 33% compost by volume into degraded urban soils (e.g., soils with low levels of organic matter, physical disturbance and/or compaction) to optimize plant and soil health and minimize nutrient leaching “the optimal compost will generally have a C:N ratio of 10–20, P-content < 1.0 percent and a soluble salt content between 1.0 and 3.5 mmhos/cm.”

*Table 10. Recommended ranges for key compost parameters for select compost uses. Source: Alexander (2020a, 2020b, 2020c, 2020d, 2020e, 2020f, 2020g, 2020h, 2020i, 2020j, 2020k).*

<table>
<tr><th rowspan="2">Parameters[a, e]</th><th rowspan="2">Units of measure</th><th colspan="8">Compost Use</th></tr>
<tr><th>Crop production</th><th>Edible gardens and landscaping[f]</th><th>Topsoil manufacturing</th><th>Turfgrass installation & maintenance</th><th>Upgrading marginal soils</th><th>Bioretention media</th><th>Erosion control blankets, vegetated[g]</th><th>Erosion control blankets, non-vegetated</th></tr>
<tr><td>pH[b]</td><td>pH units</td><td colspan="6">6.0–8.5</td><td colspan="2"></td></tr>
<tr><td>Soluble salt concentration[b] (electrical conductivity)</td><td>dS/m (mmhos/cm)</td><td>Maximum 20</td><td colspan="4">Maximum 10</td><td>Maximum 5</td><td colspan="2">Maximum 10</td></tr>
<tr><td>Moisture content</td><td>% wet weight basis</td><td colspan="8">30%–60%</td></tr>
<tr><td>Organic matter content</td><td>%, dry weight basis</td><td colspan="5">30%–65%</td><td>25%–65%</td><td colspan="2">25%–100%</td></tr>
<tr><td>Particle size</td><td>% passing a selected mesh size, dry weight basis</td><td colspan="5">95% pass through 3/8-inch screen or smaller</td><td colspan="3">100% passing 3 inches<br>90%–100% passing 1 inch<br>65%–100% passing 3/4 inch<br>0%–75% passing 1/4 inch<br>Max particle length of 6 inches</td></tr>
<tr><td>Stability – $CO_2$ evolution rate</td><td>mg $CO_2$-C per g OM per day</td><td colspan="6">< 4</td><td colspan="2">< 8</td></tr>
<tr><td>Maturity – (bioassay) seed emergence seedling vigor</td><td>% relative to positive control</td><td>N/A</td><td colspan="5">Minimum 80%</td><td colspan="2">N/A</td></tr>
<tr><td>Physical contaminants (man-made inerts)</td><td>% dry weight basis</td><td colspan="4">< 0.5% (0.25% film plastic)</td><td>< 1.0%</td><td colspan="3">< 0.5% (0.25% film plastic)</td></tr>
<tr><td>Chemical contaminants[c]</td><td>mg/kg (ppm)</td><td colspan="8">Meet or exceed EPA Class A standard, 40 CFR § 503.13, Tables 1 and 3 levels</td></tr>
<tr><td>Biological contaminants: indicator organisms, fecal coliform bacteria and/or salmonella[d]</td><td>MPN per gram dry weight</td><td colspan="8">Meet or exceed EPA Class A standard 40 CFR § 503.32(a) levels</td></tr>
</table>

*Notes:* dS/m = deciSiemens/meter; mg/kg = milligram per kilogram; mmhos/cm = millimhos per centimeter; MPN = most probably number; ppm = parts per million; OM = organic matter.

[a] Recommended test methodologies are provided in Test Methods for the Examination of Composting and Compost (USCC, 2002).

[b] The pH and soluble salt content of the final amended soil is more relevant to the establishment and growth of a particular plant than the pH or soluble salt content of the specific compost used to amend the soil. The pH and soluble salt content of the compost is diluted when mixed with the native soil, so testing for these parameters in the amended soil is suggested. Each specific plant species requires a specific pH range. Each plant also has a salinity tolerance rating, and maximum tolerable quantities are known. Most ornamental plants and turfgrass species can tolerate a soil/media soluble salt level of 2.5 dS/m and 4 dS/m, respectively. Seeds, young seedlings and salt-sensitive species often prefer soluble salt levels at half those levels.

[c] EPA Class A standard, 40 CFR § 503.13, Tables 1 and 3 levels = arsenic 41 ppm, cadmium 39 ppm, copper 1,500 ppm, lead 300 ppm, mercury 17 ppm, molybdenum 75 ppm, nickel 420 ppm, selenium 100 ppm, zinc 2,800 ppm.

[d] EPA Class A standard, 40 CFR § 503.32(a) levels = salmonella.

[e] Landscape architects and project (field) engineers may modify the allowable compost specification ranges based on specific field conditions and plant requirements. [f] Higher soluble salt concentrations may be allowed where salt-tolerant plants are established, or lower application rates are used. If concerned about soluble salt content, heavily water the planting bed after planting, allowing for the salts to leach. Compost possessing a higher soluble salt content often also possesses a higher amount of plant nutrients.

[g] Maximum salt allowances may be 10 dS/m if seed germination trials confirm both germination and vigor of 80% or more.

# 11.2 Environmental Performance

The following sections outline desirable compost qualities for specific environmental functions. Research on the role of compost qualities relative to environmental functions is also summarized, including studies that have explored differences in performance associated with compost derived from different feedstocks.

## 11.2.1 Soil Structure Conditioning

Composts with the following qualities will generally perform better for soil structure conditioning (Ozores-Hampton et al., 2022; Wilson et al., 2018):

- High organic matter content
- High C content
- Low to moderate levels of soluble salts
- High microbial content

All composts are soil conditioners because they add C to the soil, improving soil structure, water storage, and water and air movement. Composts with greater levels of organic matter and C provide more soil conditioning benefits (Ozores-Hampton et al., 2022; Wilson et al., 2018). Heyman et al. (2019) evaluated the effects of composts manufactured from different feedstocks (animal manure, yard trimmings, food scraps) on soil and plant health and noted considerable variability in characteristics among the nine composts tested. All compost types improved soil aggregate stability, organic matter content and SOC levels.

## 11.2.2 Soil Water Retention

Qualities of compost incorporated into soils that facilitate soil water retention include (Ozores-Hampton et al., 2022; Rynk, Schwarz, et al., 2022):

- High organic matter content
- High stability
- Fine texture
- A high C:N ratio (for mulch)

According to Rynk, Schwarz, et al. (2022), highly stable compost made from feedstocks with a finer texture and high organic matter content results in greater water-holding capacity. Chapman et al. (2022) found that manure compost applications resulted in higher soil moisture levels in comparison to OFMSW compost. The water retention capacity of a given compost is very important when it is used in soil-less media for growing plants in containers and may also be a consideration if compost is being used to improve the quality of coarse-textured soils (Stehouwer et al., 2022).

## 11.2.3 Soil Fertilization

Compost nutrient levels vary according to the types of feedstock used (Faucette et al., 2006; Ozores-Hampton, 2021b). Generally, the most important qualities for compost used for soil fertilization are (Kelley et al., 2022; Ozores-Hampton et al., 2022):

- High organic matter content
- High content of N, P, K (and plant essential micronutrients)
- A relatively low C:N ratio (e.g., below 18:1)
- High stability
- High maturity

Variations in nutrient levels within and among feedstocks can result in differences in soil fertilization post-compost use. Kelley et al. (2022) compared the performance of food-based versus manure-based compost in supplying nutrients (N, P, K) to greenhouse-grown spinach (in sandy soils). Four composts were compared: a commercial manure-based compost, composted dairy manure solids, a commercial food-based compost (blended with plant residues and high-C forest products), and a non-commercial food-based compost. The compost application rates were designed to control for 90 lbs N $ac^{-1}$. The commercial manure-based compost and the non-commercial food-based compost were both associated with improved spinach yields, which was attributed to greater initial levels of K and plant-available N. The non-commercial food waste compost was the only compost associated with greater soil P levels than manure compost at the time of harvest for spinach, roughly two months after planting. The dairy manure solids compost and commercial food-based compost did not improve yield. It was believed that the relatively high C:N ratio of 23.8 for the dairy manure solids compost likely contributed to N immobilization in the soil. The dairy manure solids compost and commercial food-based compost were deemed to function better as soil conditioners rather than soil fertilizers.

Faucette et al. (2006) compared the performance of four compost/compost blends seeded with Common Bermudagrass in soils physically disturbed by construction activities; the blends were: (1) biosolids compost blanket; (2) a yard trimmings compost blanket; (3) an OFMSW compost and mulch blanket (2:1 compost to mulch by volume); and (4) a poultry litter compost, mulch and gypsum blanket. The OFMSW treatment increased soil P the most, followed by biosolids compost, poultry litter compost and yard trimmings compost, respectively; however, the differences were not statistically significant relative to the control. The OFMSW treatment increased soil P by more than 2.5 times relative to the yard trimmings treatment, even though it had the lowest initial P content. In addition, the biosolids compost was associated with significantly more weed biomass than the yard trimmings compost, which was linked to a higher proportion of mineral N content ($NH_4$ and $NO_3$) in the biosolids compost despite having a similar C:N ratio.

Kelley et al. (2020) found that compost derived from food waste resulted in greater soil $NO_3$ levels than manure compost over a two-month period. Heyman et al. (2019) found that compost made from manure or food scraps resulted in the largest, greenest plants yet were also associated with greater leaching of N and P. In contrast, compost made from woody materials was detrimental to plant growth because it facilitated N immobilization. Low-nutrient feedstocks or those with a high C:N ratio are typically better suited for uses where maximizing vegetation growth is not a primary objective (e.g., green stormwater infrastructure). Table 11 shows levels of N, P and K typically observed in compost derived from different feedstocks.

*Table 11. N, P and K concentrations and N mineralization rates of compost. Source: adapted from Ozores-Hampton (2021b).*

| Feedstocks | N (%) | P (%) | K (%) | Rate of N release (% yr$^{-1}$) |
|---|---|---|---|---|
| Biosolids | 3–6 | 2–3 | 0.10–0.15 | 3.0–20 |
| Feedlot manure | 1.9–2.2 | 0.3–1.2 | 0.6–3.2 | 3.0–15 |
| Horse manure | 0.5 | 0.2 | 0.4 | 10 |
| Dairy manure | 1.2–1.5 | 0.3 | 0.9 | 6.0–5 |
| Poultry manure | 1.3–5 | 3.0 | 2.0 | 20 |
| Food waste (unspecified type) | 1.1–1.8 | 0.03–0.09 | 0.35–0.45 | 2.0–12 |
| Fruit and vegetable waste | 1.39 | 0.26 | 1.19 | 10 |
| Brewery waste solids | 1.3–1.8 | 0.02 | 0.13–0.18 | 5.0–10 |
| Olive mill waste | 3.5 | 0.17 | 2.3 | 20 |
| OFMSW | 2.3 | 1.11 | 0.64 | 3.0–10 |
| Yard trimmings | 1.0–1.2 | 0.2–0.3 | 0.2–1.4 | 2.0–10 |

Although a nutrient analysis can identify the amount of nutrients in a compost, it cannot indicate the quantities that are immediately available for plant uptake (NRCS, 2000). The rate at which nutrients are released may vary among different types of compost (see Table 11) (Case & Jensen, 2019). Organic forms of N within compost must be mineralized to the inorganic N forms (i.e., $NH_3$ and $NO_3$) before most plants can use it (Stehouwer et al., 2022). Compost with higher levels of $NH_3$ and $NO_3$ will provide N to plants more quickly (Alexander, 2020f). N mineralization rates may be greater for compost made from N-rich feedstocks such as manures and biosolids and less for compost derived from C-rich feedstocks such as yard trimmings or wood shavings (Stehouwer et al., 2022). This is important because if a finished compost's C:N ratio is less than 20, organic N will be mineralized in the soil and become available for plants. The use of stable compost possessing a C:N ratio of roughly 15:1 is ideal because it allows more of the compost-derived N to be used by plants (Alexander, 2020f). Compost with C:N ratios greater than 25 have a higher likelihood of immobilizing inorganic forms of N in the soil (Stehouwer et al., 2022) (See also Section 2.2). Both Kelley et al. (2022) and Heyman et al. (2019) observed that composts with a C:N ratio above 20 inhibited plant growth, likely due to N immobilization in the soil. Composters routinely mix different feedstocks together to adjust the C:N ratio into the range desired for specific end uses.

### 11.2.4 Runoff and Erosion Control

Key qualities that improve the performance of compost for runoff and erosion control include (Alexander, 2016; Ozores-Hampton et al., 2022):

- High organic matter content
- High C:N ratio
- High stability
- High maturity
- PRFP
- Coarse texture (particularly when used as a slope blanket; see Table 10)

A compost with a coarse texture and a high C:N ratio is obtained by using a greater content of woody feedstock (Alexander, 2020c). Woody fractions increase protection from raindrop impact and can increase surface roughness and slow the flow of runoff. This enhances infiltration and decreases the potential for sediment (and associated pollutants) to be transported off-site by runoff (Alexander, 2016; Faucette, 2012a). Also, using low-nutrient feedstocks or those with a high C:N ratio helps reduce nutrient leaching and increase pollutant capture for applications where vegetation growth is not a primary objective (e.g., compost filter socks).

An increasing number of studies have assessed the capabilities of different compost blends to reduce runoff and erosion. For example, the benefits of yard trimmings and biosolids compost blends have been compared by measuring runoff volume and the export of nutrients and sediment in post-construction highway embankments (Owen et al., 2020, 2021). One study indicated that yard trimmings and biosolids compost treatments (a 2:1 topsoil-compost blend) and pure compost with straw mulching were more effective at reducing stormwater runoff compared to that of a topsoil standard (Owen et al., 2020). Owen et al. (2021) compared yard trimmings and biosolids compost blends to a current stability practice used for final grade turfgrass establishment on physically disturbed soils. In the controlled greenhouse study, runoff volume was reduced for only the biosolids compost treatment (40%–98% reduction from standard practice), compared to the topsoil/straw standard treatment. Conversely, increased runoff volume by 1.5-, 1.4- and 20-fold was observed for yard trimmings compost, topsoil-biosolids compost mix (2:1), and topsoil-yard trimmings compost mix (2:1), respectively. An increase in compost percent (pure compost versus topsoil/compost blends) resulted in a 96%–99% reduction in sediment mass export and a 89%–98% reduction in volume runoff due to the organic matter increase, which led to greater soil aggregation, water-holding capacity, and soil hydraulic conductivity and reduced soil bulk density.

Faucette et al. (2005) found differences in the performance of four composts (derived from poultry litter, biosolids, OFMSW and yard trimmings) at reducing stormwater runoff. Infiltration rates were highest for the OFMSW and yard trimmings compost treatments, which both allowed 51% more water to infiltrate the surface relative to the bare soil control. In comparison, poultry litter and biosolids had infiltration rate increases of 43% and 31%, respectively. Reductions in runoff were greatest for the poultry litter and biosolids compost treatments over the one-year study, with runoff volume reductions of 43% and 33%, respectively.

## 11.2.5 Pollutant Removal

The following qualities are important for compost used to remove pollutants (e.g., compost filter socks) (Ozores-Hampton et al., 2022):

- High organic matter
- High C:N ratio
- High stability
- Moderate-to-coarse texture
- Low levels of soluble contaminants (e.g., nutrients, metals, toxins)

Generally, composts high in C, such as those including wood or straw feedstocks, produce compost that is better at filtering and trapping sediment and other pollutants carried by runoff (Ozores-Hampton, 2021a; Rynk, Schwarz, et al., 2022). Brown et al. (2015) compared the ability of three blends of compost (biosolids/yard trimmings, yard trimmings/food waste and manure/sawdust) in bioretention soil mixtures to remove pollutants from leachate collected from a synthetic stormwater solution. All treatments reduced $NH_3$, $NO_3$ and Zn concentrations, and Cu removal (total and dissolved) was greater than 90% for all treatments. The biosolids/yard trimmings compost was less effective than the other materials at removing Zn, with a removal efficiency of approximately 50% (Brown et al., 2015).

Compost blends with topsoil have been observed to decrease nutrient runoff in a post-construction setting. Compost blends containing yard trimmings are capable of controlling erosion, and they have also been reported to filter, bind and degrade contaminants from stormwater runoff (Alexander, 2016; Faucette, 2009; Faucette et al., 2013). Owen et al. (2020) found total P mass export was lower in most compost treatments (with compost derived from either yard trimmings or biosolids) compared with a standard topsoil treatment.

As described in Section 10, composts may have contaminants that originate in certain feedstocks and can be a source of environmental pollution. For example, composts higher in nutrients, such as those based on food waste, biosolids, or animal manure, can potentially contribute nutrients to water bodies, albeit likely less than contributed by conventional inorganic fertilizers (Basta et al., 2016; Heyman et al., 2019; Oladeji et al., 2020; Ozores-Hampton, 2021a; Rynk, Schwarz, et al., 2022). The risk is greater during storm events or periods when plants are not actively growing (NRCS, 2010). Chapman et al. (2022) found that manure compost applications resulted in higher amounts of leachate when compared to compost derived from OFMSW. Owen et al. (2021) reported that yard trimmings compost and biosolids compost addition led to P and N export increases of 1.5- to 51-fold and 2.2- to 3.3-fold, respectively, due to increased runoff concentrations (for pure compost treatments) or increased runoff volume (in topsoil/compost mixtures). In an earlier study, Owen et al. (2020) observed that a 2:1 biosolids compost-topsoil blend with straw mulch was associated with a 36% increase in N export and a 15% increase in P export relative to the standard topsoil with straw mulch treatment. It was recommended that the biosolids treatment not be used to replace the standard topsoil treatment for slope stabilization along highways due to increased nutrient export.

Hurley et al. (2017) suggested that compost made from low-N and P feedstocks, such as yard trimmings or leaves, might be a more suitable option for protecting water quality. Substances that bind N and P compounds can also be added to stormwater and erosion control applications that use compost to prevent leaching and capture nutrients. Brown (2016) found that adding Fe-based water treatment residuals (at 2%–4% dry weight) to compost prevented P leaching and allowed for the removal of P from simulated stormwater. Another study found that compost filter socks (from land clearing and yard trimmings) with unspecified natural sorbents added to them removed an average of 34% of soluble P, 54% of $NH_4^+$ (as N) and 11% of $NO_3$-N from stormwater runoff compared to using filter socks alone (Faucette et al., 2013).

When selecting compost for a specific application, consideration should be given to the potential for undesirable soil and water quality effects, which are likely to vary based on the amount of compost being used. Laboratory analyses targeting potential pollutants of concern may be warranted for certain types of projects, such as large-scale roadside erosion control projects.

## 11.2.6 Carbon Sequestration

The qualities of compost that are suggested to increase C sequestration include (Ozores-Hampton et al., 2022; Wuest & Reardon, 2016):

- High organic matter content
- High stability
- Nutrient Levels (P content)

There is limited research comparing C sequestration in soils among compost types. Wuest and Reardon (2016) found that SOC was highly correlated with compost P content, suggesting that the use of composts manufactured from materials with a relatively high P content, such as biosolids, OFMSW and manure, may have greater potential for C sequestration than composts made from feedstocks lower in P such as food waste and yard trimmings. Additionally, using feedstocks with higher nutrient levels results in higher microbial activity and greater plant growth following compost application. Over time, the increase in soil and plant productivity can further increase SOC levels.

## 11.2.7 Microbial Communities and Disease Suppression

The following compost qualities are preferable to suppress plant disease and enhance communities of beneficial microorganisms (Neher et al., 2022; Ozores-Hampton et al., 2022):

- PRFP (see Sections 10.3.4 and 11 for more information)
- Moderate stability
- High maturity
- High organic matter
- High C:N ratio
- Low to moderate levels of soluble salts and low $NH_3$ content
- High abundance of microbes

The abundance and diversity of microbial communities within compost are related to compost's disease-suppression qualities. General improvements in soil health associated with compost addition include a more robust microbial population, with reductions in disease causing microbes. Soils amended with compost are reported to have a different microbial community structure than soils amended with raw or vermicomposted manures, including differences in $NH_3$-oxidizing bacteria (Lazcano et al., 2021). In a previously referenced study by Heyman et al. (2019), all compost amendments increased soil respiration (a measure of microbial activity) and a soil protein index, an autoclaved citrate extractable (ACE) that measures organically bound N that microbes can make available for plants. The greatest increase in the ACE soil protein index score was associated with a compost manufactured from food waste and yard trimmings, and the greatest increase in soil respiration was observed in the treatment involving composted wood chips.

There is evidence that compost feedstocks can affect the utility of compost in helping to suppress plant disease. The most reliable disease-suppressive composts are those made with woody materials, like tree bark, wood chips and woody yard trimmings. Tree bark and other woody materials consist mostly of lignin, cellulose, tannins and waxes, a mixture that resists decomposition. After composting, the disease-suppressive effects of composted barks last for several years in the soil, depending on the tree species from which the bark originated and how much compost was added to the soil (Neher et al., 2022). In contrast, food and livestock feed wastes (e.g., spoiled hay or grain), animal manures, biosolids, and other similar feedstocks with a lower C:N ratio mostly consist of readily decomposable compounds that will not last as long in the soil (Neher et al., 2022). Heyman et al. (2019) found that manure-based compost treatments tended to be associated with a greater incidence of root pathogens.

### 11.2.8 Weed Suppression

The compost qualities that are reported to aid in weed suppression include (Ozores-Hampton et al., 2022):

- High stability
- Moderate maturity
- Coarse texture
- PRFP

Compost that contains a significant coarse woody fraction is known to improve weed suppression, as the coarse particles tend to "float" on the soil surface, creating a mat. Faucette et al. (2006) suggested that composts with a lower N content and higher C:N ratio will perform better for weed control. The completion of a PRFP during compost manufacturing helps ensure that weed seeds are destroyed by high temperatures so the finished compost does not introduce weeds where it is applied (see Section 11 for more information on PRFP).

# 12. Rates and Frequency of Compost Applications

Application rates, frequency and timing can influence the benefits of compost. In general, greater amounts of compost are applied during an initial application to a site. After initial application, the rate is typically less for most maintenance functions unless the compost is periodically applied as a mulch for established vegetation. Soil application rates for most uses generally range from 1/8 inch (e.g., for topdressing vegetated soils) to 4 inches deep (e.g., for use as a mulch), which approximates to 8 to 268 tons $ac^{-1}$ wet wt. (Ozores-Hampton et al., 2022). NRCS recommends that application rates should not exceed 50 t $ac^{-1}$ dry wt. due to difficulty in incorporating compost into soils when applied at depths greater than 1–2 inches (NRCS, 2010).

One-time compost applications tend to show limited soil fertilization benefits; fertility benefits improve markedly with repeated compost applications (Stehouwer et al., 2022). For intensive uses of soils (such as agriculture) that tend to promote a more rapid decomposition of organic matter, compost is typically applied at a frequency of once every one to five years to maintain soil health benefits (Ozores-Hampton et al., 2022). Studies suggest that an annual application of compost is required to help sustain soil health and plant growth (Abbey et al., 2022; Ozores-Hampton et al., 2022; White et al., 2020). For example, Abbey et al. (2022) evaluated the differences in soil characteristics and crop yields in response to annual or biennial applications of OFMSW compost at a rate of 6.7 tons $ac^{-1}$ to soil plots in Manitoba, Canada. In year five of the experiment, soil plots with annual compost applications had significantly greater water-holding capacity, SOM, plant macro- and micro-nutrient levels (N, P, K, Mg, Fe, Zn) and significantly lower bulk density. Yields of green beans, lettuce and beets were also compared, with beet yields being significantly greater in plots with annual compost applications. Annual compost applications appeared to be associated with greater functional diversity in the soil bacteria community. The most notable negative effects of annual compost applications were an increase in the heavy metal molybdenum in both treatments and a substantial increase in soil salinity under the annual compost applications; however, it is unclear whether the observed levels were cause for concern. Some crops are sensitive to elevated levels of soil salinity and metals, although an increase in soil salinity from compost applications (or other amendments and fertilizers) is more typical for arid and semi-arid climates (Sullivan & Miller, 2001). In this regard, undesirable effects of compost use on soil health may be mitigated through the selection of compost with lower levels of undesirable constituents and adaptive soil health management based on soil quality monitoring.

No standardized method exists for determining the appropriate compost application frequency or rate to support specific uses (e.g., C sequestration, fertilization, soil conditioning, soil water conservation, erosion control and pollutant removal). Several approaches, however, are used to select compost application rates, which depend largely on the desired effect. According to Ozores-Hampton et al. (2022), compost application rates should consider:

- **Targets for SOM content**: With clay soils, it has been estimated that an SOC-to-clay ratio greater than 1:10 will support good soil structure on agricultural soils (Johannes et al., 2017).[2]

[2] Maximum equilibrium levels of SOM vary by soil texture and aeration. For example, SOM levels on coarse-textured, well-aerated soils where SOM decomposes relatively rapidly have an upper limit of SOM of approximately 2%. Additionally, the authors noted a soil with 50% clay may need twice as much organic matter as a soil with 10% clay to facilitate the development of stable soil aggregates. 50 t $ac^{-1}$ of dry organic matter would need to be added to raise SOM in the upper 6 inches of soil by 1%, although this is a generalized estimate for an instantaneous amount of SOM rather than an estimate of what would be required to attain equilibrium levels of SOM, accounting for organic matter additions and losses through mineralization over time. Therefore, achieving an SOM-to-clay ratio greater than 1:10 would require many years of compost applications for soils with a high clay content under practical application rates of organic matter applications (e.g., ≤50 t $ac^{-1}$. dry weight) (Magdoff & Van Es, 2021).

- **Plant nutrient targets:** Targets are determined in a similar way to the usage of conventional fertilizers, although for N, mineralization rates and N carryover from prior applications are important to estimate; for agriculture, this often requires supplemental fertilizer to meet crop nutrient demands.
- **Soil nutrient thresholds:** The thresholds are associated with crop nutrient demand or regulatory limits; the target nutrient content of the compost must be known when applying this approach.
- **Local research or conventions:** These rates are based on historical use by local operations or composter recommendations; they are often based on compost type, crop, climate, soil type, etc.
- **Contamination limits**: These limits are based on regulatory limits for contaminants such as pathogens, heavy metals, pesticides and other synthetic chemicals.
- **Cost limitations:** Application rates may be constrained by the cost of purchase and material handling (e.g., transporting and spreading bulky material can incur large costs).
- **Compost availability:** Compost supplies (or compost with desired qualities) may be locally limited.

When applied to sites that have existing vegetation, compost is typically applied on the surface, either as a thin topdressing (e.g., for turfgrass) or as a thicker mulch around plants. For example, a 4-inch layer of compost is typical for mulching garden beds, landscaping beds and around trees. For most agricultural crops, the cost of compost generally constrains application rates (Ozores-Hampton et al., 2022), except for higher-value crops like small fruits (e.g., strawberries) and fruit/nut trees where compost applications can be more targeted around individual plants. In horticulture, compost may be used at 5%–60% of the container growing media volume. Compost is generally not used at greater rates in container growing media because most compost formulations are overly porous, do not have a sufficient water-holding capacity, and may have elevated levels of soluble salts that can harm plants (Ozores-Hampton et al., 2022).

For stormwater management, the typical amount of compost used ranges from 10%–30% of media volume for stormwater infiltration practices (such as bioswales) to 100% when used in filtration devices (such as compost filter socks and filter berms). However, when used in stormwater filtration devices, it is important to use a compost type that will not leach nutrients and other contaminants that can degrade water quality (Section 10 discusses the compatibility of different compost feedstocks for various functions such as pollutant removal).

For most usages involving the application of compost to soils with depleted levels of organic matter, the benefits will generally increase as the compost application rate increases. In this regard, higher application rates are particularly beneficial for intensively managed or physically disturbed soils (e.g., cultivated agricultural lands, road or building construction sites) but less so for soils that already have adequate organic matter (e.g., residential lawns) (Brown & Beecher, 2019). For any given site and intended purpose, there is a point at which increasing the application rate or frequency will not result in corresponding benefit gains. For example, when using seeded compost blankets to control soil erosion and stormwater runoff, application depths greater than 2 inches tend not to provide additional hydrologic benefits and may inhibit seed germination (Faucette, 2023). On agricultural lands, this may occur after a point at which a greater application rate is no longer economical (Ozores-Hampton et al., 2022).

Depending on the specific compost usage and site, high application rates may increase the risk of unintended consequences. For example, application rates targeted to meet crop N demand can result in excessive levels of P when a compost with a low N:P ratio is used; excessive levels of P can pose a risk to water quality and may harm plants (Shrestha et al. (2020). Therefore, when compost is used to add nutrients, the nutrient content of the receiving soil should be monitored. High application rates may increase the levels of soluble salts (Abbey et al., 2022) or other contaminants, such as herbicide residues that can harm plants (Rynk, Schwarz, et al., 2022). This can be managed by selecting compost made from feedstocks that typically have low levels of soluble salts or contaminants, particularly when plants with a known sensitivity are being grown. It should be noted that if compost is used at regular agronomic rates, a high salt concentration in compost is unlikely to cause problems as it becomes diluted by the lower salt content of the receiving soils. In fact, in soils with high levels of salts, compost can be added as a means to reduce the impact of excess salinity (See Section 8.3). Salt levels are mostly a concern for certain applications that rely on high application rates (e.g., for contaminated soil remediation), in areas where salts are a problem (arid areas with limited irrigation to leach salts from soils), or when compost is used within potting mixes.

Research on higher application rates has suggested mixed results, depending on site conditions and the type of feedstocks used in the compost. Kranz et al. (2022) found that compost incorporated at rates up to 50% by volume in a sandy clay soil did not increase nutrient and heavy metals loads in runoff. The authors noted that their results contrasted with several other studies that found increased loads of nutrients and certain metals in runoff following compost applications along roadsides. For nutrients, compost application rates are generally more likely to have a substantially wider margin of error relative to conventional inorganic fertilizer applications, owing to compost's lower nutrient content and gradual nutrient release rate (Adelman & Kney, 2010). For example, the risk of nutrient pollution to water quality from applying 25% more compost than recommended is likely to be much lower than applying 25% more conventional phosphate fertilizer than recommended.

Overall, effective application rates vary depending on the objective (e.g., nutrient supply, water retention, mulch, potting mix), crop to be grown, soil characteristics and environment. Table 12 below summarizes typical compost application rates and frequencies for various applications. Furthermore, Tables 1 through 3 in Section 2 summarize the application rates from various studies and the benefits observed for specific soil characteristics.

*Table 12. Typical rates and frequency for compost applications. Sources: (Alexander, 2016); Alexander (2020a, 2020c, 2020d, 2020e, 2020f, 2020h, 2020i, 2020j); Ozores-Hampton et al. (2022).[a]*

| Application | Approximate rate[b] | Frequency | Application notes |
|---|---|---|---|
| Field crops (e.g., grains, legumes, potatoes, hay, pasture, cotton, sugar beets) | 2–10 t $ac^{-1}$[c, d] | Annually or less | Amount and frequency are often limited by cost; cost can be reduced by using compost that is less mature and stable; applied before planting, after harvest, or on fallow fields. |
| Vegetable crops | ≤ 50 t $ac^{-1}$[c, d] | Initial application | Sandy soils or tropical regions. |
| | 5–15 t $ac^{-1}$[c, d] | Initial application | Most crops. |
| | 2–5 t $ac^{-1}$[c, d] | Annually or less | Most crops. |
| | < 1 t $ac^{-1}$[d] | Annually or less | Specialty compost used for microbial augmentation. |
| Small fruits (e.g., strawberries, raspberries, blueberries) | 134–268 t $ac^{-1}$ of plant row[e,f] | Annually or less | Typically applied as a 2–4-inch surface mulch. Compost type must be aligned with plant tolerances; for example, blueberries have narrow tolerances for N, K, pH and soluble salts. |
| Vineyards | Broadcast: 2–15 t $ac^{-1}$ of vine row[e,f]<br><br>As a mulch: 134 t $ac^{-1}$ of vine row[e,f] | Annually<br><br>Once every 3–5 years | Rate and timing must be adjusted based on grape tolerances, nutrient requirements, and site-specific conditions; for example, grape quality is sensitive to soil N and moisture levels. |
| Fruit and nut trees | 20–50 t $ac^{-1}$[d,e] | Initial application | With cover crops, 5–10 t $ac^{-1}$ is also effective; may be lower if applied in bands where trees are to be planted. |
| | 134–268 t $ac^{-1}$ of tree row[e,f] | Annually | As a mulch, 2–4-inch thick and with a coarse woody texture to inhibit N supply to weeds. |
| Forestry (Rural/Urban) | ≥ 50 t $ac^{-1}$ | Annually or less | As a roughly 1-inch topdressing Compost may be slightly immature; this use offers less regulatory restrictions on use of biosolids compost. |
| Nursery/greenhouse container growing media | 5%–50% of media volume | N/A | Amount varies based on application (e.g., seed mixes, potted plants, bedding plants and nursery stock), compost characteristics and plant requirements/tolerances; must ensure composting process achieved pathogen-killing temperatures. |
| Field nursery production | 34–67 t $ac^{-1}$ of plant row[d,f] | Initial application | 0.5–1 inch in tree rows or planting holes; must ensure composting process achieved pathogen-killing temperatures. |

| Application | Approximate rate[b] | Frequency | Application notes |
|---|---|---|---|
| | 67–134 t $ac^{-1}$ of plant row[f] | Annually or less | As a mulch, 1–2-inch depth of coarse compost may be applied; must ensure composting process achieved pathogen-killing temperatures. |
| Turfgrass establishment | 67–134 t $ac^{-1}$[d] | Initial application | 1–2-inch depth. |
| Turfgrass maintenance | 8–17 t $ac^{-1}$ | Annually | 1/8–1/4-inch depth. |
| Landscaping | 67–268 t $ac^{-1}$[d,f] | Initial application for new beds | 1–4-inch layer for new landscape beds, depending on existing soil texture and organic matter content. |
| | 67–134 t $ac^{-1}$[f] | Annually or less, maintenance of beds | 1–2-inch layer of shallow incorporation, or as a surface mulch. |
| | 67–201 t $ac^{-1}$ [f] | Initial application, physically disturbed soils | 1–3-inch layer for revegetation of physically disturbed soils. |
| Remediation of urban soils | Incorporated into soil at a volume of 33% | Initial application | Recommended compost attributes: C:N ratio of 10–20, P content < 1.0%, soluble salt content of 1.0–3.5 mmhos/cm. |
| Surface mulching, general purpose | ≤ 268 t $ac^{-1}$[f] | Every 3 years | ≤ 4-inch layer on garden beds, landscaped areas, around trees. |
| Highway construction and maintenance | 67–134 t $ac^{-1}$ | Initial application | 1–2-inch layer. |
| Green infrastructure | 10%–30% of media volume | During establishment | Green roofs, rooftop gardens, rain gardens<br>To reduce N and P export in stormwater runoff: compost feedstocks/amendments high in Fe and Al can immobilize excess P; use plants with high N requirement. |
| Erosion control and stormwater management | 67–134 t $ac^{-1}$ | Initial application | Compost blanket with seed incorporated, 1–2-inch depth, uniformly applied; on steeper slopes, may be underlain by netting or wood fiber blankets (Beighley et al., 2010) or mulched with straw (Owen et al., 2021). |
| | 10%–30% by volume | During establishment | Bioretention units, bioswales |
| | Compost filter sock, filter berm: 100% by volume | N/A | To reduce P export in stormwater runoff: compost feedstocks/amendments high in Fe and Al can immobilize excess P. |

*Notes*: Al = aluminum; mmhos/cm = millimhos per centimeter; N/A = not applicable. t $ac^{-1}$ = tons per acre

[a] Compost is typically not used as the sole source of plant nutrients.

[b] Application rates are wet weights per acre; some rates are based on a conversion from depth to mass per unit area, based on an assumed density of 1000 lbs $yd^{-1}$ following Table 16.6 in Ozores-Hampton et al. (2022).

[c] Rate should be based on crop N demand and soil P levels.

[d] Typically incorporated into the soil.

[e] Pasteurized compost may be needed to prevent introduction of disease.

[f] This rate applies only within the rows or other areas containing the plantings, rather than an entire acreage of a field or site; e.g., if only half of a field is covered in plant rows, then the application rate accounting for the entire field area would be one-half of what is reported in the table.

# 13. Site Characteristics

The benefits of compost use vary by the characteristics of the site on which it is used. Soil characteristics, climate, topography and land use influence the effectiveness of compost use, and understanding these site-specific factors is important for optimizing the benefits.

## 13.1 Soils

The soil health benefits of compost use and its effects on environmental functions vary depending on the type of soil to which it is applied. As discussed in Section 2, compost use affects a variety of physical, chemical and biological soil characteristics. Yet, there is inherent variation in soil characteristics across multiple spatial scales, from the site to the landscape scale. For example, sandy soils typically have low amounts of organic matter, low fertility and high infiltration rates, while clayey soils typically have slow infiltration rates but a high capacity to retain nutrients and water. It is, therefore, important to consider how the performance of compost use varies with differences in soil characteristics.

### 13.1.1 Physical Characteristics

The texture of a soil influences its structure and, therefore, its capacity for water storage and water/gas movement. Soils with a greater soil particle aggregation, lower bulk density, greater porosity and higher water-holding capacity can better support the growth of plants and microorganisms. The physical benefits of compost are greatest for compacted or poorly structured soils, and the benefits diminish as soil bulk density decreases and porosity increases. Soils that are more highly degraded (e.g., soils with low levels of organic matter, highly disturbed and/or compacted) will require a larger amount of compost to improve soil structure (Ozores-Hampton et al., 2022).

It is difficult to predict the specific effect that a compost application may have on the structure, water and air permeability, water storage, and water movement due to site-specific variations in soil characteristics. Tables 1 and 2 in Section 2 report the observed results for soil bulk density and water infiltration, respectively, following compost applications on soils of different textures. Nevertheless, some generalizations may be made about how compost can affect these physical soil characteristics.

In fine-textured soils (e.g., clay, clay loam, fine silt), adding compost helps to reduce bulk density, improve soil particle aggregation and increase porosity. These effects help alleviate problems associated with dense soils, such as low friability and poor drainage. Compost may have little or no effect on the available water-holding capacity in soils with a large proportion of clay. However, improvements in the structure of clay soils following compost application can increase water infiltration, thereby reducing surface runoff (Rynk, Cooperband, et al., 2022).

Compost application to sandy soils increases organic matter content, soil particle aggregation, water retention, nutrient supply/retention and microbial activity (Hill, 2021). Research also suggests that adding compost in sandy soils facilitates moisture dispersion by improving the lateral movement of water from its point of application (Gould, 2015; USCC, 2008). Due to their lower matrix potential and larger pore sizes, sandy soils hold significantly less water by weight than clay soils, which can lead to drought stress for plants (Brown & Cotton, 2011). Therefore, the potential to improve water storage from compost applications is greatest in sandy soils (Brown & Cotton, 2011; Rynk, Cooperband, et al., 2022). In California, Brown and Cotton (2010) found that compost improved the total water-holding capacity in both sandy loam and sandy agricultural soil sites, but with a proportionally greater increase in the soil with a sandier texture. Sandy soils receiving 10–15 t $ac^{-1}$ of compost can see increases in the water-holding capacity of 5%–10% (McConnell et al., 1993); the improvement is dependent on initial soil conditions, such as depth of the soil, existing SOM content and antecedent moisture levels. For upgrading marginal-quality sandy soils, general recommendations include a 3-inch layer of surface-applied compost or a 12-inch depth of compost incorporation into the soil (Alexander, 2020j).

In loamy soils (sand, silt, clay mixtures), the benefits from compost reflect a combination of those observed in clay and sandy soils. Brown and Cotton (2011) found that finer-textured silty loam soil displayed a larger improvement in water infiltration rate after compost additions when compared with sandy loam and sandy soil types; compost amendments increased the infiltration rate in the silty loam, with the average infiltration time decreasing by more than 90%.

Organic soils (i.e., Histosols), such as those formed in wetlands, are less likely to display measurable benefits to soil structure, water movement and water storage from compost application (Winfield, 2020). These soils exhibit a high water-holding capacity that is not likely to be significantly increased by compost application. An exception to this would be where an organic soil has been degraded, compost may be useful in restoring natural conditions, such as in wetland restoration (Governo et al., 2003; USCC, 2008, 2022a). Wetland soils that have been drained and used for agriculture typically undergo significant changes in their structure and organic matter content. Heavy applications of compost can be used when restoring converted wetlands to help repair soil, hydrologic and biological conditions and processes.

Lastly, soil characteristics can influence the leaching of dissolved N and P derived from compost. N and P losses from compost tend to be greater in areas that become saturated with water, such as riparian areas, floodplains, in green stormwater infrastructure (Hurley et al., 2017), as well as in well-drained soils that receive relatively high rainfall (Heyman et al., 2019). However, this is likely true for most nutrient sources. Some evidence indicates that N and P leach less on deeper soils (Heyman et al., 2019).

### 13.1.2 Chemical Characteristics

The effect that compost has on nutrient availability varies depending on soil chemistry factors, including organic matter levels, pH and the presence of minerals, such as iron oxides. Nutrient availability in a healthy soil with high organic matter will show much less response to compost addition than a degraded soil. Soils with high organic matter content typically have high CEC, and adding compost may not further increase CEC and nutrient availability. Additionally, the influence of compost on nutrient availability can vary by soil texture; however, the nutrient content and C:N ratio of the compost will have a much greater influence than soil texture. Many sandy soils have constrained fertility due to inadequate organic matter and clay content. Compost has been shown to improve soil quality in sandy areas by increasing SOM, water-holding capacity, plant nutrients and CEC (Ozores-Hampton et al., 2011). It has been estimated that compost applications at a rate of 15–30 t $ac^{-1}$ (assumed to be wet weight) can increase the CEC of sandy soils by 10% (Shiralipour, 1998).

The pH of soil can influence the solubility of nutrients and minerals. In this regard, adding compost might affect fertilizer requirements and amendments needed to adjust soil pH (e.g., lime/S) (USCC, 2008). The effect of compost additions on pH is not equal across differing soil types. Compost addition may raise, lower, or have no effect on soil pH (USCC, 2008). Its effect depends on factors including the pH of the compost, its content of cations and the pH buffering capacity of the soil. For example, a high pH compost applied to a low pH sandy soil will likely increase soil pH, but the same compost applied at the same rate to a low pH, clayey soil may result in little or no change in soil pH (Stehouwer et al., 2022). However, most finished composts have a pH near neutral such that a general rule of thumb is that their application shifts soil pH towards neutral.

Acidic soils can have a lower availability of N, P and K; therefore, compost applications may help increase the availability of these nutrients by buffering pH. It was estimated that a compost application rate of 10–20 tons $ac^{-1}$ of a slightly alkaline compost typically increases pH by 0.5–1.0 in acid soil (Tyler, 2021). However, using compost to substantially raise the pH of organic soils (e.g., soils formed in wetlands that typically contain a relatively high organic matter content and have a low pH) may not be desirable or achievable. In contrast, as soil basicity increases, P availability is decreased, and micronutrients, such as Fe and Mn, tend to be immobilized. Therefore, adding compost to alkaline soils to bring the soil pH closer to neutral will increase micronutrient availability. In calcareous soils that have restricted Fe availability to plants, compost may be effective in increasing Fe bioavailability and alleviating deficiencies in plants (Ozores-Hampton, 2021a).

Also, when compost is applied to iron-oxide-rich soils (e.g., highly weathered Ultisols), P availability and leaching can be inhibited because these soils have a high P binding capacity (Evanylo et al., 2008). The slower rate at which N and P become available to plants from compost can be an advantage on sites where there are concerns about the degradation of water quality from nutrient pollution. N and P losses can be minimized through management techniques, such as accounting for site conditions using compost with lower amounts of N and P, as appropriate (Beighley et al., 2010); using application rates that target plant nutrient demands (Shrestha et al., 2020); aligning the timing of compost application with periods of plant growth to facilitate nutrient uptake (Heyman et al., 2019); and using sorbents that increase N and P retention where compost-based practices are used for stormwater management (Brown et al., 2015; Faucette et al., 2013).

### 13.1.3 Soil Limitations

The C sequestration potential of compost varies considerably among land use types. Soils that have been physically disturbed, resulting in net SOC losses, have a greater C sequestration potential. Brown and Beecher (2019) found that C sequestration associated with biosolids compost application at the site scale was greatest on disturbed soils (including new housing developments, neglected urban soils and highway rights-of-way), lesser on dryland agricultural sites, and the least on intensively managed landscapes (e.g., residential yards with existing vegetation). This is because intensively managed landscapes tend to have relatively high existing levels of SOC reserves. However, agricultural lands in the United States will likely have the greatest C sequestration potential at the national scale, given the net total acreage and the vast C deficit that currently exists in these soils (Sanderman et al., 2017). More information about C sequestration potential is provided in Section 4.

It is worth noting that there are unique soils where compost applications are undesirable. For example, serpentine soils are known for their high metal content and low fertility, and alvar is a very shallow soil formed from limestone bedrock. Both soils harbor unique plant communities adapted to harsh conditions. Compost applications to these soils are unlikely to be beneficial to the native plant communities (Winfield, 2020). Additionally, areas where native plant communities are adapted to conditions with low nutrient availability and low water availability may not benefit from compost application (Winfield, 2020). For example, it is unclear whether desert soils and their associated native plant communities would benefit from compost amendments.

## 13.2 Climate

Geographic variability in climate affects the benefits of compost processes post-application. Air and soil temperatures affect the rate of microbial growth and activity and thus the rate of compost decomposition, with warmer climates supporting faster compost decomposition and colder climates slowing it down. The compost nutrient release rate is also affected by regional climatic conditions (Alexander, 2020e). N mineralization rates are faster under warm, moist conditions, and they are slower under hot and dry or cold and wet conditions (Stehouwer et al., 2022).

SOC levels vary across the conterminous United States (Sundquist et al., 2009). Areas of higher SOC partially reflect climatic conditions that inhibit organic matter decomposition and other geographic variations that influence soils, such as topography. Regions with cooler, humid climates (Pacific Northwest, Northeast and high elevations in the Sierra Nevada and Rocky Mountain ranges) tend to have high levels of SOC. The eastern Great Plains region, which has humid, moist summer conditions and cold winters, also displays relatively high SOC levels. Another region with high levels of SOC are humid coastal areas of southeastern states; this appears to correspond largely with hydric (i.e., wetland) soils. This suggests that maintaining benefits, such as improved SOC, improved soil structure, enhanced soil fertility and decreased runoff, in warm to hot and humid climates is likely to require a greater frequency of applications and amount of compost relative to colder regions due to the higher organic matter mineralization rates (Alexander, 2016; Stoffella et al., 2014; Tyler, 2021).

In arid climates, the key benefits of compost use may be improved water infiltration and retention in soils (Ozores-Hampton et al., 2022). However, compost may not be beneficial for soils supporting natural vegetation communities in hot, arid climates where plant communities are adapted to soils with limited organic matter and moisture content. In addition, the Na and Cl content of composts may worsen the effects of soil salinity on plant growth in dry climates (Brown & Chaney, 2016; Devine et al., 2022). Irrigation can be used to leach out detrimental salts (e.g., Na and Cl), although irrigation water can also contain relatively high levels of salts (Reddy & Crohn, 2012) and may also leach plant nutrients (e.g.,

$NO_3$) (Gondek et al., 2020). Notably, the use of compost with a high electrical conductivity but low Na and Cl levels may help mitigate soil salinity problems (Gondek et al., 2020).

# 13.3 Topography

Topography, or the physical features of a site, such as its slope, aspect and elevation, affect compost use benefits (Archuletta & Faucette, 2014). Slope, elevation and aspect affect the distribution of water, temperature and light, which in turn can affect soil structure and fertility, the distribution of plant species, and the growth/health of vegetation (Magdoff & Van Es, 2021). In sites with a northerly aspect, compost may help soil retain heat, promoting vegetation growth and supporting biodiversity. On southerly aspects, compost may help soils retain moisture. Thus, a site's topography should be considered before applying compost to maximize its benefits and support sustainable land use practices. Site modifications or alternative compost management practices may sometimes be necessary to achieve optimal results (Davis et al., 2023).

Slope affects the amount of runoff and erosion on a site, which impacts the effectiveness of compost application (Owen et al., 2021). Compost is most effective in reducing soil erosion and improving soil quality on soils with lesser slopes. On steep slopes, compost is more prone to removal and export by runoff, reducing its effectiveness in improving soil health. As mentioned in Section 7, this may be mitigated to a certain degree by using additional materials to help stabilize compost blankets on steeper slopes (Beighley et al., 2010). However, such slopes may inhibit or exclude the use of mechanical spreading equipment (Winfield, 2020).

Elevation can affect the rate of decomposition of compost and nutrient availability in the soil. At high elevations, cooler temperatures may slow the release of nutrients from compost, but at the same time, the slower decomposition of compost may prolong the soil health benefits.

# 14. Economic Value of Compost Production and Use

This section summarizes the economic value of compost production and use to the compost manufacturing industry, their suppliers and customers and society as a whole (i.e., when environmental benefits are assigned monetary value). Though this report focuses on the use of compost, the feasibility of compost use is tightly tied to compost production. This is true for both environmental (e.g., GHG emissions reductions) and economic value realized through the compost industry. Where there is a demand for compost, production becomes more feasible; where sufficient compost is being produced, there are more options for use (e.g., for projects that require large amounts of material).

## 14.1 Compost Manufacturing

Although compost is not a product with a high monetary value, recent growth in the sector throughout the United States indicates that compost manufacturing can be a profitable venture (EREF, 2024). This is mainly due to the ongoing availability of large volumes of inexpensive feedstocks, the relatively simple manufacturing process, and increasing awareness of the benefits of compost use. The subsections below explore the economics of compost manufacturing, with a focus on jobs, revenues, and operating costs. The recovery of monetary value from discarded organic materials and the monetary value of avoided environmental impacts (resulting from the diversion organic materials from landfills and incineration facilities) are also discussed.

### 14.1.1 Size and Employment

Compost production generates revenue and creates jobs (Beattie, 2014; Platt et al., 2013; Platt et al., 2008). Approximately 3,000–5,000 composting facilities exist in the United States (EPA, 2023d), and the industry has been growing. The amount of MSW organics composted in the United States increased by 21% between 2005 and 2018 (EPA, 2020a). Survey data from the Environmental Research and Education Foundation (EREF) also indicates that the number of facilities increased by 55% between 2016 and 2021, with an 83% increase in tonnage processed (EREF, 2024).

A government estimate of employment for the sector is not available because composting facilities have historically reported under various NAICS codes. The EREF survey found facilities employed an average of 6.9 people per 10,000 tons of organics processed. In Maryland, the compost industry employs two times more workers than landfills and four times more than the state's waste incinerators on a per-ton basis (Platt et al., 2013). Although lower than the national average calculated by EREF above, this equates to 4.2 jobs per 10,000 tons processed. For every $12.21 million invested in the compost industry in the state, twice as many jobs are supported on a per-dollar-capita investment basis compared to landfills (Platt et al., 2013). In addition, the compost manufacturing industry can be local economic multiplier when the source materials, labor, business ownership and customers are part of the same community.

### 14.1.2 Revenues

The composting industry can charge a price for both receiving material and supplying material. Operations that can readily sell their product and charge tipping fees are most often financially sound and profitable (Governo et al., 2003). Similar to landfills and incinerators, compost companies can charge tipping fees for waste recycling services. The cost varies depending on the type of feedstock, the processing method or mechanism, and the specific region where the operation is situated. In the southeastern United States, for instance, tipping fees per ton of materials can range from $0–$20 for manures, $0–$25 for wood, $15–$30 for yard wastes, $25–$45 for MSWs, $40–$60 (or more) for biosolids and $45–$65 for liquids (Coker et al., 2022). According to a report by the Commission for Environmental Cooperation (2017), food waste in the United States contributes to approximately $1.61 billion in tipping fees annually, primarily to disposal-oriented solutions, such as landfilling. Currently, 60%

of food waste generated by retail, food service and households is sent to landfill, with incineration as the next most common pathway (EPA, 2023a). This highlights the potential that exists to increase the volume of organic materials composted and the associated revenue that can be generated through tipping fees.

Compost companies also generate revenue by selling compost to commercial and residential customers for subsequent use. Prices vary based on the quality of the finished product and on market-level awareness of the benefits of compost application. Typical prices for different compost formulations range from roughly $7–$57 per cubic yard (Rynk, Cooperband, et al., 2022), with an average of approximately $10 per cubic yard (Goldstein, 2020b). Some specialized products can sell for higher prices. For example, aged-leaf compost used for stormwater pollutant filtration can sell for around $250 per cubic yard. Although not considered to be conventional compost, vermicompost (the product of vermicomposting, or worm composting) can sell for premium prices in the range of $200 to $1,100 per cubic yard (Rynk, Cooperband, et al., 2022). Compost companies can secure revenue through larger multiyear contracts with commercial businesses and local governments.

The economic returns for compost companies mainly depend on the scale of operations and extent of capital investments. For example, in Minnesota, a 2013 survey of state composters attained a combined gross revenue of $14.2 million from compost (Minnesota Composting Council 2014). When scaled to the entire state, the composting industry overall earned an estimated $47.7 million in gross revenues: 26% from private facilities and 74% from public facilities. A cost-benefit analysis of an in-vessel composting facility at Kean University in New Jersey found that the system could generate a profit of $15,664 a year from selling compost-grown vegetables to the university cafeteria and local communities. The return increased to $27,945 when educational and environmental benefits were considered (Mu et al., 2017). A payback period of 7.3 years was estimated for the Kean University composting facility.

Three case studies illustrate payback periods from capital investments in compost manufacturing. Brown et al. (2009) found that the payback period for a $4.1 million investment in a food waste composting facility was approximately 1.7 years. The payback period fell to 1.2 years when carbon credits (totaling $862,846; carbon credits and carbon sequestration valuation are discussed further in Sections 14.1.5 and 14.2.3) were factored into estimates (Brown et al., 2009). A pilot composting program at Texas State University, which included setting up and operating a composting site, suggested that although the system resulted in an initial net loss of $4,900, a net gain of $3,360 was estimated in subsequent years and the payback period was less than two years (Sanders et al., 2011). Lastly, a cost-benefit analysis of an in-vessel composting system at Kean University in New Jersey found that the system could generate a profit of $15,664 per year from the sale of vegetables grown with the addition of soil amendment (essentially an immature compost) from the in-vessel composter to the university cafeteria and local communities. The return increased to $27,945 when educational and environmental benefits were considered. A payback period of 7.3 years was estimated for the Kean University facility (Mu et al., 2017).

## 14.1.3 Operating Costs

It is important to weigh revenues against the costs of operating a composting facility. Compost manufacturers incur costs related to labor, fuel, equipment usage, maintenance and power consumption. Labor costs can range from $5.37 to $16.11 per ton of feedstock handled, depending on various factors, such as composting method, available equipment and local labor rates. The fuel costs associated with composting are typically linked to equipment operation, transportation of feedstocks to the composting facilities and delivery of final compost products to the market. Electrical power can also factor in, with costs ranging from $1.41 to $2.01 per ton of feedstock handled. C-based amendments can contribute significantly to overall operating costs, with amendments like sawdust costing around $33.55 per ton (transportation included) (Coker, 2010). Finally, a study of contamination at composting facilities indicated that 21% of operating costs are associated with the removal of physical contaminants, such as glass, metal and plastics, with plastics accounting for up to 85% of physical contamination by volume (CLP, 2024).

## 14.1.4 Recovering Value from Waste

The clearest economic benefit of compost production is the ability to recapture lost value and beneficial function from food waste and other organic materials that are otherwise landfilled or incinerated. ReFED, a multistakeholder nonprofit aimed at reducing food waste, found that edible food is valued at $5,400 per ton ($2.70 per pound) at purchase, but this value drops to less than $100 per ton by the time any remaining food is ready for disposal (ReFED, n.d.) However, these scraps have positive value, and disposal or landfill represents a loss of potential value. In a study of approximately 150 compost manufacturers in the United States, the U.S. Composting Council estimated the economic value of nutrients recycled through compost use to be about $96.6 million U.S. dollars (USD) for N, P and K and $20.5 million USD for C (USCC, 2021).

At the local scale, decentralized compost use reduces collection/treatment costs associated with food waste, avoids landfill disposal fees and lowers costs from fertilizer use (Pai et al., 2019). Given that some communities must haul materials to distant landfills, diverting organic materials to local or community composting facilities could reduce transportation costs (and associated GHG emissions). On-site composting at the University of Minnesota (e.g., using food waste produced on campus) was estimated to reduce waste-hauling fees by $346 per ton on average (Beattie, 2014).

### 14.1.5 Avoided Waste Management Emissions

Producing compost from organic waste rather than landfilling or incinerating it reduces environmental impact, and those reductions can provide economic value. The avoided environmental impacts (e.g., reduced GHG emissions) and improvement in ecosystem sustainability (e.g., C sequestration, soil health and water quality) translate to economic benefits that can be estimated as a dollar value. There are also social benefits that are more difficult to capture using traditional market valuation methods.

Some studies provide insights into the economic value associated with reduced GHG emissions. Heller (2019) reported the C footprint of food waste in North America to be worth $450 billion annually based on the social cost of C (also known as the SCC, the discounted monetary value of future climate change damages from the emission of one additional metric ton of $CO_2$). The compost-to-waste ratio in the United States is expected to increase 8% by 2030, which is estimated to reduce C emissions by 30 million tons of $CO_2e$, worth $16.1 billion in cost savings (Farhidi et al., 2022).

Compost production also has the potential to generate economic value to compost industry and/or its suppliers or customers through C credits (also known as offsets) for avoided emissions (composting rather than landfilling). These credit programs, still in the early stages of development in the United States, are designed to incentivize GHG reductions and are available for composting of organic materials if composting is not required by regulations (i.e., through mandatory recycling or landfill bans for organic materials). Each credit typically represents a reduction of 1 metric ton of $CO_2$ or $CO_2e$ from the atmosphere. The Climate Action Reserve is one program that offers credits for diverting food waste to composting facilities (“U.S. Organic Waste Composting Protocol”) (Climate Action Reserve, 2024). The credits can then be traded or sold to companies or organizations seeking to offset their own emissions. In 2021, the global average C credit price on the voluntary market was $4.13/ton of $CO_2e$ (The World Bank, 2022). In 2009, Brown et al. (2009) estimated the hypothetical value of C credits (from avoided $CH_4$ emissions) for individual OFMSW composting facilities to be $883,950. For additional information on carbon sequestration valuation, see Section 14.2.3.

## 14.2 Compost Use

Overall, there is a lack of comprehensive economic evaluations examining changes in net costs and profitability associated with compost use. The available evidence related to cost of purchase and economic value of benefits, such as water quality improvements, carbon sequestration and ecosystem services, is presented in this section.

### 14.2.1 Compost Purchase

Certainly, the cost of using composted livestock manure in agriculture is greater than the cost of using the same livestock manure in a raw form. Yet the magnitude of changes in net costs and profitability when compost use supplements or replaces conventional practices and materials can also be highly situational. Net costs depend on multiple factors, including the type of feedstocks used to make a compost, where the compost is used, how it is used, what benefits are being considered in the analysis and the time span over which benefits are being considered. For example, economic evaluations of compost use in agriculture are complicated by the number of variables that can be affected by a specific compost use, such as costs related to compost purchase, equipment, fuel, fertilizer, soil amendments, pesticides, irrigation and cropping materials (e.g., mulch). Evaluations must also account for factors such as compost quality, crop types, crop yields, crop losses (e.g., due to disease, pests, drought) and the market value of crops (Endelman et al., 2010; Julian et al., 2012; Reeve et al., 2012).

There is some evidence that compost use can reduce production and maintenance costs in agriculture and horticulture associated with a decreased reliance on inorganic fertilizers, synthetic pesticides and irrigation (Alexander, 2020e, 2020f, 2020h, 2020i; Hussey & Harrison, 2005). For example, compost use as a topdressing for turfgrass reduced the costs of fertilizer and pesticides, water usage and field reseeding at the 44 acre Massachusetts Development Complex in Devens by approximately \$1,339 $ac^{-1}$ $yr^{-1}$ (Hill, 2021). Yet the net effect of compost use on production and maintenance costs in agriculture and horticulture appears to be highly situational (Chan et al., 2011; Endelman et al., 2010; Julian et al., 2012; Reeve et al., 2012). For example, Julian et al. (2012) found that the use of compost and sawdust as a mulch was less economical than the use of weed mats during the establishment of blueberry orchards in Oregon due to the increased costs associated with weed management.

Farms, nurseries and municipalities that produce their own compost can save on expenses by reducing or eliminating the need to purchase compost, fertilizers, or other soil-enhancing products. Additionally, it has been noted that composted manure is easier and cheaper to transport than raw manure, in part because composting reduces the volume of dry matter by at least 50% (NRCS, 2010). For operations that do not produce their own compost, the cost of purchasing and applying compost on large acreages may be a barrier to use. However, qualifying landowners and other entities may be able to receive financial assistance through the USDA NRCS to help pay for the cost of compost applications. Soil C amendment application (which includes compost use) on agricultural lands, forest lands and developed lands is an eligible cost-share practice through certain NRCS Programs and Initiatives (NRCS, 2022).

### 14.2.2 Water Quality Improvements

Market-based water quality programs can provide insights into the monetary value of benefits of water quality improvements from compost use. For example, Faucette (2012a) performed a financial analysis of the use of compost blankets for stormwater and water quality management compared to traditional on-site stormwater management. The study estimated that, for a 3-inch, 24-hour storm event on a 10-acre site, a compost blanket would produce 54,300 gallons of water and substantially decrease pollution load generation from the site, given that pollutant pollution loads are correlated to stormwater volume. The same site with an impervious surface would produce 752,100 gallons of water, a 1,400% difference. The subsequent size of a stormwater management pond to address the runoff under the impervious surface scenario would need to be 14 times bigger. This represents a loss of land that could otherwise be used and would increase design, construction and maintenance costs in addition to the environmental costs mentioned above. The total cost increase to treat the higher volume of stormwater from the impervious area was \$231,260 (Faucette, 2012a). The Center for Neighborhood Technology provides a number of other publications that quantify the benefits and value of green stormwater infrastructure (CNT, 2011; CNT & SB Friedman Devleopment Advisors, 2020; EPA, 2014).

Compost use can also play a part in nutrient trading programs (akin to C credits), facilitating the attainment of total maximum daily load (TMDL) limits and water quality standards. TMDLs define the maximum allowable pollutant levels that water bodies can receive while still complying with state water quality standards (Bell & Platt, 2014). The Federal Clean Water Act mandates that states establish TMDLs as part of their watershed implementation plans to restore impaired water bodies nationwide. Nutrient credits provide a market-based approach to meeting TMDL targets by effectively assigning monetary values to the reduction or removal of a unit of nutrient pollution. Entities such as municipalities, industrial facilities, or agricultural operations (e.g., Confined Animal Feeding Operations) that surpass their nutrient reduction targets could generate nutrient credits and sell or trade them with other entities that have yet to meet their reduction targets. The credits are based on the nutrient load that would be released into water bodies if nutrient reduction practices were not implemented. Once registered, verified and certified, credits can be traded or sold to regulated entities, such as wastewater treatment plants or other industrial facilities facing increasing on-site water quality compliance costs (Ross, 2012a).

As an example, using composted manure on agricultural fields rather than raw manure is an eligible means of generating nutrient credits in Pennsylvania (Pennsylvania Department of Environmental

Protection, 2021). A credit is based on a calculation of N and P reductions (pounds) per ton of manure compost; one credit is equal to one pound of N or P. An auction by the Pennsylvania Infrastructure Investment Authority (PENNVEST) sold 20,000 pounds of N reduced from point sources (2012) for $4.65/credit, and 2,000 pounds of N reduced from point sources (2014) for $4.39/credit in the Susquehanna River Basin (Ross, 2012b). This highlights the potential monetary value that could be achievable through compost use as part of nutrient trading programs.

### 14.2.3 Carbon Sequestration

Estimating a precise cost for the sequestration of C in soil from compost use is difficult. The International Solid Waste Association reported that for typical yard trimmings compost, C sequestration values range from $4.54 to $8.17 per ton (wet weight) of compost applied to soils (Gilbert et al., 2020b). Other methods focus on the "cost of carbon" in the context of climate mitigation and emissions. Table 13 summarizes the range of potential economic values associated with this level of sequestration based on five $CO_2$e valuation methods:

- **SCC method:** Estimates the costs of C emissions to society as a whole ($190.50/ton $CO_2$e [in 2020 dollars]) and is intended to be a comprehensive estimate of climate change damages and includes variables such as changes in net agricultural productivity, human health, potential property damage (e.g., from increased flood risk) and energy system costs (e.g., changes in heating and cooling costs) (Sarinsky & Weatherford, 2024).
- **Abatement Cost Estimate:** Is based on the price needed to initiate behavioral and infrastructure change to meet specific targets, such as the Paris climate change accord (Gilbert et al., 2020b).
- **Market Price of Carbon method:** Estimates values for C abatement in terms of the emission trading scheme, the upper ($59.00/ton $CO_2$e) and lower bound ($17.00/ton $CO_2$e) are determined by the Carbon Pricing Bill Tracker in this estimation (Hafstead, 2021).
- **Willingness-to-Pay approach:** Estimates how much people are willing to pay to add a particular good or service or remove a good or service (McGoodwin, 2018). In this case, the inflation-adjusted rate is $35.89/ton $CO_2$e (EPIC News, 2021).

The U.S. Composting Council estimated that compost use in the United States resulted in roughly 368,000 tons of $CO_2$e sequestered in soil in 2020 (USCC, 2021). Depending on the "cost of carbon" method, the values estimated range from $6 million to $70 million assuming 368,000 tons $CO_2$e are sequestered annually.

*Table 13. Economic values generated from reduced C emissions through compost use based on different "cost of carbon" estimates.*

| Method | Price ($ $tCO_2e^{-1}$) | Approximate total economic value per year (millions of dollars)[a,b] |
|---|---|---|
| Social cost of carbon (damage costs avoided) approach | 190.50 | $70 |
| Abatement cost estimate approach | 68.72 | $25 |
| Market price of C approach (upper-bound) | 59.00 | $22 |
| Market price of C approach (lower-bound) | 17.00 | $6 |
| Willingness-to-pay approach | 35.89 | $13 |

*Notes:*

$ $t\,CO_2e^{-1}$ = dollars per ton carbon dioxide equivalent.

[a] Per annum value rounded to the nearest million.

[b] Calculated using value of 368,000 t CO2e sequestered in U.S. soils in 2020. Estimate was based on assumptions that approximately 4 million tons of compost (wet wt.) were applied to soils, moisture content was about 50%; and variable rates of SOC increase in the southern (25 lbs SOC $ac^{-1}$ $yr^{-1}$ $t^{-1}$ dry mass added), middle (41 lbs SOC $ac^{-1}$ $yr^{-1}$ $t^{-1}$ dry mass added), and northern (57 lbs SOC $ac^{-1}$ $yr^{-1}$ $t^{-1}$ dry mass added) thirds of the United States The calculations did not consider emissions avoided from landfilling or incineration nor processing or transportation emissions. It was stated that this was a conservative estimate since the calculations were performed using data from 25% of member composters who responded to the survey.

### 14.2.4 Ecosystem Services

Directly and indirectly, ecosystems have a profound impact on human welfare, thereby contributing to the total economic value enjoyed by society. As Section 9 of this report describes, compost application provides a range of environmental benefits that support healthy ecosystems, which supply beneficial goods and services to society and promote human well-being. Hence, compost use acts to support the enhancement of ecosystem services (EPA, 2023c). A common framework for evaluating such contributions divides ecosystem services into four categories (Brauman et al., 2014):

- **Provisioning services:** Services derived from products obtained from ecosystems
- **Regulating services:** Services obtained from the regulation of ecosystem processes
- **Supporting services:** Services that maintain ecosystem processes and functions, such as soil formation, primary productivity and provisioning of habitat
- **Cultural services:** Services that contribute to the cultural, spiritual, or aesthetic aspects of human well-being

Numerous studies document the economic value of various ecosystem services, many of which can be linked to compost. Table 14 summarizes some of the potential ecosystem services associated with compost use and, where possible, identifies the estimated economic value of these services. The economic values reported are not always directly attributable to compost. They are estimates of the value of broad ecosystem services that are linked, at least in part, to the use of compost. Compost use also supports cultural ecosystem services(e.g., water-based recreational activities); however, they are not fully addressed in the table because they are more difficult to attribute with an economic value.

*Table 14. Summary of economic values associated with benefits and ecosystem services from compost use.*

| Environmental benefit | Ecosystem services | Economic value |
|---|---|---|
| Soil health improvement | Provisioning services:<br>• Agricultural production and consumption<br>• Increased crop yield<br>• Increased high-quality food production and consumption<br>• Increased food security<br>• Income<br><br>Regulating services:<br>• Water conservation<br>• Regulation of organism biodiversity<br>• Groundwater recharge<br>• Erosion control and flood mitigation<br>• Disease and pest regulation<br>• Vegetation reestablishment<br><br>Supporting services:<br>• Soil formation<br>• Biomass generation<br>• Nutrient cycling and regulation<br>• Water cycling<br>• Creation of diverse microbial communities<br>• Riparian restoration<br>• Wetland creation and restoration | Indirect value estimate:<br>According to the University of Vermont, the total value of ecosystem services from improved soil health on Vermont farms is approximately \$31 $ac^{-1}$ $yr^{-1}$, providing a total value of nearly \$25 million $yr^{-1}$ across Vermont agricultural lands (Dube et al., 2022).<br><br>Indirect value estimate:<br>Jenkins et al. (2010) estimate the value of three of the many ecosystem services produced by wetland restoration. These services include GHG mitigation, N mitigation and waterfowl recreation. The social welfare value of wetland restoration is found to be between \$709 and \$734 $ac^{-1}$ $yr^{-1}$, with GHG mitigation valued between \$209 and \$270, N mitigation at \$151 and waterfowl recreation at \$20.<br><br>Indirect value estimate:<br>Costanza et al. (2014) provided dollar values for the ecosystem services associated with agriculture. On a per-acre basis, soil formation is valued at \$289.<br><br>Indirect value estimate:<br>Estimated annual losses from inefficient water use or inadequate infiltration can range from \$165 $ac^{-1}$ (for irrigated pasture) to \$988 $ac^{-1}$ (for orchards) in equivalent purchase power in 2020 (Boyle et al., 1989).<br><br>Indirect value estimate:<br>One inch of topsoil has been valued at \$2967 $ac^{-1}$ in 2022 (based on the potential cost to replenish nutrients and SOC lost via erosion) (Bly, 2022). |
| Water conservation | Provisioning services:<br>• Increased high-quality food production and consumption<br>• Food security<br>• Income<br><br>Regulating services:<br>• Water conservation<br>• Erosion and flood control<br>• Drought mitigation<br><br>Supporting services:<br>• Soil formation<br>• Vegetation reestablishment<br>• Nutrient cycling<br>• Water cycling | Direct value estimate:<br>According to a national survey carried out by the Municipal Water Infrastructure Committee (MWIC), the median annual maintenance cost of bioretention devices is approximately \$1.63 per square foot, with costs ranging from as low as \$0.31 per square foot to as high as \$5.43 per square foot. The survey also reports average annual maintenance costs, which vary between \$590 and \$9,157, with a median value of \$2,006 (Boyle et al., 1989). |

| Environmental benefit | Ecosystem services | Economic value |
|---|---|---|
| Water quality protection | Provisioning services:<br>• Food quality and quantity (fish)<br>• Fresh water access<br><br>Regulating services:<br>• Retention and infiltration of stormwater<br>• Pollutant filtration<br>• Restoration of natural rates of stormwater infiltration, peak flow, pollutant loading and evapotranspiration<br><br>Cultural Services:<br>• Access to water-based recreational activities | Indirect value estimate:<br>The value of clean water and water quality was seminally established by Carson and Mitchell (1993), who estimated the annual household willingness to pay for freshwater quality at $481 across fishing, boating and swimming.<br><br>Indirect value estimate:<br>Infiltration basins can cost $819–$1,768 per cubic meter (2015 dollars) with a P removal efficiency of 65% (EPA, 2015). Compost can reduce the costs associated with nutrient pollution treatment. |
| Carbon sequestration | Regulating services:<br>• Carbon sequestration<br>• Climate change resilience<br>• Air quality regulation<br><br>Supporting services:<br>• Soil formation<br>• Nutrient cycling<br>• Water cycling | Direct value estimate:<br>An EPA study in Leadville, CO, where biosolids and compost were applied to reduce metal toxicity found that net C sequestration was worth $4,443–$7,899 $ac^{-1}$ **(Brown & Chaney, 2016)**. |

*Notes*: ac $yr^{-1}$ = acres per year

# 15. Compost Use at Scale

This section discusses the potential for increasing the use of compost at scales that match the available volume of discarded organic materials. While the use of compost has increased in recent years in the United States, the full potential of associated benefits may only be realized with scaled-up usage through both decentralized (smaller: farms, communities, households, etc.) and centralized (larger: municipalities, industries, etc.) systems. Compost use currently tends to be at a local scale, largely due to the costs associated with transporting bulky materials with relatively low per unit monetary value. The measurable benefits are typically localized, but scaled-up compost use across multiple projects and sectors generates cumulative benefits and co-benefits that can support national or regional environmental sustainability goals (e.g., C neutrality, food sustainability, water quality targets). Creating parity among the available supply of compostable materials, the quantity of compost that is manufactured, and the quantity of compost used is referred to in this section as compost use "at scale."


*Figure 20. Bins for separating recyclables, compostables and trash for curbside collection in Seattle, WA. Photo courtesy of Seattle Public Utilities.*

## 15.1 Current Scale of Compost Use

Compost usage has spread far beyond the agricultural, horticultural and landscaping sectors. Compost is now used to revegetate degraded soils following construction activities and in practices used to manage urban stormwater runoff (Archuletta & Faucette, 2014; Faucette et al., 2006). It is also used to help revegetate former mine lands, improve heavily degraded urban soils (e.g., brownfields and Superfund sites) and restore ecosystem functions in wetlands (Basta et al., 2016; Brown & Chaney, 2016; Governo et al., 2003). As detailed in Section 4, compost use can also facilitate climate mitigation, adaptation and resilience.

In 2024, EREF, sponsored by the U.S. Composting Council, published a survey of composting facilities that includes a summary of the relative distribution of compost sales among a variety of sectors. The results of this compost use survey are displayed in Figure 21 and provide some understanding of the use in various sectors (EREF, 2024). Agriculture was the leading sector based on the sales distribution, followed by compost/mulch distributors, landscaping and horticulture. Note that these results only address commercially available compost (i.e., excluding compost produced on-farm for use on-farm) and do not indicate the end use of the compost for every sector (e.g., the end uses of compost purchased by compost and mulch distributors is unknown).

Compost production is growing overall, reflecting an increase in demand that is likely associated with greater recognition of the benefits of compost use. Between 2005 and 2018, the amount of MSW organics composted in the United States increased by 21% (EPA, 2020b). The number of composting facilities in the United States increased by 55% between 2016 and 2021 (from roughly 3,000 to more than 5,000), with an 83% increase in tonnage processed by survey respondents (EREF, 2024).

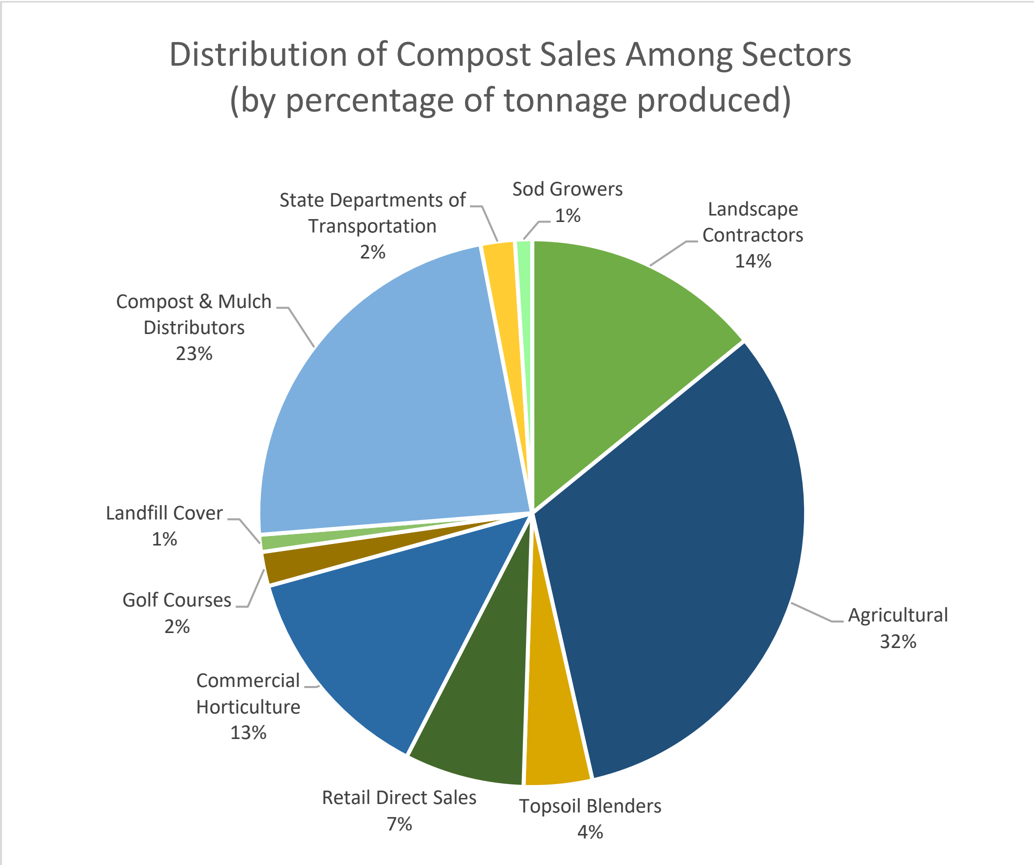


*Figure 21. Relative distribution of compost sales among sectors in the United States (EREF, 2024).*

## 15.2 Availability of Organic Material

The scale of potential benefits from compost use is connected to the volume of available compostable material. The annual demand for compost is estimated to be ten times greater than the supply (Goldstein, 2020b), even though the availability of compostable materials is not usually a limitation. In particular, the amount of food waste and yard trimmings going to landfills and the amount of raw manure used in agricultural production could support an increase in the scale of compost use. Compostable food waste and yard trimmings accounted for over 98 million tons (over 30%) of MSW generated in the United States in 2018 (EPA, 2020b). Yard trimmings are the most frequently composted MSW; roughly 60% were composted in 2018 (EPA, 2020b). In 2019, an estimated 102 million tons of food waste was landfilled in the United States (EPA, 2023a), and only 5% of food waste generated from food retail, food service, residential and food bank sectors was composted (EPA, 2023a). There is also vast potential for “hidden” food waste from food manufacturing and processing sectors (such as seafood processing waste, nut shells, fruit peels and corn cobs) to be used for compost (Rynk, Schwarz, et al., 2022). The percentage of food waste composted from these sectors was estimated to be 1.5% in 2019 (EPA, 2023a). Nearly 50% of biosolids are landfilled or incinerated, representing another large quantity of material suitable for composting (Brown, Miltner, et al., 2012). Additionally, much of the roughly one billion tons of manure generated annually in United States agriculture (Ribaudo et al., 2003; Zhang & Schroder, 2014) has the potential to be routinely composted before application on fields.

Local factors can dictate the availability of organic material with food waste, yard trimmings and biosolids more typically obtainable in urban areas, while agricultural residues, byproducts and manure are readily attainable in rural settings.

# 15.3 Examples of Sector Expansion Opportunities

A variety of opportunities exist to increase the scale of compost use. Initiatives that improve the health of agricultural soils, enhance water resource protection efforts, and support carbon neutrality can support expansion. This section explores the potential for growth of compost use with focus on these three initiatives as examples.

## 15.3.1 Agriculture

Conventional agricultural operations represent a relatively untapped market that can potentially purchase and use large volumes of compost (Alexander et al., 2022). In California, large-scale compost use has been suggested as an option to help remediate degraded agricultural soils (Harrison et al., 2020), highlighting scale and market potential.

A lack of compost quality standardization, challenges with large-scale compost applications, insufficient knowledge of benefits, and application costs are potential barriers to scaling up compost use in both organic and conventional agricultural operations. Purchasing compost for use across large-scale farm acreages may be prohibitive for farmers, particularly for crops with a potentially low or volatile profit margin. The cost and availability of equipment to apply large volumes of compost and the time required to complete such applications are other barriers to widespread agricultural use. As noted in Section 14.2.1, farmers may be able to obtain financial assistance through the USDA NRCS to help purchase compost and pay for the cost of compost applications.

Increasing on-farm composting and use of that compost is another option for operations that have an ample supply of compostable materials. Farmers, however, may not have sufficient knowledge or time to manufacture compost with the desired characteristics for a specific agricultural use (e.g., compost nutrient levels, when intended as a replacement or supplement to inorganic fertilizers or raw manures). Furthermore, there is a risk that inadequate control over the composting process could result in potential negative consequences. For example, applying an immature, unstable compost to crop fields can be detrimental to crop growth.

Ensuring that an ongoing supply of commercial quantities of compost remains stable and mature may require laboratory testing. The U.S. Composting Council’s Seal of Testing Assurance Program uses laboratory analysis to provide certified information on key compost characteristics. It should be noted that this program standardizes the reporting of compost characteristics but does not ensure product standardization. Compost manufacturers are not required to standardize or even characterize their composts. A lack of standardization is a likely barrier to scaling up agricultural compost use among farmers, who rely on information about fertilizer, pesticide and soil amendment characteristics in tailoring applications for soils and crops. In summary, scaling up compost use in agriculture would likely require the ability to procure and apply an affordable supply of compost with standardized qualities, or at least qualities that are consistently characterized.

Certified organic farming has the potential to increase compost use; however, there are barriers to more widespread compost use in organic agriculture due to certification regulations and usage limitations (Alexander et al., 2022). In organic agriculture, compost is used in place of inorganic fertilizers and amendments to augment soil fertility and build SOM. The presence of prohibited contaminants or feedstocks may prevent a compost from being certified for use in organic agriculture and, therefore, would prohibit certified organic farms from using it in growing operations. For example, compost made from biosolids or synthetic food packaging or service ware (even if certified compostable) is prohibited for use in organic agriculture (USDA, 2019).

## 15.3.2 Water Resource Protection

As outlined in Sections 3 and 7, compost can be used in various stormwater control practices, such as rain gardens, bioretention cells and permeable pavements. This versatility allows for a wide range of potential applications for compost in stormwater management, which increases the potential for scaling up its use.

### *15.3.2.1 Stormwater Control*

In communities across the country, there is a growing recognition of the importance of GI for stormwater management and water quality protection. Compost use within GI can be a cost-effective and sustainable alternative to traditional stormwater control practices. In some cases, state and local governments create financial incentives to increase compost use in GI. In other cases, government regulations require the use of compost in GI. For example, local governments may require that compost-topsoil blends be used for all commercial revegetation projects on the physically disturbed soils resulting from building and road construction.

Washington's Soils for Salmon initiative is one example of how builders, developers and landscapers use compost to improve soil quality on building sites and protect nearby waterways from stormwater runoff (WORC, 2023). Programs such as this play an important role in scaling up the use of compost because they facilitate growth in the demand for compost use. Furthermore, linking compost use to community values, such as the conservation of salmon, helps increase awareness of the benefits of compost use. The discussion of water quality trading and nutrient credits in Section 14.2.2 describes other possible incentives to expand use.

The Soils for Salmon Program in Washington State has established compost use as a fundamental component of efforts to improve the health of soils disturbed by construction activities. Improved soils and vegetation help reduce the impacts of urban stormwater on salmon-bearing streams.

### *15.3.2.2 LEED Certification*

Commercial and residential developers have begun incorporating compost into their infrastructure projects to earn Leadership in Energy and Environmental Design (LEED) credits. For instance, to meet several categories in the LEED-New Construction (LEED-NC) ranking system, a 1,100-acre development project in Greenville, South Carolina, exclusively used compost-based products for a range of purposes, including perimeter control, inlet protection, slope stabilization, bioswales and rain garden/bioretention mechanisms (Faucette, 2009). LEED certification and other such incentives are a particularly effective way for governments to promote compost use at scale and secure associated water quality and conservation benefits. These measures are important in creating more sustainable and resilient water management systems.

### *15.3.2.3 Water Conservation*

Some municipalities now recommend or require compost use as an approach to improving water conservation. For example, Leander, Texas, requires that compost be mixed with topsoil on all new landscapes (residential and non-residential) (Bell & Platt, 2014). The measure constitutes a greater effort to expand community-scale water conservation efforts in a drought-prone region with complex water rights. Water conservation benefits have myriad implications, especially for the agricultural sector. Commercial farming has played a central role in exacerbating ongoing U.S. water supply challenges (Jury & Vaux Jr, 2007; Pimentel et al., 1997). Scaling up compost use in the agricultural sector may, therefore, help conserve water supplies for not only agricultural production but also for other critical uses, such as municipal drinking water supplies.

### 15.3.3 Carbon Neutrality

Creating and using compost can help businesses, communities, municipalities and states work toward goals of decreased GHG emissions and carbon neutrality. As discussed in Section 4, opportunities exist to divert more organic materials from landfills, greatly reducing GHG emissions. Data from EPA suggests that roughly 100 million tons of food waste can be diverted from landfills (EPA, 2020b) to compost manufacturing facilities, which would decrease $CH_4$ emissions from landfills by up to 60% (EPA, 2023g).

Scaling up compost production and use can be achieved through a combination of individuals (e.g., backyard and community composting) supplementing the activities of existing businesses (e.g., farms, wood products, food processors) and by centralized facilities specializing in compost manufacturing. Centralized composting of diverted organic materials has large-scale potential and is regarded as a sustainable waste management alternative with numerous environmental co-benefits (ReFED, n.d.). Such recycling solutions typically achieve scale through "large municipal programs that coordinate policy, collection infrastructure, and centralized processing facilities"(ReFED, n.d.). However, the cumulative effect of individuals and businesses can meet local needs where centralized composting facilities do not exist.

There is vast potential to increase soil C sequestration across large scales within the United States. In Washington state, it has been estimated that soil applications of compost made from available food waste and yard trimmings could sequester nearly 44,000 tons of C annually (Brown et al., 2011). Brown, Miltner, et al. (2012) estimated that roughly 3 million t C $yr^{-1}$ could be sequestered on urban lands throughout the United States using compost derived from urban-sourced organic materials.

## 15.4 Examples of State Expansion Opportunities

Increasing awareness of benefits and use, incentivization programs, and restrictions on landfilling of potential feedstock can drive the scale up of compost. In most states, the quantity of compost that could be produced given available yard and food waste far outweighs the quantity actually produced. Growing the supply and use of compost may require research, new technologies, policy levers, and/or targeted education, depending on a state or region's specific circumstances.

For instance, a study looking at composting in Florida found that more than 5.7 million tons of compost could be produced using yard debris and food waste (Li et al., 2010). Growth of the market for compost use in Florida could be accelerated with further research as follows (Li et al., 2010):

(1) Develop a quick method for determining the maturity of compost
(2) Develop and demonstrate simple composting devices for household use
(3) Develop passive (low maintenance) composting systems for producers
(4) Explore market development for compost use

California provides another example. California's State Bill (SB) 1383 is one example of a statewide strategy to scale up compost production and use. It targets landfill $CH_4$ emissions by endeavoring to divert 75% of organic materials from landfills by 2025. Researchers at the University of California–Merced modeled the composting system required to achieve this target using a geospatial model (Compost Allocation Network) that simulates waste production and transportation in all of California's cities and farms. The model considered various waste production, compost application and compost conversion scenarios. Results suggested that a system that recycles nutrients between cities and local farms could help California meet SB 1383 while reducing state emissions by 5.7 ± 11.1 million tons of $CO_2e$ annually (Harrison et al., 2020). Assuming that most of the compost would be applied to local farmland, this system could provide the state with an opportunity to improve or remediate its agricultural soils. From a national standpoint, the potential for large-scale emissions reductions through compost production and use is high. According to Farhidi et al. (2022), the current ratio of compost to waste in the United States is around 10% and is expected to rise to 18% by 2030 based on trends (Farhidi et al., 2022). Scaling up compost production through landfill diversion can minimize harmful emissions while generating considerable economic and environmental benefits from compost use.

A study in Georgia found that the largest potential markets for compost were erosion control, kaolin mine land reclamation and landscaping (Governo et al., 2003). The study noted that the state lacks a compost production facility in the region of the kaolin industry, highlighting that more connected strategic planning may be needed to develop potential opportunities for compost use. Improved awareness of benefits and publication of specifications from the state DOT and Soil and Water Conservation Commission were suggested as approaches to encourage the creation of more composting facilities throughout the state (Governo et al., 2003).

State Departments of Transportation (DOTs) provide another opportunity for scale-up. State DOTs often apply compost to roadside soils to establish vegetation, control erosion and protect adjacent ecosystems from pollutants. In Washington State, regulations require that 80% of the funds for soil improvement on rights-of-way be dedicated to compost use. DOTs in Texas and California also focus on specialized use of compost. Brown (2020) estimated that if the California DOT were to use compost annually along all the roadway rights-of-way it manages, approximately 19% of the food waste/yard trimmings (145,000 tons out of 750,740 tons) produced by California in a single year would be used. Local governments are prominent consumers of compost and can directly scale up their own use.

## 15.5 Feasibility of At-Scale Use

An increase in both supply and demand are needed to achieve at-scale compost use and benefits, given the amount of available feedstock and the potential uses for compost across a range of sectors. Many communities, businesses and institutions have already adopted compost use programs, demonstrating that composting is a viable and practical solution to reduce waste sent to disposal and improve soil health. Additionally, its utility to sectors from agriculture to stormwater management underlines the variety of potential users and the potential to scale up use. The environmental benefits of compost use are well-supported by scientific research, which provides a strong justification for governments, businesses and individuals to invest in and promote compost use on a larger scale. The potential scale of benefits can only be realized by exploiting opportunities to use compost as a substitute for conventional soil amendments. However, there are gaps in existing literature and data analysis regarding the overall supply and demand potential for compost.

Generally, compost quality does not appear to be a limiting factor for scaling up compost use, provided recommended practices are followed. Contamination (e.g., plastics) may pose a challenge for composting facilities processing certain feedstocks, such as mixed food waste and compostable food packaging and service ware (more in Section 10.3). Compost production facilities can tailor compost quality (see Section 11 for context) to specific end uses (e.g., by incorporating specific feedstocks or blending certain materials into the finished compost), and there are different quality standards for different uses. Tailoring compost quality characteristics and marketing of compost for specific end uses and user needs (e.g., agricultural production or erosion control) is likely more important than concerns that relate to the availability of compost for large-scale use.

Promoting compost use on a larger scale would maximize associated environmental benefits and reduce per-unit costs, thereby further encouraging use and expanding market potential. Strategies to increase compost use, such as incentives, awareness campaigns and landfill restrictions, can stimulate a positive feedback cycle in which increased compost use drives an increase in compost production, which in turn magnifies the cumulative environmental and societal benefits, leading to more demand for compost use.

# 16. Conclusions and Research Needs

This report summarizes and synthesizes information from key scientific literature about the value of compost use in the United States. Section 16.1 provides general conclusions. Section 16.2 describes research needs to further improve the understanding of the value of compost use in sectors of interest in this report and at a broader scale.

## 16.1 Conclusions

In the United States, compostable food waste, yard trimmings and wood comprise approximately 40% of landfilled MSW and 38% of the MSW that is incinerated (EPA, 2020a). Composting these organic materials reduces GHG emissions from landfills and produces a valuable soil amendment that benefits many sectors. Additionally, roughly 2 trillion pounds of compostable livestock manure is generated in U.S. agriculture each year, most of which is applied to agricultural fields in a raw form (Ribaudo et al., 2003; Zhang & Schroder, 2014), and nearly 50% of U.S. biosolids are landfilled or incinerated (Brown, Miltner, et al., 2012). The potential volume available emphasizes the existing opportunity to create a more sustainable system of transforming organic materials into compost, a resource that provides benefits for soils, water resources and climate resilience.

A large body of scientific literature reports that appropriate compost use leads to substantial environmental benefits. Despite differences among studies (e.g., the magnitude of benefits observed, use cases, location), the scientific evidence is clear that compost use offers numerous benefits for soil health, plant growth and environmental sustainability. As a soil amendment, it improves the properties of soils and growing media physically (structurally), chemically (nutritionally) and biologically. Adding organic matter rejuvenates and fortifies overall soil health with cascading benefits for plants, water resources and ecosystems. The soil health improvements from compost use support the growth of plants (root development and access to water plus nutrients, such as N, P and K) and increase the abundance of beneficial soil organisms, such as worms and certain microbes. Furthermore, the stable organic matter from compost provides valuable benefits to soils that inorganic fertilizers do not supply. The key benefits associated with biological, chemical and structural soil health are reviewed in Table 15.

*Table 15. Summary of soil health benefits associated with compost use.*

| Soil health benefits | | |
|---|---|---|
| **Biological benefits** | **Chemical benefits** | **Structural benefits** |
| Microorganism diversity and abundance: Up to 2 times greater soil microbial activity (e.g., bacteria, fungi) has been observed following compost applications (Brown & Cotton, 2011). | SOC: Increases in SOC up to 300% have been observed (Brown & Cotton, 2011).<br><br>Soil acidity and pH: Compost can buffer soil pH and retain Ca and Mg, maintaining a favorable soil acidity level that improves availability of nutrients (i.e., N and P) for plant uptake (Wilson et al., 2018).<br><br>Soil nutrients: Although not considered a fertilizer, compost can provide significant quantities of N, P, K and various other plant nutrients (e.g., ≥ 50% of an annual crop's initial fertilizer requirements) (Alexander, 2020e; Ozores-Hampton, 2019).<br><br>Soil contaminants: The organic matter and microbes in compost help immobilize and break down contaminants that harm plants and animals, water quality, and human health. | Soil density/ compaction: Reductions up to 35% have been observed (Brown & Cotton, 2011; Evanylo et al., 2016; Mohammadshirazi et al., 2017; Ozores-Hampton, 2019).<br><br>Soil permeability and water infiltration: Increases in infiltration rates up to 183% have been observed (Cogger et al., 2008; Mohammadshirazi et al., 2017).<br><br>Soil water-holding capacity: 35%–57% increases in water storage observed (Brown & Cotton, 2011; Ozores-Hampton, 2021c).<br><br>Soil erosion: Reductions in sediment transport of up to 99% have been observed (Alexander, 2020c). |

The associated improvements in soil health result in co-benefits for water conservation, water quality and broader climate resilience goals. Compost-based practices reduce stormwater runoff, conserve water and improve water quality in various urban and rural settings (Evanylo et al., 2008; Faucette, 2009, 2012a; Faucette et al., 2005). Compost use also assists with wildfire recovery efforts by reducing storm runoff that can contaminate drinking water sources with ash, sediment and toxins, thereby reducing water treatment costs. These benefits help build resilience to climate-driven changes in the water cycle (Faucette et al., 2005; IPCC, 2022; Rynk, Cooperband, et al., 2022). At the landscape scale, associated improvements in soil health and plant growth have the potential to support the health of a variety of ecosystems, such as parks, wetlands, aquatic ecosystems, prairies and forests. The key water resource management and ecosystem benefits of compost use are summarized in Table 16.

*Table 16. Summary of benefits and avoided impacts for water resources and ecosystems from compost use.*

| Water resources and ecosystems | |
|---|---|
| **Benefits** | **Avoided impacts** |
| Stormwater management: Compost can improve the ability of stormwater (e.g., berms, filter socks, blankets) and GI practices (bioretention areas and rain gardens) to control/treat runoff (Bell & Platt, 2014; Faucette et al., 2013; Faucette, Governo, et al., 2009). Compost blankets or erosion control mats applied to slopes and construction sites often prevent erosion and sediment runoff better than conventional practices involving topsoil placement and/or hydroseeding (Bakr et al., 2012; Faucette, 2007; Faucette et al., 2005).<br><br>Water conservation: Compost can hold up to five times its weight in water (Faucette, 2009). This helps increase water infiltration into soils, improve water retention and reduce evaporation (Ozores-Hampton et al., 2022). In this manner, compost reduces surface runoff during wet periods and reduces irrigation needs during dry periods (Brown et al., 2008; Ozores-Hampton et al., 2022).<br><br>Groundwater recharge: Compost use can increase the amount of water entering and moving through the soil, thereby recharging groundwater (Faucette, 2012b; Magdoff & Van Es, 2021).<br><br>Ecosystem resilience: Compost use improves soil health, which supports the biodiversity of plants and animals, including important pollinator species (Magdoff & Van Es, 2021). In this manner, compost can contribute to the protection and restoration of a variety of ecosystems, such as wetlands, forests and prairies. By improving soil health, compost can also accelerate recovery of wildfire-damaged lands (Meyer et al., 2001). | Water use: Broad-scale compost use can help to reduce the over-use of limited groundwater supplies and the de-watering of streams and rivers by decreasing irrigation requirements in agricultural and urban areas.<br><br>Water pollution: Using compost in watershed conservation efforts can prevent contaminants (nutrient fertilizers, sediment, pathogens (e.g., *E. coli*), heavy metals, synthetic chemicals) from entering groundwater and surface water bodies. (Faucette, Cardoso-Gendreau, et al., 2009; Faucette et al., 2005; Nicholson et al., 2017; Tyler et al., 2011). This helps protect water quality and prevent aquatic ecosystem degradation.<br><br>Erosion: Compost improves vegetation cover by providing essential nutrients and organic matter to the soil (Brown & Beecher, 2019), reducing the amount of bare soil exposed to rain and runoff while increasing the amount of precipitation that infiltrates into the soil and is absorbed by plants. This decreases the amount of sediment transported to surface waters, thereby helping to protect aquatic habitats. |

Climate change is leading to more frequent and severe weather events (such as heavy precipitation events and prolonged heat waves and drought) and changes to ecosystems and biodiversity across many parts of the United States (IPCC, 2022; USGCRP, 2018). In the face of warming air temperatures and changing precipitation patterns, compost use has emerged as a versatile, low-cost solution that supports climate resilience and offers the potential to mitigate impacts. It is a relatively simple, effective and scalable way to contribute to reducing C emissions and increasing climate resilience across communities. As communities and ecosystems prepare for impacts from a changing climate, compost production and use helps to build resilience by revitalizing soils, conserving water, sequestering C and reducing GHG emissions (Brown et al., 2017; Brown, Miltner, et al., 2012; IPCC, 2022). The key benefits and avoided impacts related to climate resilience and mitigation are shown in Table 17.

*Table 17. Summary of benefits and avoided impacts for climate mitigation and resilience from compost use.*

<table>
<tr><th colspan="2">Climate mitigation and resilience</th></tr>
<tr><th>Benefits</th><th>Avoided impacts</th></tr>
<tr><td>Carbon sequestration: Compost use contributes to soil carbon sequestration.<br>• Nearly four times more C is sequestered by applying food waste compost to soil instead of landfilling it (Brown, 2016).<br>• Research indicates that 0.18 to 0.67 tons C per ton of C applied can be sequestered in agricultural soils (Peltre et al., 2012).<br>• Roughly 3 million t C $yr^{-1}$ could be sequestered on U.S. urban lands using compost derived from urban-sourced organic materials (Brown, Miltner, et al., 2012).<br><br>Flood resilience: Compost-amended soil absorbs and retains stormwater, reducing runoff and its contribution to flooding (Faucette, 2012a, 2007; Faucette et al., 2005).<br><br>Drought resilience: Compost application mitigates drought impacts by enhancing soil structure, water retention and nutrient availability, fostering resilient plants with deeper root systems. This reduces irrigation needs and minimizes soil degradation, providing resilience during drought conditions (Basche, 2017; Magdoff & Van Es, 2021).<br><br>Water quality resilience: Compost use reduces runoff and soil erosion and prevents pollutants from entering water bodies (Archuletta & Faucette, 2014; Bell & Platt, 2014; Faucette et al., 2013), which helps increase the resilience of aquatic ecosystems to climate change.<br><br>Urban heat resilience: Urban compost use bolsters resilience against heat by improving soil moisture levels and enhancing the growth of trees and other plants that provide shade and evaporative cooling, especially around buildings and paved surfaces. The enhanced conditions mitigate heat stress, foster green spaces and promote a more livable urban environment (Chapman et al., 2022; Faucette, 2009).<br><br>“Climate-Smart Agriculture”: Compost use can be a key technique in Climate-Smart Agriculture, improving soil health, C sequestration, water retention and nutrient availability, thereby enhancing crop productivity and resilience to climate change (Winfield, 2020).<br><br>Wildfire resilience: Compost use can also help accelerate the recovery of fire-damaged lands (e.g., forestry) through improvements in soil health, reduced surface runoff, reduced soil erosion and provision of essential nutrients to vegetation (McFarland, 2009; Meyer et al., 2004; Meyer et al., 2001).</td><td>GHG generation: Compost production avoids GHG generation ($CO_2$, $CH_4$ and $N_2O$) when organic materials are diverted from landfills and when animal manure is composted before application (Brown & Beecher, 2019; Brown et al., 2009; Morris et al., 2014). In addition, substantial GHG reductions occur when compost is substituted for conventional materials in various management practices:<br>• Compared to landfilling, it is estimated that composting food waste and applying it to soils results in nearly 5 times less GHG emissions to the atmosphere (Brown, 2016).<br>• Composting agricultural manure followed by application to crop fields can reduce GHG production compared to the application of raw manure (Brown et al., 2009; Kim et al., 2014; Lazcano et al., 2021; Walling & Vaneeckhaute, 2020)<br>• Substituting inorganic N fertilizer with compost can decrease $N_2O$ (another potent GHG) released from soils and aquatic environments receiving fertilizer runoff (Brown et al., 2008).<br>• Peatland ecosystems sequester roughly one-third of the global soil C and play an important role in the global C cycle (Nelson et al., 2021). Substitution of peat used in agriculture and horticulture with compost can significantly reduce GHG generation associated with the mining and use of peat (Levis & Barlaz, 2011; Saer et al., 2013). It also reduces the extraction of the C sequestered in peatland ecosystems.</td></tr>
</table>

Compost use has considerable value for a variety of sectors, including agriculture, horticulture and landscaping, GI and stormwater management, ecosystem conservation and restoration (e.g., wetlands creation, wildfire rehabilitation), and contaminated site remediation (Ozores-Hampton et al., 2022). Furthermore, scientific studies have demonstrated that compost use can outperform conventional materials and practices that are typically utilized in sectors such as landscaping and stormwater management (Evanylo et al., 2016; Faucette, Governo, et al., 2009; Faucette et al., 2005). Table 18 highlights the key benefits of compost use for the five sectors examined in this report:

*Table 18. Summary of key benefits of compost use across different sectors.*

| Benefit | Sector | | | | |
|---|---|---|---|---|---|
| | Agriculture | Horticulture & landscaping | Green infrastructure & stormwater management | Ecosystem conservation & restoration | Contaminated site remediation |
| Decreased stormwater runoff | ✓ | ✓ | ✓ | ✓ | ✓ |
| Decreased soil erosion | ✓ | ✓ | ✓ | ✓ | ✓ |
| Reduced surface water & groundwater pollution | ✓ | ✓ | ✓ | ✓ | ✓ |
| Decreased irrigation requirements | ✓ | ✓ | | | |
| Reduced contamination of crops by human pathogens | ✓ | ✓ | | | |
| Improved plant establishment & growth | ✓ | ✓ | ✓ | ✓ | ✓ |
| Improved crop yield & crop quality | ✓ | ✓ | | | |
| Increased carbon sequestration | ✓ | ✓ | ✓ | ✓ | ✓ |
| Soil fertilization | ✓ | ✓ | ✓ | ✓ | ✓ |
| Immobilization/degradation of soil contaminants | ✓ | ✓ | ✓ | | ✓ |
| Plant disease suppression | ✓ | ✓ | | | |
| Weed suppression | ✓ | ✓ | | | |

There are, however, challenges and risks associated with compost use that vary with the feedstock blends used to manufacture compost and how the finished compost is used (e.g., use for large-scale production of edible crops versus the replacement of peat in potting mixes for ornamental plants versus a compost filter sock used to filter pollutants from stormwater). For example, compost feedstocks may contain undesirable contaminants, such as plastic, glass and/or harmful chemicals such as PFAS (Rynk, Schwarz, et al., 2022), which could be introduced to a site through compost use. Research is active and needed on the transformation and fate of microplastics and PFAS in compost, and a risk assessment for PFAS in soil-like media is yet to be developed. Additionally, research indicates that for some applications, such as stormwater control, it is important to consider levels of nutrients in compost and potential leaching to surface or groundwater (Davis et al., 2023; Faucette et al., 2005; Heyman et al., 2019).

Economically, compost manufacturing and use sustains green jobs throughout the organics recovery cycle and subsequent use (Beattie, 2014; Platt et al., 2013). For example, composting facilities have been found to generate an average of approximately seven jobs per 10,000 tons of organic materials processed (EREF, 2024). Markets and applications for compost include agriculture and horticulture, landscaping and nurseries, vegetable and flower gardens, sod production and roadside projects, wetlands creation, GI, soil remediation and land reclamation, sports fields and golf courses, sediment and erosion control, and stormwater management. The avoided environmental impacts (e.g., GHG emissions, fertilizer use) and improvement in ecosystem sustainability (e.g., C sequestration, soil health and water quality) also translate to economic benefits that can be estimated as a dollar value (see examples in call-out box). Social benefits are also evident through the enhancement of ecosystem services, although these are difficult to quantify using traditional market valuation methods.

Compost use at greater scales can contribute to broader sustainability efforts in the United States due to its relatively low cost, versatility and potential for integration with other sustainable practices. The large volume of compostable materials (e.g., food waste, yard trimmings and animal manure) generated in the United States offers vast potential to scale up compost production, compost use and associated environmental benefits. However, it has been estimated that the annual demand for compost is ten times greater than the supply (Goldstein, 2020b). Local factors can dictate the availability of organic material, with food waste, yard trimmings and biosolids more typically obtainable in urban areas, while agricultural residues, byproducts and manure are readily attainable in rural settings. Compost use tends to be localized, largely due to the costs associated with transporting bulky materials with relatively low per-unit monetary value. The measurable benefits also tend to be localized; however, scaled-up compost use across multiple projects and sectors can generate cumulative and cascading benefits that support national or regional environmental sustainability goals (e.g., C neutrality, food sustainability, water quality targets).

Incentives for composting (e.g., collection services, rewards programs) and limitations on the landfilling of organic materials, particularly food waste, can increase the availability of compost to better meet demand. State and local governments are well-positioned to increase awareness about the value of compost and can play a leading role in promoting use in sectors such as stormwater management or agriculture. Such approaches can stimulate a positive feedback cycle in which increasing compost use drives compost production, which in turn magnifies the cumulative environmental and societal benefits and leads to further demand for compost. This can maximize environmental benefits and reduce per-unit costs, further encouraging use and expanding the market potential. Whether at the individual, community, municipal or regional level, expanding compost use can contribute to the broader goals associated with climate change and environmental sustainability.

## 16.2 Research Needs

Additional research is needed in the following areas to improve understanding of the environmental and economic value of compost use at scale and address current challenges to increasing the use of compost.

**Comparative studies**: Additional comparative studies are needed to evaluate the effectiveness of compost use relative to conventional land management practices (e.g., inorganic fertilizer use, application of raw manure, traditional stormwater BMPs, erosion control practices such as topsoil placement and hydroseeding), and the associated life cycle environmental and economic tradeoffs

### Economic Value – Examples

**Soil health:** According to the University of Vermont, the value of improved soil health on Vermont farms is approximately $31/acre/year, providing a total value of nearly $25 million/year (Dube et al., 2022).

**Agricultural productivity:** Agricultural lands amended with compost may be of higher quality due to improvements in soil health. This can translate to improved crop yield, quality and revenue. For example, a single application of compost (at 22 t $ac^{-1}$) increased the average yield of dryland wheat in Utah by 1.0 t $ac^{-1}$ in the two years immediately following application (Reeve et al., 2012). After 16 years, the wheat yield associated with the compost application remained greater (0.2 t $ac^{-1}$) than control plot yields.

**Reduced input and maintenance costs:** Compost application reduces costs associated with fertilizers, pesticides, herbicides and irrigation (Alexander, 2020e; Maynard & Hill, 2000). In a Massachusetts turfgrass maintenance program, cost savings of approximately $38,000 per year were seen by using compost (Hussey & Harrison, 2005).

**Soil carbon sequestration:** An EPA study in Leadville, CO where biosolids and compost were applied to reduce metal toxicity found that net carbon sequestration was worth $10,974-$19,510 per hectare (Brown & Chaney, 2016).

**Water conservation:** Potential annual losses from inefficient water use or inadequate infiltration of water into soils can vary from $165 per acre for irrigated pasture to as much as $988 per acre for orchards (Boyle et al., 1989).

(e.g., net GHG emissions of composting and applying manure versus storage and application of raw manure).

**Compost characteristics for specific uses**: Although information exists on compost quality for different end uses, there remains a need to better characterize the environmental performance of compost blends, e.g., to standardize or optimize compost recipes to achieve characteristics suitable for different end uses. Further research about designing and producing composts for specific end uses can help inform stakeholders (e.g., making compost blends specifically for contaminant removal from stormwater). There is also a need to characterize how variations in compost stability and maturity affect its suitability and performance for common applications.

**Compost contamination**: Research is needed on the transformation and fate of microplastics and other emerging contaminants such as PFAS in compost, and a risk assessment for PFAS in soil-like media needs to be developed. Research is also needed to explore acceptable compost contamination levels dependent on the setting and purpose of compost use (e.g., for the revegetation of a mine site versus in agriculture to produce food). Strategies, methods, and technologies should be further developed to reduce contaminant (e.g., soluble salts, PFAS, plastics) levels in feedstocks and final compost to reduce or avoid undesirable consequences for certain compost uses, such as food production. Additionally, further research is needed on contaminant removal from food waste feedstocks and compostable labels/packaging, as well as whether in-home food dehydrators or other pre-processing technologies reduce the level of contamination.

**Longer-term studies**: Many studies on the benefits of compost use are short-term (e.g., less than 10 years) and do not consider the long-term effects of compost on soil health, C sequestration and other environmental factors. Long-term studies are needed to fully understand the effects of compost use over time.

**Economic studies**: As discussed earlier in the report, further economic analysis of compost use for various sectors is needed. This would help to distinguish circumstances in which compost use reduces net costs and/or increases net profitability from circumstances where compost use is not economical.

**Tool development**: Developing a calculator that quantifies potential environmental outcomes and economic costs from compost use would be useful for stakeholders considering increased compost use. Such a tool could be informed by the best-available science and compare compost use to conventional land management practices. A user could assess variations in key environmental factors based on site conditions and use cases.

**Environmental benefits of compost use at scale**: Further analysis is needed to quantify the potential net environmental benefits that might occur if compost is more widely used over large scales. Current scientific studies focus more on localized use or site-specific benefits. There is limited literature that assesses potential benefits over regional to national scales, considering broad potential uses of compost in all sectors discussed in this report.

**Combining compost with inorganic nutrients or amendments**: New research is needed to explore optimizing compost use by combining both organic and inorganic nutrient sources or other amendments (for example, biochar) to better align with crop nutrient requirements. The goal would be to increase crop yield, reduce leaching, improve nutrient use efficiency and reduce environmental impacts. Determining N mineralization rates and gaining an improved understanding of how various composts affect P cycling is a critical component of utilizing diverse compost feedstocks because mineralization rates are affected by the interaction of compost type, soil, application rates and methods, and environmental conditions (Ozores-Hampton, 2019).

# Glossary

- **Aerobic**: Relating to, involving, or requiring free oxygen.
- **Anaerobic:** Relating to, involving, or requiring an absence of free oxygen.
- **Anaerobic digestion (AD):** A process in which microorganisms break down organic materials, such as food waste, grease, manure and wastewater solids, in the absence of oxygen. The products of *AD* are digestate, which can be used as a fertilizer or soil amendment, and biogas, which can be captured and used for energy production.
- **Banding:** The placement of compost in concentrated bands or rows near plant roots, maximizing nutrient availability and reducing competition from weeds.
- **Biochar:** Fine-grained charcoal made by heating biomass (e.g., wood, manure, crop residues and solid waste) with limited to no oxygen (Camps & Tomlinson, 2015). It has a greater persistence in the environment than its parent materials because its C is in a more stable form (Meyer-Kohlstock et al., 2015).
- **Biosolids**: A product of the wastewater treatment process. During wastewater treatment, the liquids are separated from the solids. Those solids are then treated to produce a nutrient-rich product known as biosolids. Biosolids are divided into Class A and Class B based on treatment methods for pollutants, pathogens and vector attraction reduction. Biosolids that are beneficially used must meet federal and state requirements.
- **Broadcast spreading:** The even distribution of compost across a wide area, typically using a spreader or spreading by hand, to ensure uniform coverage and nutrient availability.
- **Bulking agent:** Organic material, such as wood chips, added to compost primarily to help create good pore structure for air flow. Often provides part of C source as well.
- **Carbonaceous feedstocks:** Compost feedstocks with a C:N ratio are considered to be high, generally above 40:1.
- **Carbon-to-nitrogen ratio (C:N ratio):** The ratio of C to N mass in organic materials being composted. A balanced *C:N ratio* (generally 25–40:1) in a compost feedstock mixture promotes optimal decomposition and microbial activity (Rynk, Schwarz, et al., 2022). Compost feedstocks with *C:N ratios* below 40 are generally referred to as "nitrogenous," while feedstocks with higher ratios are referred to as "carbonaceous."
- **Carbon sequestration:** Biologically or geologically mediated storage of C in a C pool that inhibits the emission of $CO_2$ (a GHG) to the atmosphere.
- **Cation exchange capacity (CEC):** The capacity of the soil to attract and hold onto positively charged mineral ions, or cations. The presence of clay and organic matter increases a soil's *CEC.*
- **Climate adaptation:** Actions or conditions that increase the ability to cope with changing climate conditions, such as changes in air temperature and precipitation patterns and amounts.
- **Climate mitigation:** Actions that reduce the emission of GHGs that contribute to climate change.
- **Climate resilience:** The ability to recover from or reduce vulnerability to climate-related disturbances, such as floods, wildfire and drought.
- **Co-composting:** The process of combining different types of organic materials, such as food waste and yard waste, to be composted together, benefiting from their complementary characteristics.
- **Cold composting:** A slower composting method that occurs at ambient temperatures, usually 50–77 °F (10–25 °C). *Cold composting* requires more time for organic materials to break down completely.
- **Compost:** A biologically stable soil amendment produced by the aerobic (i.e., oxygen-required) decomposition of organic (i.e., C-based) materials.
- **Compost application:** The process of adding compost to the soil, typically through broadcast spreading, banding, incorporating into soils, topdressing, side-dressing or applying as a mulch.

- **Compost application rates:** The recommended amount of compost to be applied to soil or plants, usually measured in cubic yards, tons, or pounds per area, to ensure proper nutrient balance and desired soil improvements.
- **Compost blanket:** The application of compost in a thin layer used to provide immediate soil protection and promote vegetation growth on a slope or area prone to erosion. Grass seed is typically incorporated into the compost before application.
- **Compost maturity:** The point at which the more readily degraded organic materials/compounds have completed their degradation while less readily degradable organic materials/compounds remain. *Compost maturity* can be evaluated through analysis of C:N ratio, oxygen uptake and seed germination rates. Mature compost is low in phytotoxic acids.
- **Compost quality standards:** Guidelines or criteria used to evaluate the physical, chemical and biological characteristics of compost, ensuring it meets specific requirements for agricultural, horticultural, landscaping and other purposes.
- **Compost stability:** An indication of the rate of organic material degradation under existing conditions. The organic matter in a stable compost is resistant to further decomposition.
- **Compostable materials:** Any organic materials capable of being broken down by microorganisms through composting. Manufactured compostable products (e.g., compostable plates, forks and food packaging) are certified by recognized organizations that use standardized test protocols.
- **Composting:** The managed, aerobic (oxygen-required) biological decomposition of organic materials by microorganisms.
- **Composting amendment:** An ingredient in a mixture of composting raw materials included to improve the overall characteristics of the mixture. *Composting amendments* often add C, dryness, or porosity to the mixture.
- **Composting ratio:** The proportion of N-rich and C-rich materials in a compost pile or system. A balanced *composting ratio* is important for successful composting and proper decomposition.
- **Conventional composting:** Degradation of organic materials through the biological processes of microorganisms (e.g., bacteria, fungi and actinomycetes) under aerobic conditions at moderately high temperatures (generally 130–160 °F).
- **Denitrification:** An anaerobic biological process that converts N compounds to N gas ($N_2$) or nitrous oxide ($N_2O$).
- **Erosion control:** The prevention or reduction of soil erosion by increasing soil stability and promoting vegetative cover.
- **Feedstocks:** Different types of raw organic materials (e.g., food waste, manure and yard trimmings) used for composting.
- **Fertility enhancement:** The improvement of soil fertility by adding compost, which provides essential nutrients, enhances nutrient retention and promotes microbial activity.
- **Hot composting:** A composting method that generates high temperatures (130–160 °F, or about 54–71 °C) by actively managing the compost pile. The heat accelerates decomposition and kills pathogens and weed seeds.
- **Incorporation:** The mixing of compost into the soil through techniques such as tilling, digging, or plowing, ensuring the organic matter is distributed throughout the root zone.
- **Inorganic fertilizers:** Fertilizers that provide essential plant nutrients not derived from organic materials, such as synthesized N (e.g., via the Haber-Bosch process) and mined P.
- **Landfill diversion:** The practice of diverting organic materials from landfills to other pathways, such as composting, to reduce the generation of GHGs and produce resources that can generate environmental benefits.
- **Macronutrients:** Essential nutrients required by plants in relatively large quantities, including nitrogen (N), phosphorus (P) and potassium (K), which are provided by compost.
- **Micronutrients:** Essential nutrients required by plants in small quantities, such as boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo) and zinc (Zn), which can be supplied by compost.
- **Microorganisms:** Small living organisms, including bacteria, fungi, actinomycetes and protozoa.

- **Mulch:** A layer of material applied to the soil surface to conserve moisture, suppress weeds and moderate soil temperature. Examples of materials that can be used as mulch include compost, wood chips, grass clippings, leaves, straw, cardboard and newspaper.
- **Municipal solid waste, organic fraction (OFMSW):** The fraction of municipal solid waste that is biodegradable. It typically consists of yard trimmings and food waste but also might include other organic materials such as paper, cardboard and wood.
- **Nitrogenous feedstocks:** Compost feedstocks considered to have a low-to-moderate C:N ratio, generally below 40:1.
- **Nutrient release:** The gradual release of nutrients from compost into the soil solution, making them available for plant uptake over an extended period.
- **pH:** A measure of the acidity or basicity of a solution, measured as the concentration of hydrogen ions.
- **Regenerative agriculture:** A food production system that nurtures and restores soil health; seeks to protect climate, water resources and biodiversity; and enhances farms' productivity and profitability.
- **Soil aggregation:** Binding together of soil particles through various chemical, physical and biological soil processes.
- **Soil amendment:** Any material, such as compost, added to soil to improve its physical properties (e.g., structure, drainage and water-holding capacity) and provide nutrients for plant growth.
- **Soil bulk density:** The level compactness of a soil measured as the dry mass of a soil sample divided by its volume, typically reported in units of grams per cubic centimeter. It is affected by the density of mineral particles and organic matter as well as the amount of pore space in the soil.
- **Soil carbon sequestration:** The long-term storage of C within soils through biologically and physically mediated processes that inhibit the emission of $CO_2$ into the atmosphere.
- **Soil conditioner:** A soil additive that stabilizes the soil, improves its resistance to erosion, increases its permeability to air and water, improves its texture and the resistance of its surface to crusting, makes it easier to cultivate, and otherwise improves its quality.
- **Soil fertility:** The ability of soil to support plant growth by providing essential nutrients, good structure and favorable water-holding capacity, which can be enhanced by adding compost.
- **Soil health:** The continued capacity of the soil to function as a vital living ecosystem that sustains plants, animal and humans.
- **Soil organic carbon (SOC):** C compounds in the soil derived from soil organic matter (i.e., degradable C).
- **Soil organic matter:** Live plant and animal tissues, along with dead organisms, organic C-based secretions and excretions from organisms, in various phases of decomposition within the soil.
- **Soil porosity:** The amount of void space in the soil into which air and water can flow. Greater *soil porosity* results in lower soil bulk density.
- **Soil structure:** The spatial arrangement of soil particles and aggregates. *Soil structure* affects water infiltration, aeration, root penetration and microorganism habitat.
- **Soil texture:** A characterization of soil type based on the relative proportions of sand, silt and clay in a particular soil.
- **Soil tilth:** The physical condition of soil as related to its ease of tillage, fitness as a seedbed and promotion of seedling emergence and root penetration.
- **Sustainable agriculture:** A farming system that aims to minimize environmental impact, conserve natural resources and enhance soil health by using practices such as composting, crop rotation, reduced tillage, leaving more crop residue on fields and reduced chemical inputs.
- **Thermophilic composting:** The phase of the composting process in which temperatures reach above 104 ˚F. During this stage, heat-tolerant bacteria continue to eat simple compounds with high-energy yield. With sufficient food, water and air, these microbes can bring the temperature up to 150 ˚F or higher.
- **Topdressing:** The application of a thin layer of compost on the surface of the soil around plants, providing a slow release of nutrients and improving soil structure.
- **Vermicomposting:** A process involving the use of worms (such as *Eisenia fetida*) and microorganisms to accelerate the decomposition of organic materials at moderately low

temperatures (generally 55–85 °F) and produce "worm castings" for their value to soil and plant health.

- **Water-holding capacity:** The ability of soil to hold and retain moisture.
- **Water infiltration:** The process by which water enters the soil surface, largely affected by soil porosity.
- **Water percolation:** The process by which water moves through the soil profile after infiltrating the soil surface.
- **Weed suppression:** Reducing weed growth by creating a favorable environment for desired plants, improving competition, and providing a physical barrier to weed establishment.
- **Yard trimmings:** A general term used to describe organic materials such as grass clippings, leaves and branches trimmed from trees, shrubs and gardens. Usually does not include logs, stumps, or other woody materials.

# References


Abbey, L., Yurgel, S. N., Asunni, O. A., Ofoe, R., Ampofo, J., Gunupuru, L. R., & Ajeethan, N. (2022). Changes in Soil Characteristics, Microbial Metabolic Pathways, TCA Cycle Metabolites and Crop Productivity following Frequent Application of Municipal Solid Waste Compost. *Plants*, *11*(22), Article 3153. https://doi.org/10.3390/plants11223153

Adeleke, K. A., Atoloye, I. A., Creech, J. E., Dai, X., & Reeve, J. R. (2021). Nutritive and non-nutritive effects of compost on organic dryland wheat in Utah. *Agronomy Journal*, *113*(4), 3518-3531. https://doi.org/10.1002/agj2.20698

Adelman, M. J., & Kney, A. D. (2010). Techniques for nitrogen management in municipal solid waste composting. World Environmental and Water Resources Congress 2010: Challenges of Change, Providence, RI.

Alexander, R. (2005). *AAPFCO Soil Amendment/Compost Uniform Product Claims*. https://cdn.ymaws.com/www.compostingcouncil.org/resource/resmgr/images/use_compost/AAPFCO_Uniform_Product_Claim.pdf

Alexander, R. (2016). *Compost: The Sustainable Solution*. Retrieved August 1, 2023 from https://naturcycle.com/wp-content/uploads/2016/04/MSWmgtRAA-article-Jan2016.pdf

Alexander, R. (2017). Compost Fares Well In Fertilizer And Soil Amendment Rules. *BioCycle*, 43-46. https://alexassoc.net/organic_recylcing_composting_documents/Compost%20fares%20well%20in%20fertilizer%20and%20soil%20amendment%20rules.pdf

Alexander, R. (2020a). *Compost Use Applications- A Return on Investment (ROI): Bioretention Media*. https://www.compostfoundation.org/Portals/2/Images/Bioretention.pdf

Alexander, R. (2020b). *Compost Use Applications- A Return on Investment (ROI): Edible Gardens*. https://www.compostfoundation.org/Portals/2/Images/Edible%20Gardens.pdf

Alexander, R. (2020c). *Compost Use Applications- A Return on Investment (ROI): Erosion Control Blanket*. https://www.compostfoundation.org/Portals/2/Images/Erosion%20Control.pdf

Alexander, R. (2020d). *Compost Use Applications- A Return on Investment (ROI): Landscape Gardens* Commercial compost - general compost). https://www.compostfoundation.org/Portals/2/Images/Landscape%20Gardens.pdf

Alexander, R. (2020e). *Compost Use Applications- A Return on Investment (ROI): Row Crop Production* Commercial compost - general compost). https://www.compostfoundation.org/Portals/2/Images/Row%20Crop.pdf

Alexander, R. (2020f). *Compost Use Applications- A Return on Investment (ROI): Supplementing Plant Nutrition*. https://www.compostfoundation.org/Portals/2/Images/Supplementing.pdf

Alexander, R. (2020g). *Compost Use Applications- A Return on Investment (ROI): Topsoil Manufacturing* Commercial compost - general compost). https://www.compostfoundation.org/Portals/2/Images/Topsoil.pdf

Alexander, R. (2020h). *Compost Use Applications- A Return on Investment (ROI): Turf Installation*. https://www.compostfoundation.org/Portals/2/Images/Turf%20Installation.pdf

Alexander, R. (2020i). *Compost Use Applications- A Return on Investment (ROI): Turf Maintenance*. https://www.compostfoundation.org/Portals/2/Images/Turf%20Maintenance.pdf

Alexander, R. (2020j). *Compost Use Applications- A Return on Investment (ROI): Upgrading Marginal Soils*. https://www.compostfoundation.org/Portals/2/Images/Upgrading.pdf

Alexander, R. (2020k). Compost Use in North Carolina Soils for Turf Establishment and Maintenance. *North Carolina Turfgrass*, 20-22. https://alexassoc.net/organic_recylcing_composting_documents/Compost%20Use%20in%20NC%20Soils%202-20.pdf

Alexander, R. (2023). 7/2/2023 Personal Communication. In EPA (Ed.).

Alexander, R., Tyler, R., Schwarz, M., & Ziegenbein, J. (2022). Chapter 18 - Compost marketing and sales. In R. Rynk (Ed.), *The Composting Handbook* (pp. 879-912). Academic Press. https://doi.org/10.1016/B978-0-323-85602-7.00014-5

Alferez, F. (2021). Compost utilization in fruit production. *Compost Utilization in Production of Horticultural Crops*, 51-58. https://www.taylorfrancis.com/chapters/edit/10.1201/9781003140412-5/compost-utilization-fruit-production-fernando-alferez?context=ubx&refId=b850a695-aaac-45ce-9470-a9e97dec471e

Ali, U., Sajid, N., Khalid, A., Riaz, L., Rabbani, M. M., Syed, J. H., & Malik, R. N. (2015). A review on vermicomposting of organic wastes. *Environmental Progress & Sustainable Energy*, *34*(4), 1050-1062.

Alvarez-Campos, O., Evanylo, G. K., & Badzmierowski, M. J. (2018). Development and Assessment of Exceptional Quality Biosolids Products for Urban Gardens. *Compost Science & Utilization*, *26*(4), 232-243.

Archuletta, R., & Faucette, B. (2014). *Compost blankets for runoff and erosion control*. https://spvsoils.com/wp-content/uploads/2022/12/Compost-Blankets-USDA-NRCS-2014.pdf

Aslam, D. a. V., J. (2009). Tools To Evaluate Compost Phytotoxicity. *BioCycle*, *50*(12), 28. https://www.biocycle.net/tools-to-evaluate-compost-phytotoxicity/

Attanayake, C. P., Hettiarachchi, G. M., Harms, A., Presley, D., Martin, S., & Pierzynski, G. M. (2014). Field evaluations on soil plant transfer of lead from an urban garden soil. *Journal of Environmental Quality*, *43*(2), 475-487.

Attanayake, C. P., Hettiarachchi, G. M., Martin, S., & Pierzynski, G. M. (2015). Potential bioavailability of lead, arsenic, and polycyclic aromatic hydrocarbons in compost-amended urban soils. *Journal of Environmental Quality*, *44*(3), 930-944.

Attanayake, C. P., Hettiarachchi, G. M., Palomo, M., Pierzynski, G. M., & Calderon, B. (2021). Phytoavailability of lead for vegetables in urban garden soils. *ACS Agricultural Science & Technology*, *1*(3), 173-181.

Badzmierowski, M. J., Evanylo, G. K., & Ervin, E. H. (2020). Biosolids amendments improve an anthropogenically disturbed urban turfgrass system. *Crop Science*, *60*(3), 1666-1681.

Bakr, N., Weindorf, D. C., Zhu, Y., Arceneaux, A. E., & Selim, H. M. (2012). Evaluation of compost/mulch as highway embankment erosion control in Louisiana at the plot-scale. *Journal of Hydrology*, *468-469*, 257-267. https://doi.org/10.1016/j.jhydrol.2012.08.040

Basche, A. (2017). *Turning Soils into Sponges. How Farmers Can Fight Floods and Droughts*. https://www.ucsusa.org/resources/turning-soils-sponges

Basta, N. T., Busalacchi, D. M., Hundal, L. S., Kumar, K., Dick, R. P., Lanno, R. P., Carlson, J., Cox, A. E., & Granato, T. C. (2016). Restoring ecosystem function in degraded urban soil using biosolids, biosolids blend, and compost. *Journal of Environmental Quality*, *45*(1), 74-83. https://doi.org/10.2134/jeq2015.01.0009

Batjiaka, R., & Brown, S. (2019). Creating topsoils and soil conditioners from biosolids and urban residuals. *Journal of Environmental Quality*, *49*, 1020-1031.

Beattie, A. (2014). Cost-benefit analysis of food-waste composting program at UMM. *Scholarly Horizons: University of Minnesota, Morris Undergraduate Journal*, *1*(1), 1.

Beck, J. E., Schroeder-Moreno, M. S., Fernandez, G. E., Grossman, J. M., & Creamer, N. G. (2016). Effects of cover crops, compost, and vermicompost on strawberry yields and nitrogen availability in North Carolina. *HortTechnology*, *26*(5), 604-613. https://doi.org/10.21273/HORTTECH03447-16

Beecher, N., & Brown, S. (2018). PFAS and organic residuals management. *BioCycle*, *59*(6), 20. https://www.biocycle.net/pfas-organic-residuals-management/

Beighley, R. E., Scholl, B., Faucette, L. B., & Governo, J. (2010). Runoff characteristics for construction site erosion control practices. *Journal of irrigation and drainage engineering*, *136*(6), 405-413. https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29IR.1943-4774.0000202

Bell, B., & Platt, B. (2014). *Building Healthy Soils with Compost to Protect Watersheds*. https://www.ilsr.org/wp_ilsr/wp-content/uploads/2013/05/Compost-Builds-Healthy-Soils-ILSR-5-08-13-2.pdf

Bernal, M. P., Sanchez-Monedero, M. A., Paredes, C., & Roig, A. (1998). Carbon mineralization from organic wastes at different composting stages during their incubation with soil. *Agriculture, Ecosystems & Environment*, *69*(3), 175-189.

Bernal, M. P., Sommer, S. G., Chadwick, D., Qing, C., Guoxue, L., & Michel, F. C., Jr. (2017). Current Approaches and Future Trends in Compost Quality Criteria for Agronomic, Environmental, and Human Health Benefits. In *Advances in agronomy* (Vol. 144, pp. 143-233). Academic Press Inc. https://doi.org/10.1016/bs.agron.2017.03.002

Biek, S. K., Khudur, L. S., & Ball, A. S. (2024). Challenges and Remediation Strategies for Per-and Polyfluoroalkyl Substances (PFAS) Contamination in Composting. *Sustainability*, *16*(11), 4745.

Biernbaum, J. (2012). *Organic Matters: Feeding the Soil and Building Soil Quality*. https://www.canr.msu.edu/hrt/uploads/535/78622/Organic-Matters-figure-6pgs.pdf

Billings, S. A., Lajtha, K., Malhotra, A., Berhe, A. A., de Graaff, M.-A., Earl, S., Fraterrigo, J., Georgiou, K., Grandy, S., Hobbie, S. E., Moore, J. A. M., Nadelhoffer, K., DPierson, D., Rasmussen, C., Silver, W. L., Sulman, B. N., Weintraub, S., & Weider, W. (2021). Soil organic carbon is not just for soil scientists: measurement recommendations for diverse practitioners. *Ecological Applications*, *31*(3). https://doi.org/https://doi.org/10.1002/eap.2290

Block, D. (2000). Controlling erosion from highway projects. *BioCycle*, *41*(1), 59-59.

Bly, A. (2022). *The costs of erosion: topsoil's role in food security*. South Dakota State University Extension Service. Retrieved July 19, 2023 from https://extension.sdstate.edu/costs-erosion-topsoils-role-food-security

Boyle, M., Frankenberger, W. T., & Stolzy, L. H. (1989). The infuence of organic matter on soil aggregation and water infltration. *J. Prod. Agric.*, *2*(4), 290–298.

Brauman, K. A., van der Meulen, S., & Brills, J. (2014). Ecosystem Services and River Basin Management. In J. Brils, W. Brack, D. Mueller-Grabherr, P. Negrel, & J. E. Vermaat (Eds.), *Risk-Informed Management of European River Basins* (Vol. 29, pp. 265-294). Springer, Berlin, Heidelberg. https://link.springer.com/chapter/10.1007/978-3-642-38598-8_10

Brinton, W. (2010). Characterizing Compost Completeness. *BioCycle*, *51*(4), 31. https://www.biocycle.net/characterizing-compost-completeness/

Brown, M. W., & Tworkowski, T. (2004). Pest management benefits of compost mulch in apple orchards. *Agric. Ecosyst. Environ.*, *103*, 465-472.

Brown, S. (2016). Greenhouse gas accounting for landfill diversion of food scraps and yard waste. *Compost Science & Utilization*, *24*(1), 11-19. https://doi.org/10.1080/1065657X.2015.1026005

Brown, S. (2020). Connections: Calculating Potential For Compost Use On Highways [12/19/2022]. *BioCycle*. http://www.fullcirclemushroomcompost.com/wp-content/uploads/2020/08/Biocycle-Pt3-DOT-Usage.pdf

Brown, S. (2023, 5/9/2023). Connections: Unpacking Environmental Justice And Contaminated Soils. *BioCycle*. https://www.biocycle.net/connections-environmental-justice-contaminated-soils/

Brown, S. (2024). 4/2/24 Personal Communication. In EPA (Ed.).

Brown, S., & Beecher, N. (2019). Carbon Accounting for Compost Use in Urban Areas. *Compost Science and Utilization*, *27*(4), 227-239. https://doi.org/10.1080/1065657X.2019.1674224

Brown, S., Butman, D., & Kurtz, K. (2023b). Steps to circularity: Impact of resource recovery and urban agriculture in Seattle and Tacoma, Washington. *Journal of Environmental Management*, *345*, 118648.

Brown, S., & Chaney, R. L. (2016). Use of Amendments to Restore Ecosystem Function to Metal Mining-Impacted Sites: Tools to Evaluate Efficacy [Review]. *Current Pollution Reports*, *2*(2), 91-102. https://doi.org/10.1007/s40726-016-0029-1

Brown, S., Chaney, R. L., Hallfrisch, J., Ryan, J. A., & Berti, W. R. (2004). In Situ Soil Treatments to Reduce the Phyto- and Bioavailability of Lead, Zinc, and Cadmium. *Journal of Environmental Quality*, *33*(2), 522-531.

Brown, S., Chaney, R. L., Hallfrisch, J. G., & Xue, Q. (2003). Effect of Biosolids Processing on Lead Bioavailability in an Urban Soil. *Journal of Environmental Quality*, *32*(1), 100-108.

Brown, S., Chaney, R. L., & Hettiarachchi, G. M. (2016). Lead in urban soils: a real or perceived concern for urban agriculture? *Journal of Environmental Quality*, *45*(1), 26-36.

Brown, S., Clausen, I., Chappell, M. A., Williams, A., Scheckel, K. G., & Neuville, M. (2012). High-Iron Biosolids Compost–Induced Changes in Lead and Arsenic Speciation and Bioaccessibility in Co contaminated Soils. *Journal of Environmental Quality*, *41*, 1612–1622.

Brown, S., Corfman, A., Mendrey, K., Kurtz, K., & Grothkopp, F. (2015). Stormwater bioretention systems: Testing the phosphorus saturation index and compost feedstocks as predictive tools for system performance. *Journal of Environmental Quality*, *45*(1), 98-106. https://doi.org/10.2134/jeq2014.10.0414

Brown, S., & Cotton, M. (2010). Compost boost to California agriculture. *BioCycle*, *51*(1), 27-29. https://www.scopus.com/inward/record.uri?eid=2-s2.0-77149156697&partnerID=40&md5=0f976be80ebac69f6934029444000a00

Brown, S., & Cotton, M. (2011). Changes in Soil Properties and Carbon Content Following Compost Application: Results of On-farm Sampling. *Compost Science and Utilization*, *19*(2), 87-96. https://doi.org/10.1080/1065657X.2011.10736983

Brown, S., Cotton, M., Messner, S., Berry, F., & Norem, D. (2009). *Methane avoidance from composting*. https://www.climateactionreserve.org/wp-content/uploads/2009/11/Reserve_Composting_Issue_Paper_Final.pdf

Brown, S., Faucette, B., & Kurtz, K. (2017). *The Compost & Climate Connection* (G. Black, L. Loder-Rossiter, K. Nix, B. Simone, S. Subler, & J. Ziegenbein, Eds.). Compost Research and Education Foundation. https://www.compostfoundation.org/Education/Publications

Brown, S., & Goldstein, N. (2016). The Role of Organic Residuals in Urban Agriculture. In S. Brown, K. McIvor, & E. Hodges Snyder (Eds.), *Sowing Seeds in the City: Ecosystem and Municipal Services* (pp. 93-106). Springer Netherlands. https://doi.org/10.1007/978-94-017-7453-6_6

Brown, S., Kennedy, L., Cullington, M., Mihle, A., & Lono-Batura, M. (2019). Relating pharmaceuticals and personal care products in biosolids to home exposure. *Urban Agriculture & Regional Food Systems*, *4*(1), 1-14.

Brown, S., Kruger, C., & Subler, S. (2008). Greenhouse Gas Balance for Composting Operations. *Journal of Environmental Quality*, *37*(4), 1396-1410. https://doi.org/10.2134/jeq2007.0453

Brown, S., Kurtz, K., Bary, A., & Cogger, C. (2011). Quantifying Benefits Associated with Land Application of Organic Residuals in Washington State. *Environmental Science & Technology*, *45*(17), 7451-7458. https://doi.org/10.1021/es2010418

Brown, S., Mahoney, M., & Sprenger, M. (2014). A comparison of the efficacy and ecosystem impact of residual-based and topsoil-based amendments for restoring historic mine tailings in the Tri-State mining district. *Science of the Total Environment*, *485*, 624-632.

Brown, S., Miltner, E., & Cogger, C. (2012). *Carbon sequestration potential in urban soils*. https://link.springer.com/chapter/10.1007/978-94-007-2366-5_9

Brown, S., Sprenger, M., Maxemchuk, A., & Compton, H. (2005). Ecosystem function in alluvial tailings after biosolids and lime addition. *Journal of Environmental Quality*, *34*(1), 139-148.

Buffam, I., & Mitchell, M. E. (2015). Nutrient cycling in green roof ecosystems. In *Green roof ecosystems* (pp. 107-137). https://link.springer.com/chapter/10.1007/978-3-319-14983-7_5?fromPaywallRec=true

Busby, R. R., Torbert, H. A., & Gebhart, D. L. (2007). Carbon and nitrogen mineralization of non-composted and composted municipal solid waste in sandy soils. *Soil Biology and Biochemistry*, *39*(6), 1277-1283.

Camps, M., & Tomlinson, T. (2015). *The use of biochar in composting*. https://biochar-international.org/wp-content/uploads/2018/04/Compost_biochar_IBI_final.pdf

Candanosa, R. M. (2021). Reducing Emissions to Lessen Climate Change Would Yield Dramatic Health Benefits by 2030. https://climate.nasa.gov/news/3134/reducing-emissions-to-lessen-climate-change-would-yield-dramatic-health-benefits-by-2030/

Carroll, A. (2016). Brownfields as sites for urban farms. In *Sowing Seeds in the City: Ecosystem and Municipal Services* (pp. 339-349).

Carson, R. T., & Mitchell, R. C. (1993). The value of clean water: The public's willingness to pay for boatable, fishable, and swimmable quality water. *Water Resources Research*, *29*(7), 2445-2454. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/93WR00495

Case, S. D. C., & Jensen, L. S. (2019). Nitrogen and phosphorus release from organic wastes and suitability as bio-based fertilizers in a circular economy. *Environmental Technology*, *40*(6), 701-715. https://doi.org/https://doi.org/10.1080/09593330.2017.1404136

CEC (Commission for Environmental Cooperation). (2017). *Characterization and Management of Food Loss and Waste in North America*. http://www.cec.org/files/documents/publications/11774-characterization-and-management-food-waste-in-north-america-foundational-report-en.pdf

Chan, K. Y., Orr, L., Fahey, D., & Dorahy, C. G. (2011). Agronomic and Economic Benefits of Garden Organics Compost in Vegetable Production. *Compost Science & Utilization*, *19*(2), 97-104. https://doi.org/10.1080/1065657X.2011.10736984

Chapman, E. J., Small, G. E., & Shrestha, P. (2022). Investigating potential hydrological ecosystem services in urban gardens through soil amendment experiments and hydrologic models. *Urban Ecosystems*, *25*(3), 867-878. https://doi.org/10.1007/s11252-021-01191-7

Choi, Y. J., Kim Lazcano, R., Yousefi, P., Trim, H., & Lee, L. S. (2019). Perfluoroalkyl acid characterization in US municipal organic solid waste composts. *Environmental Science & Technology Letters*, *6*(6), 372-377.

Clark, M., & Douds, D. D. (2011). Compost enhances growth and nutrient content of cover crops. *Journal of Sustainable Agriculture*, *35*(8), 878-896. https://doi.org/10.1080/10440046.2011.583465

Clark, M., & Douds, D. D. (2021). Compost enhances growth and nutrient content of cover crops. *Journal of Sustainable Agriculture*, *35*(8), 878-896. https://doi.org/10.1080/10440046.2011.583465

Climate Action Reserve. (2024). *Climate Action Reserve: Climate Forward*. https://www.climateactionreserve.org/

CLP. (2024). *Don't spoil the soil. The challenge of contamination at composting sites*. Closed Loop Partners. https://www.closedlooppartners.com/research/contamination-at-composting-facilities/

CNT. (2011). *The Value of Green Infastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits*. https://cnt.org/publications/the-value-of-green-infrastructure-a-guide-to-recognizing-its-economic-environmental-and

CNT, & SB Friedman Devleopment Advisors. (2020). *Green Stormwater Infrastructure Impact on Property Values*. https://cnt.org/publications/green-stormwater-infrastructure-impact-on-property-values

Cogger, C., Brown, S., & Kurtz, K. (2016). Soil formation and nutrient cycling. In *Sowing Seeds in the City: Ecosystem and Municipal Services* (pp. 25-52). Springer. https://link.springer.com/book/10.1007/978-94-017-7453-6

Cogger, C., Hummel, R., Hart, J., & Bary, A. (2008). Soil and redosier dogwood response to incorporated and surface-applied compost. *HortScience*, *43*(7), 2143-2150.

Cogger, C. G., Bary, A. I., Myhre, E. A., & Fortuna, A.-M. (2013). Biosolids Applications to Tall Fescue Have Long-Term Influence on Soil Nitrogen, Carbon, and Phosphorus. *Journal of Environmental Quality*, *42*(2), 516-522.

Coker, C. (2006). Environmental Remediation By Composting. *BioCycle*, *47*(12), 18. https://www.biocycle.net/environmental-remediation-by-composting/

Coker, C. (2010). Controlling Costs In Compost Manufacturing. *51*(9), 26. https://www.biocycle.net/controlling-costs-in-compost-manufacturing/

Coker, C. S. (2021). Compost utilization in ornamental and nursery crop production. In *Compost Utilization in Production of Horticultural Crops* (pp. 77-84). CRC Press. https://www.taylorfrancis.com/chapters/edit/10.1201/9781003140412-7/compost-utilization-ornamental-nursery-crop-production-craig-coker?context=ubx&refId=b19ee597-bb7c-47a0-a20e-73b0742d200a

Coker, C. S., King, M., Gilbert, J., Rivin, J. M., Wentz, R., Schwarz, M., Faucette, B., & Tyler, R. (2022). Chapter 19 - Composting economics. In R. Rynk (Ed.), *The Composting Handbook* (pp. 913-943). Academic Press. https://doi.org/10.1016/B978-0-323-85602-7.00016-9

Coker, C. S., & Ozores-Hampton, M. (2021). Compost tea foliar disease suppression in horticulture crops. In *Compost Utilization in Production of Horticultural Crops* (pp. 123-134). CRC Press. https://www.taylorfrancis.com/chapters/edit/10.1201/9781003140412-11/compost-tea-foliar-disease-suppression-horticulture-crops-craig-coker-monica-ozores-hampton

Compton, J. E., & Boone, R. D. (2000). Long-term impacts of agriculture on soil carbon and nitrogen in New England forests. *Ecology*, *81*(8), 2314-2330.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., Farber, S., & Turner, R. K. (2014). Changes in the global value of ecosystem services. *Global Environmental Change*, *26*, 152-158. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2014.04.002

Crohn, D. M., Chaganti, V. N., & Reddy, N. (2013). Composts as post-fire erosion control treatments and their effect on runoff water quality. *Transactions of the ASABE*, *56*(2), 423-435.

CWC. (n.d.). *Compost Blankets*. Crow Wing County. Retrieved August 1, 2023 from https://www.crowwing.gov/DocumentCenter/View/739/Compost_Blankets1?bidId=

Davis, A. P., Aydilek, A., Felton, G. K., & Forgione, E. R. (2023). *Achieving Highway Runoff Volume and Pollutant Reduction Using Vegetated Compost Blankets: A Guide* (NCHRP Research Report 1040). https://nap.nationalacademies.org/catalog/27032/achieving-highway-runoff-volume-and-pollutant-reduction-using-vegetated-compost-blankets-a-guide

Davis, A. P., Hunt, W. F., & Traver, R. G. (2022). Green Infrastructure Stormwater Control Measures. In *Green Stormwater Infrastructure Fundamentals and Design*. John Wiley & Sons. https://www.wiley.com/en-us/Green+Stormwater+Infrastructure+Fundamentals+and+Design-p-9781118590195

de Gannes, V., Eudoxie, G., & Hickey, W. J. (2018). Feedstock Carbon Influence on Compost Biochemical Stability and Maturity. *Compost Science and Utilization*, *26*(1), 59-70. https://doi.org/10.1080/1065657X.2017.1362675

DeLonge, M. S., Ryals, R., & Silver, W. L. (2013). A Lifecycle Model to Evaluate Carbon Sequestration Potential and Greenhouse Gas Dynamics of Managed Grasslands. *Ecosystems*, *16*(6), 962-979. https://doi.org/10.1007/s10021-013-9660-5

Devarajan, N., McGarvey, J. A., Scow, K., Jones, M. S., Lee, S., Samaddar, S., Schmidt, R., Tran, T. D., & Karp, D. S. (2021). Cascading effects of composts and cover crops on soil chemistry, bacterial communities and the survival of foodborne pathogens. *Journal of Applied Microbiology*, *131*(4), 1564-1577. https://doi.org/10.1111/jam.15054

Devine, S. M., Steenwerth, K. L., & O'Geen, A. T. (2022). Soil health practices have different outcomes depending on local soil conditions. *CALIFORNIA AGRICULTURE*, *76*(1), 46-55. https://doi.org/10.3733/ca.2022a0005

Dieter, C. A., Maupin, M. A., Caldwell, R. R., Harris, M. A., Ivahnenko, T. I., Lovelace, J. K., Barber, N. L., & Linsey, K. S. (2018). *Estimated use of water in the United States in 2015: U.S. Geological Survey Circular 1441*. https://pubs.usgs.gov/publication/cir1441

Djodjic, F., Börling, K., & Bergström, L. (2004). Phosphorus leaching in relation to soil type and soil phosphorus content. *Journal of Environmental Quality*, *33*(2), 678-684.

Dosskey, M. G., Vidon, P., Gurwick, N. P., Allan, C. J., Duval, T. P., & Lowrance, R. (2010). The Role of Riparian Vegetation in Protecting and Improving Chemical Water Quality in Streams1. *JAWRA Journal of the American Water Resources Association*, *46*(2), 261-277. https://doi.org/https://doi.org/10.1111/j.1752-1688.2010.00419.x

Dube, B., White, A., Darby, H., & Ricketts, T. (2022). *Valuation of soil health ecosystem services*. https://agriculture.vermont.gov/sites/agriculture/files/documents/Water_Quality/PES/Valuation%20of%20soil%20health%20ecosystem%20services_VTPESTask5_V1.pdf

Dubelko, M., Schutzki, R., Andresen, J., & Cregg, B. (2022). Compost addition, but not tillage, affects establishment of urban highway plantings. *Urban Forestry and Urban Greening*, *75*, Article 127688. https://doi.org/10.1016/j.ufug.2022.127688

Duble, R. L. (n.d.). *Water Management on Turfgrasses*. Texas Cooperative Extension.

Ducey, T. F., Novak, J. M., Sigua, G. C., Ippolito, J. A., Rushmiller, H. C., Watts, D. W., Trippe, K. M., Spokas, K. A., Stone, K. C., & Johnson, M. G. (2021). Microbial response to designer biochar and compost treatments for mining impacted soils. *Biochar*, *3*(3), 299-314. https://doi.org/10.1007/s42773-021-00093-3

Dudka, S., Das, K., & Miller, W. (1998). *Blends of composted biosolids and bottom ash as potting media to grow ornamentals* (Composting in the Southeast: 1998 Conference Proceedings, September, Issue. https://p2infohouse.org/ref/12/11575.pdf

Dunifon, S. N., Evanylo, G. K., Maguire, R. O., & Goatley, J. M., Jr. (2011). Soil Nutrient and Fescue (Festuca spp.) Responses To Compost and Hydroseed on a Disturbed Roadside. *Compost Science and Utilization*, *19*(3), 147-151. https://doi.org/10.1080/1065657X.2011.10736993

Dupigny-Giroux, L.-A. L., Mecray, E. L., Lemcke-Stampone, M. D., Hodgkins, G. A., Lentz, E. E., Mills, K. E., Lane, E. D., Miller, R., Hollinger, D. Y., & Solecki, W. D. (2018). *Northeast*. https://pubs.er.usgs.gov/publication/70201872

Dupont, T., & Granatstein, D. (2018). *Compost Use for Tree Fruits*. W. S. U. Extension. http://treefruit.wsu.edu/publications/compost-use-for-tree-fruit/

Dynarski, K. A., Bossio, D. A., & Scow, K. M. (2020). Dynamic Stability of Soil Carbon: Reassessing the "Permanence" of Soil Carbon Sequestration [Review]. *Frontiers in Environmental Science*, *8*. https://doi.org/10.3389/fenvs.2020.514701

Eghball, B. (2003). Leaching of phosphorus fractions following manure or compost application. *Communications in Soil Science and Plant Analysis*, *34*(19-20), 2803-2815.

Ekinci, K. (2013). Composting Short Paper Fiber with Broiler Litter and Additives: Part I: Effects of Initial pH and Carbon/Nitrogen Ratio On Ammonia Emission. *Compost Science & Utilization*, *8*(2), 160-172. https://doi.org/10.1080/1065657X.2000.10701761

Eleazer, W. E., W.S. Odle, Y. Wang, and M.A. Barlaz. (1997). Biodegradability of municipal solid waste components in laboratory-scale landfills. *Environmental Science and Technology*, *31*, 911-918.

Endelman, J. B., Reeve, J. R., & Hole, D. J. (2010). Economically optimal compost rates for organic crop production. *Agronomy Journal*, *102*(4), 1283-1289. https://doi.org/10.2134/agronj2009.0525

EPA. (1997). *Innovative Uses of Compost. Bioremediation and Pollution Prevention* (EPA530-F-97-042). https://nepis.epa.gov/Exe/ZyNET.exe/10000LSU.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1995+Thru+1999&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C95thru99%5CTxt%5C00000007%5C10000LSU.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL

EPA. (2007). *The Use of Soil Amendments for Remediation, Soil Amendments for Remediation, Revitalization, and Reuse* (EPA 542-R-07-013). https://www.epa.gov/sites/default/files/2015-08/documents/soil_amendments_542-r-07-013.pdf

EPA. (2011). *Terrestrial Carbon Sequestration. Analysis of Terrestrial Carbon Sequestration at Three Contaminated Sites Remediated and Revitalized with Soil Amendments* (EPA-542-R-10-003). https://semspub.epa.gov/work/HQ/153374.pdf

EPA. (2014). *The Economic Benefits of Green Infrastructure: A Case Study of Lancaster, PA* (EPA 800-R-14-007). https://www.epa.gov/sites/default/files/2015-10/documents/cnt-lancaster-report-508_1.pdf

EPA. (2015). *A Compilation of Cost Data Associated with the Impacts and Control of Nutrient Pollution* (EPA 820-F-15-096). https://www.epa.gov/sites/default/files/2015-04/documents/nutrient-economics-report-2015.pdf

EPA. (2020a). *Advancing Sustainable Materials Management: 2018 Fact Sheet. Assessing Trends in Materials Generation and Management in the United States*. https://www.epa.gov/sites/default/files/2021-01/documents/2018_ff_fact_sheet_dec_2020_fnl_508.pdf

EPA. (2020b). *Advancing Sustainable Materials Management: 2018 Tables and Figures. Assessing Trends in Materials Generation and Management in the United States*. https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf

EPA. (2021a). *Climate Adaptation Action Plan*. https://www.epa.gov/system/files/documents/2021-09/epa-climate-adaptation-plan-pdf-version.pdf

EPA. (2021b). *Emerging Issues in Food Waste Management: Persistent Chemical Contaminants* (EPA/600/R-21/115). https://www.epa.gov/system/files/documents/2021-08/emerging-issues-in-food-waste-management-persistent-chemical-contaminants.pdf

EPA. (2021c). *Emerging Issues in Food Waste Management: Plastic Contamination* (EPA/600/R-21/116). https://www.epa.gov/system/files/documents/2021-08/emerging-issues-in-food-waste-management-plastic-contamination.pdf

EPA. (2021d). *From Farm to Kitchen: The Environmental Impacts of U.S. Food Waste - Part 1*. https://www.epa.gov/system/files/documents/2021-11/from-farm-to-kitchen-the-environmental-impacts-of-u.s.-food-waste_508-tagged.pdf

EPA. (2022a). *Basic Information about Anaerobic Digestion (AD)*. Retrieved July 10, 2023 from https://www.epa.gov/anaerobic-digestion/basic-information-about-anaerobic-digestion-ad

EPA. (2022b). *National Menu of Best Management Practices (BMPs) for Stormwater-Construction*. U.S. EPA. Retrieved July 10, 2023 from https://www.epa.gov/npdes/national-menu-best-management-practices-bmps-stormwater-construction

EPA. (2023a). *2019 Wasted Food Report: Estimates of generation and management of wasted food in the United States in 2019* (EPA 530-R-23-005). United States Environmental Protection Agency. https://www.epa.gov/system/files/documents/2023-03/2019%20Wasted%20Food%20Report_508_opt_ec.pdf

EPA. (2023b). *Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM)*.

EPA. (2023c). *Ecosystem Services Research*. Retrieved September 26, 2023 from https://www.epa.gov/eco-research/ecosystem-services-research

EPA. (2023d). *From Field to Bin: The Environmental Impacts of U.S. Food Waste Management Pathways Part 2* (EPA/600/R-23/065). https://www.epa.gov/system/files/documents/2023-10/part2_wf-pathways_report_formatted_no-appendices_508-compliant.pdf

EPA. (2023e). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021* (EPA 430-R-23-002). https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021

EPA. (2023f). *PFAS Explained*. United State Environmental Protection Agency. Retrieved August 1, 2023 from https://www.epa.gov/pfas/pfas-explained

EPA. (2023g). *Quantifying Methane Emissions from Landfilled Food Waste.* (EPA-600-R-23-064). https://www.epa.gov/system/files/documents/2023-10/food-waste-landfill-methane-10-8-23-final_508-compliant.pdf

EPA. (2023h). *Types of Composting and Understanding the Process*. https://www.epa.gov/sustainable-management-food/types-composting-and-understanding-process

https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022

EPA. (2024c). *Sustainable Management of Food Graphics*.

EPIC News. (2021). *Poll: In Response to the Increasing Threat of Climate Change, Most Americans Support Policies to Confront It*. Energy Policy Institute at the University of Chicago.

https://epic.uchicago.edu/news/poll-in-response-to-the-increasing-threat-of-climate-change-most-americans-support-policies-to-confront-it/

EREF. (2024). *Composting state of practice: results from national operations survey*. https://erefdn.org/product/composting-state-of-practice-results-from-a-national-operations-survey/

Evanylo, G., Porta, S. N., Li, J., Shan, D., Goatley, J. M., & Maguire, R. (2016). Compost practices for improving soil properties and turfgrass establishment and quality on a disturbed urban soil. *Compost Science & Utilization*, *24*(2), 136-145.

Evanylo, G., Sherony, C., Spargo, J., Starner, D., Brosius, M., & Haering, K. (2008). Soil and water environmental effects of fertilizer-, manure-, and compost-based fertility practices in an organic vegetable cropping system. *Agriculture, Ecosystems and Environment*, *127*(1-2), 50-58. https://doi.org/10.1016/j.agee.2008.02.014

Farhidi, F., Madani, K., & Crichton, R. (2022). How the US Economy and Environment can Both Benefit From Composting Management. *Environmental Health Insights*, *16*, 117863022211284. https://doi.org/10.1177/11786302221128454

Faucette, L. B. (2009). Using Compost BMPs for LEED Green Building Credits. *Land and Water*, 41. https://mcgillcompost.com/wp-content/uploads/2022/01/Using-Compost-BMPs-for-LEED-Green-Building-Credits.pdf

Faucette, L. B. (2012a). Compost in the green infrastructure tool box. *BioCycle*, *53*(10), 33-36. https://www.biocycle.net/compost-in-the-green-infrastructure-tool-box/

Faucette, L. B. (2012b). Economic case for green infrastructure. *BioCycle*, *53*(8), 36-39. https://mcgillcompost.com/wp-content/uploads/2022/01/Economic-Case-For-Green-Infrastructure.pdf

Faucette, L. B. (2023). 06/26/23 Personal Communication: Interview. In EPA (Ed.).

Faucette, L. B., Cardoso-Gendreau, F. A., Codling, E., Sadeghi, A. M., Pachepsky, Y. A., & Shelton, D. R. (2009). Storm Water Pollutant Removal Performance of Compost Filter Socks. *J. Environ. Qual.*, *38*, 1233-1239.

Faucette, L. B., Cardoso, F., Mulbry, W., & Millner, P. (2013). Performance of compost filtration practice for green infrastructure stormwater applications. *Water Environment Research*, *85*(9), 806-814. https://doi.org/10.2175/106143013X13736496908915

Faucette, L. B., Governo, J., Tyler, R., Gigley, G., Jordan, C. F., & Lockaby, B. G. (2009). Performance of compost filter socks and conventional sediment control barriers used for perimeter control on construction sites. *Journal of Soil and Water Conservation*, *64*(1), 81-88. https://doi.org/10.2489/jswc.64.1.81

Faucette, L. B., J. Governo, C.F. Jordan, B.G. Lockaby, H.F. Carino, and R. Governo. (2007). Erosion control and storm water quality from straw with PAM, mulch, and compost blankets of varying particle sizes. *Journal of Soil and Water Conservation*, *62*(6), 404-413.

Faucette, L. B., Jordan, C. F., Risse, L. M., Cabrera, M., Coleman, D. C., & West, L. T. (2005). Evaluation of stormwater from compost and conventional erosion control practices in construction activities. *Journal of Soil and Water Conservation*, *60*(6), 288. http://www.jswconline.org/content/60/6/288.abstract

Faucette, L. B., Risse, L. M., Jordan, C. F., Cabrera, M. L., Coleman, D. C., & West, L. T. (2006). Vegetation and soil quality effects from hydroseed and compost blankets used for erosion control in construction activities. *Journal of Soil and Water Conservation*, *61*(6), 355-362. https://www.filtrexx.com/application/files/1214/5928/0052/113-2006-JSWC-Compost-Blanket-Hydromulch-Vegetation-and-Soil-Quality-Publication.pdf

Faucette, L. B., Sefton, K. A., Sadeghi, A. M., & Rowland, R. A. (2008). Sediment and phosphorus removal from simulated storm runoff with compost filter socks and silt fence. *Journal of Soil and Water Conservation*, *63*(4), 257-264. https://doi.org/10.2489/jswc.63.4.257

Fernandez-Bayo, J. D., Yazdani, R., Simmons, C. W., & VanderGheynst, J. S. (2018). Comparison of thermophilic anaerobic and aerobic treatment processes for stabilization of green and food wastes and production of soil amendments. *Waste Management*, *77*, 555-564. https://doi.org/10.1016/j.wasman.2018.05.006

Francou, C., Poitrenaud, M., & Houot, S. (2005). Stabilization of organic matter during composting: Influence of process and feedstocks. *Compost Science & Utilization*, *13*(1), 72-83.

Gilbert, J., Ricci-Jurgensen, M., & Ramola, A. (2020a). Benefits of compost and anaerobic digestate when applied to soil. *Report*, *2*, 68-70. https://www.altereko.it/wp-content/uploads/2020/03/Report-2-Benefits-of-Compost-and-Anaerobic-Digestate.pdf

Gilbert, J., Ricci-Jurgensen, M., & Ramola, A. (2020b). *Quantifying the benefits of applying quality compost to soil*. International Solid Waste Association. www.iswa.org

Goldstein, N. (2020a). Compost And Mulch Utilization On California Almond Farm. *BioCycle*. https://www.biocycle.net/compost-and-mulch-utilization-on-california-almond-farm/

Goldstein, N. (2020b). Compost Markets In The U.S. *BioCycle*.

Gonçalves, F., Carlos, C., Crespi, A., Villemant, C., Trivellone, V., Goula, M., Canovai, R., Zina, V., Crespo, L., Pinheiro, L., Lucchi, A., Bagnoli, B., Oliveira, I., Pinto, R., & Torres, L. (2019). The functional agrobiodiversity in the douro demarcated region viticulture: Utopia or reality? Arthropods as a casestudy-A review. *Ciencia e Tecnica Vitivinicola*, *34*(2), 102-114. https://doi.org/10.1051/ctv/201934010102

Gondek, M., Weindorf, D. C., Thiel, C., & Kleinheinz, G. (2020). Soluble salts in compost and their effects on soil and plants: A review. *Compost Science & Utilization*, *28*(2), 59-75.

González, Á., García-Gonzalo, P., Gil-Díaz, M. M., Alonso, J., & Lobo, M. C. (2019). Compost-assisted phytoremediation of As-polluted soil. *Journal of Soils and Sediments*, *19*, 2971-2983.

Goossen, C. P., Schattman, R. E., & MacRae, J. D. (2023). Evidence of compost contamination with per- and polyfluoroalkyl substances (PFAS) from “compostable” food serviceware. *Biointerphases*, *18*, 030501. https://pubs.aip.org/avs/bip/article/18/3/030501/2894789/Evidence-of-compost-contamination-with-per-and

Gould, C. M. (2015). Compost increases water holding capacity of droughty soils. *Michigan State University Extension*.

Governo, J., Gaskin, J., Faucette, B., & Borden, D. (2003). *The compost white paper: large-scale composting in Georgia*. https://www.p2ad.org/files_pdf/whitepaper.pdf

Govindasamy, P., Muthusamy, S. K., Bagavathiannan, M., Mowrer, J., Jagannadham, P. T. K., Maity, A., Halli, H. M., GK, S., Vadivel, R., & TK, D. (2023). Nitrogen use efficiency—a key to enhance crop productivity under a changing climate. *Frontiers in Plant Science*, *14*, 1121073.

Grade, A. M., Crimmins, A. R., Basile, S., Essig, M. R., Goldsmith, L., Lustig, A. R., Maycock, T. K., McCarrick, A., & Scheetz, A. A. (2023). Appendix 5. Glossary. In A. R. Crimmins, C. W. Avery, D. R. Easterling, K. E. Kunkel, B. C. Stewart, & T. K. Maycock (Eds.), *Fifth National Climate Assessment*. U.S. Global Change Research Program. https://nca2023.globalchange.gov/chapter/appendix-5/

Graham, J. (1998). *Composted municipal wastes increase growth, yield and disease tolerance* (Composting in the Southeast: 1998 Conference Proceedings. September, Issue. https://p2infohouse.org/ref/12/11573.pdf

Granath, G., Moore, P. A., Lukenbach, M. C., & Waddington, J. M. (2016). Mitigating wildfire carbon loss in managed northern peatlands through restoration. *Scientific Reports*, *6*(28498). https://doi.org/10.1038/srep28498

Granberry, D., Kelley, W., Langston Jr, D., Rucker, K., & Diaz-Perez, J. (2001). Testing compost value on pepper transplants. *BioCycle*, *42*(10), 60-60.

Gravuer, K., Gennet, S., & Throop, H. L. (2019). Organic amendment additions to rangelands: A meta-analysis of multiple ecosystem outcomes. *Global Change Biology*, *25*(3), 1152-1170. https://doi.org/10.1111/gcb.14535

Gregory, S. V., Swanson, F. J., McKee, W. A., & Cummins, K. W. (1991). An Ecosystem Perspective of Riparian Zones: Focus on links between land and water. *BioScience*, *41*(8), 540-551. https://doi.org/10.2307/1311607

Grobe, K. (1998). Fine-tuning the soil food web. *BioCycle*, *39*(1), 42-46.

Habteweld, A. W., Brainard, D., Kravchenko, A., Grewal, P. S., & Melakeberhan, H. (2018). Effects of plant and animal waste-based compost amendments on the soil food web, soil properties, and yield and quality of fresh market and processing carrot cultivars. *Nematology*, *20*(2), 147-168. https://doi.org/10.1163/15685411-00003130

Hadar, Y., & Papadopoulou, K. K. (2012). Suppressive Composts: Microbial Ecology Links Between Abiotic Environments and Healthy Plants. *Department of Biochemistry and Biotechnology, University of Thessaly*, *50*, 133-153. https://doi.org/10.1146/annurev-phyto-081211-172914

Hafstead, M. (2021). *Carbon Pricing Bill Tracker*. Resources for the Future. https://www.rff.org/publications/data-tools/carbon-pricing-bill-tracker/

Harder, R., Giampietro, M., & Smukler, S. (2021). Towards a circular nutrient economy. A novel way to analyze the circularity of nutrient flows in food systems. *Resources, Conservation and Recycling*, *172*, 105693.

Harrison, B. P., Chopra, E., Ryals, R., & Campbell, J. E. (2020). Quantifying the Farmland Application of Compost to Help Meet California's Organic Waste Diversion Law. *Environmental Science and Technology*, *54*(7), 4545-4553. https://doi.org/10.1021/acs.est.9b05377

Heller, M. (2019). *Waste Not, Want Not: reducing Food Loss and Waste inNorth America through Life Cycle-Based Approaches* LCA; state-scale; urban waste offset - food waste compost). https://wedocs.unep.org/bitstream/handle/20.500.11822/27688/WasteNot.pdf?sequence=1&isAllowed=y

Heyman, H., Bassuk, N., Bonhotal, J., & Walter, T. (2019). Compost quality recommendations for remediating urban soils. *International Journal of Environmental Research and Public Health*, *16*(17), Article 3191. https://doi.org/10.3390/ijerph16173191

Hill, D. (2021). Compost utilization in turfgrass and lawn management. In *Compost Utilization in Production of Horticultural Crops* (pp. 85-100). CRC Press. https://www.taylorfrancis.com/chapters/edit/10.1201/9781003140412-8/compost-utilization-turfgrass-lawn-management-david-hill?context=ubx&refId=713db232-af20-465d-938d-4744e414066b

Hillel, D., Rosenzweig, C., Powlson, D. s., Scow, K., Singer, M., & Sparks, D. L. (2004). *Encyclopedia of Soils in the Environment* https://journals.lww.com/soilsci/citation/2005/08000/encyclopedia_of_soils_in_the_environment__volume.8.aspx

Ho, T. T. K., Tra, V. T., Le, T. H., Nguyen, N., Tran, C., Nguyen, P., Vo, T., Thai, V., & Bui, X. (2022). Compost to improve sustainable soil cultivation and crop productivity. *Case Studies in Chemical and Environmental Engineering*, *6*, 100211. https://doi.org/https://doi.org/10.1016/j.cscee.2022.100211

Hurley, S., Shrestha, P., & Cording, A. (2017). Nutrient Leaching from Compost: Implications for Bioretention and Other Green Stormwater Infrastructure. *Journal of Sustainable Water in the Built Environment*, *3*(3), 04017006. https://doi.org/doi:10.1061/JSWBAY.0000821

Hussey, M., & Harrison, C. (2005). Compost for turfgrass: multifaceted organic ally. *Sportsturf*. https://sturf.lib.msu.edu/article/2005aug11.pdf

Hustvedt, G., Meier, E., & Waliczek, T. (2016). The feasibility of large-scale composting of waste wool. In *Environmental Footprints and Eco-Design of Products and Processes* (pp. 95-107). Springer. https://doi.org/10.1007/978-981-10-0111-6_4

Imran, A., Sardar, F., Khaliq, Z., Nawaz, M. S., Shehzad, A., Ahmad, M., Yasmin, S., Hakim, S., Mirza, B. S., Mubeen, F., & Mirza, M. S. (2022). Tailored Bioactive Compost from Agri-Waste Improves the Growth and Yield of Chili Pepper and Tomato. *Frontiers in Bioengineering and Biotechnology*, *9*, Article 787764. https://doi.org/10.3389/fbioe.2021.787764

IPCC. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Glossary*. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/0_Overview/V0_2_Glossary.pdf

IPCC. (2022). *IPCC Sixth Assessment Report: Impacts, Adaptation and Vulnerability*. https://www.ipcc.ch/report/ar6/wg2/

Jay, J. G., Brown, S. L., Kurtz, K., & Grothkopp, F. (2017). Predictors of phosphorus leaching from bioretention soil media. *Journal of Environmental Quality*, *46*(5), 1098-1105.

Jay, J. G., Tyler-Plog, M., Brown, S. L., & Grothkopp, F. (2019). Nutrient, metal, and organics removal from stormwater using a range of bioretention soil mixtures. *Journal of Environmental Quality*, *48*(2), 493-501.

Jenkins, W. A., Murray, B. C., Kramer, R. A., & Faulkner, S. P. (2010). Valuing ecosystem services from wetlands restoration in the Mississippi Alluvial Valley. *Ecological Economics*, *69*(5), 1051-1061. https://pubs.usgs.gov/publication/70037120

Johannes, A., Matter, A., Schulin, R., Weisskopf, P., Baveye, P. C., & Boivin, P. (2017). Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? *Geoderma*, *302*, 14-21. https://doi.org/https://doi.org/10.1016/j.geoderma.2017.04.021

Johnson, G. R. (2022). PFAS in soil and groundwater following historical land application of biosolids. *Water Research*, *211*, 118035.

Julian, J. W., Strik, B. C., Larco, H. O., Bryla, D. R., & Sullivan, D. M. (2012). Costs of establishing organic northern highbush blueberry: Impacts of planting method, fertilization, and mulch type. *HortScience*, *47*(7), 866-873. https://doi.org/10.21273/hortsci.47.7.866

Jury, W. A., & Vaux Jr, H. J. (2007). The emerging global water crisis: managing scarcity and conflict between water users. *Advances in agronomy*, *95*, 1-76.

Kang, S. M., Adhikari, A., Bhatta, D., Gam, H. J., Gim, M. J., Son, J. I., Shin, J. Y., & Lee, I. J. (2022). Comparison of Effects of Chemical and Food Waste-Derived Fertilizers on the Growth and Nutrient Content of Lettuce (Lactuca sativa L.). *Resources*, *11*(2), Article 21. https://doi.org/10.3390/resources11020021

Kelley, A., Wilkie, A. C., & Maltais-Landry, G. (2020). Food-based composts provide more soil fertility benefits than cow manure-based composts in sandy soils. *Agriculture (Switzerland)*, *10*(3), Article 69. https://doi.org/10.3390/agriculture10030069

Kelley, A. J., Campbell, D. N., Wilkie, A. C., & Maltais-Landry, G. (2022). Compost Composition and Application Rate Have a Greater Impact on Spinach Yield and Soil Fertility Benefits Than Feedstock Origin. *Horticulturae*, *8*(8), Article 688. https://doi.org/10.3390/horticulturae8080688

Khaleel, R., Reddy, K., & Overcash, M. (1981). Changes in soil physical properties due to organic waste applications: a review. *Journal of Environmental Quality*, *10*(2), 133-141.

Khalilian, A., Sullivan, M., Mueller, J., Wolack, F., Williamson, R., & Lippert, R. (1998). *Composted municipal solid waste applications impacts on cotton yield and soil properties*. https://p2infohouse.org/ref/12/11574.pdf

Kim, S. Y., Pramanik, P., Gutierrez, J., Hwang, H. Y., & Kim, P. J. (2014). Comparison of methane emission characteristics in air-dried and composted cattle manure amended paddy soil during rice cultivation. *Agriculture, Ecosystems & Environment*, *197*, 60-67.

Kong, A. Y. Y., Rosenzweig, C., & Arky, J. (2015). Nitrogen dynamics associated with organic and inorganic inputs to substrate commonly used on rooftop farms. *HortScience*, *50*(6), 806-813. https://doi.org/10.21273/hortsci.50.6.806

Kranz, C. N., McLaughlin, R. A., & Heitman, J. L. (2022). Characterizing Compost Rate Effects on Stormwater Runoff and Vegetation Establishment. *Water*, *14*(5). https://mdpi-res.com/d_attachment/water/water-14-00696/article_deploy/water-14-00696.pdf?version=1645598307

Kranz, C. N., McLaughlin, R. A., Johnson, A., Miller, G., & Heitman, J. L. (2020). The effects of compost incorporation on soil physical properties in urban soils – A concise review [Review]. *Journal of Environmental Management*, *261*, Article 110209. https://doi.org/10.1016/j.jenvman.2020.110209

Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J., & van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Advances in agronomy*, *87*, 85-156.

Lal, R. (2004a). Carbon emission from farm operations. *Environment International*, *30*(7), 981-990.

Lal, R. (2004b). Soil carbon sequestration to mitigate climate change. *Geoderma*, *123*, 1-22. https://www.onpasture.com/wp-content/uploads/2017/10/Lal-Soil-carbon-sequestration-to-mitigate-climate-change.pdf

Lal, R. (2020). Soil organic matter and water retention. *Agronomy Journal*, *112*(5), 3265-3277.

Lal, R., Negassa, W., & Lorenz, K. (2015). Carbon sequestration in soil. *Current Opinion in Environmental Sustainability*, *15*, 79-86.

Larkin, R. P. (2022). Long-Term Effects of Compost Amendments and Brassica Green Manures in Potato Cropping Systems on Soil and Crop Health and Productivity. *Agronomy*, *12*(11), Article 2804. https://doi.org/10.3390/agronomy12112804

Lazcano, C., Zhu-Barker, X., & Decock, C. (2021). Effects of organic fertilizers on the soil microorganisms responsible for n2o emissions: A review [Review]. *Microorganisms*, *9*(5), Article 983. https://doi.org/10.3390/microorganisms9050983

Le Pera, A., Sellaro, M., & Bencivenni, E. (2022). Composting food waste or digestate? Characteristics, statistical and life cycle assessment study based on an Italian composting plant. *Journal of Cleaner Production*, *350*, 131552.

Leifield, J., & Menichetti, L. (2018). The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature Communications*, *9*(1071). https://doi.org/https://doi.org/10.1038/s41467-018-03406-6

Levavasseur, F., Mary, B., Christensen, B. T., Duparque, A., Ferchaud, F., Kätterer, T., Lagrange, H., Montenach, D., Resseguier, C., & Houot, S. (2020). The simple AMG model accurately simulates organic carbon storage in soils after repeated application of exogenous organic matter. *Nutrient Cycling in Agroecosystems*, *117*, 215-229.

Levine, A. J., Bean, E. Z., Hinz, F. O., Wilson, P. C., & Reisinger, A. J. (2023). Leaching of select per-/poly-fluoroalkyl substances, pharmaceuticals, and hormones through soils amended with composted biosolids. *Journal of Environmental Management*, *343*, 118185.

Levis, J. W., & Barlaz, M. A. (2011). What is the most environmentally beneficial way to treat commercial food waste? *Environmental Science and Technology*, *45*(17), 7438-7444. https://doi.org/10.1021/es103556m

Levis, J. W., Barlaz, M. A., Themelis, N. J., & Ulloa, P. (2010). Assessment of the state of food waste treatment in the United States and Canada. *Waste Management*, *30*(8-9), 1486-1494. https://doi.org/10.1016/j.wasman.2010.01.031

Lewandowski, A. M., & Cates, A. (2023). Connecting soil health and water quality in agricultural landscapes. *Journal of Environmental Quality*, *52*(3), 412-421.

Li, F., Yu, H., Li, Y., Wang, Y., Hu, D., Feng, B., & Han, Y. (2021). The quality of compost was improved by low concentrations of fulvic acid owing to its optimization of the exceptional microbial structure. *Bioresource Technology*, *342*, 125843.

Li, J., & Evanylo, G. K. (2013). The Effects of Long-term Application of Organic Amendments on Soil Organic Carbon Accumulation. *Soil Science Society of America Journal*, *77*(3), 964-973.

Li, Y., Hanlon, E., O'Connor, G., Chen, J., & Silveira, M. (2010). Land application of compost and other wastes (by-products) in Florida: Regulations, characteristics, benefits, and concerns. *HortTechnology*, *20*(1), 41-51. https://doi.org/10.21273/horttech.20.1.41

Linde, D. T., & Hepner, L. D. (2005). Turfgrass Seed and Sod Establishment on Soil Amended with Biosolid Compost. *HortTechnology horttech*, *15*(3), 577-583. https://doi.org/10.21273/horttech.15.3.0577

Logsdon, S. D., Sauer, P. A., & Shipitalo, M. J. (2017). Compost improves urban soil and water quality. *Journal of Water Resource and Protection*, *9*(4), 345-357. https://www.scirp.org/journal/paperinformation?paperid=74778

Long, R. J., Brown, R. N., & Amador, J. A. (2017). Growing food with garbage: Effects of six waste amendments on soil and vegetable crops. *HortScience*, *52*(6), 896-904. https://doi.org/10.21273/HORTSCI11354-16

Lorenz, K., & Lal, R. (2012). Terrestrial carbon management in urban ecosystems and water quality. In *Carbon sequestration in urban ecosystems* (pp. 73-100). https://link.springer.com/book/10.1007/978-94-007-2366-5

Loschinkohl, C., & Boehm, M. J. (2001). Composted Biosolids Incorporation Improves Turfgrass Establishment on Disturbed Urban Soil and Reduces Leaf Rust Severity. *HortScience HortSci*, *36*(4), 790-794. https://doi.org/10.21273/hortsci.36.4.790

Magdoff, F., & Van Es, H. (2021). *Building Soils for Better Crops Ecological Management for Healthy Soils* (10 ed.). Sustainable Agriculture Research and Education. https://www.sare.org/resources/building-soils-for-better-crops/

Maltais-Landry, G., Nesic, Z., Grant, N., Godinez, M., Thompson, B., Hsu, L. Y., & Smukler, S. M. (2019). Quantifying trade-offs among on-farm and off-farm fertility sources to make vegetable organic farming systems more sustainable. *Agriculture, Ecosystems and Environment*, *286*, Article 106657. https://doi.org/10.1016/j.agee.2019.106657

Maltais-Landry, G., Scow, K., Brennan, E., & Vitousek, P. (2015). Long-term effects of compost and cover crops on soil phosphorus in two California agroecosystems. *Soil Science Society of America Journal*, *79*(2), 688-697.

Mamo, M., Moncrief, J., Rosen, C., & Halbach, T. (2000). The effect of municipal solid waste compost application on soil water and water stress in irrigated corn. *Compost Science & Utilization*, *8*(3), 236-246.

Mandal, M., Chandran, R. S., & Balasko, J. A. (2013). Amending Subsoil with Composted Poultry Litter-II: Effects on Kentucky Bluegrass (Poa pratensis) Establishment, Root Growth, and Weed Populations. *Agronomy*, *3*(4), 670-684. https://www.mdpi.com/2073-4395/3/4/670

Martínez-Blanco, J., Lazcano, C., Christensen, T. H., Muñoz, P., Rieradevall, J., Møller, J., Antón, A., & Boldrin, A. (2013). Compost benefits for agriculture evaluated by life cycle assessment. A review. *Agronomy for Sustainable Development*, *33*(4), 721-732. https://doi.org/10.1007/s13593-013-0148-7

Maynard, A. A. (2000a). Applying Leaf Compost to Reduce Fertilizer Use In Tomato Production. *Compost Science & Utilization*, *8*(3), 203-209. https://doi.org/10.1080/1065657X.2000.10701992

Maynard, A. A. (2000b). *Compost: the process and research* (Bulletin 966). https://portal.ct.gov/-/media/caes/documents/publications/bulletins/b966pdf.pdf?la=en

Maynard, A. A., & Hill, D. E. (2000). Cumulative Effect of Leaf Compost on Yield And Size Distribution in Onions. *Compost Science & Utilization*, *8*(1), 12-18. https://doi.org/10.1080/1065657X.2000.10701744

McConnell, D. B., Shiralipour, A., & Smith, W. H. (1993). Compost application improves soil properties. *BioCycle*, *34*(4), 61-63.

McCray, J. M., Ji, S., & Ulloa, M. (2017). Influence of compost/sludge application on sugarcane yield and nitrogen requirement on a sand soil. *Journal of Plant Nutrition*, *40*(15), 2156-2167. https://doi.org/10.1080/01904167.2017.1346672

McDowell, R. W., & Sharpley, A. N. (2004). Variation of phosphorus leached from Pennsylvanian soils amended with manures, composts or inorganic fertilizer. *Agriculture, Ecosystems & Environment*, *102*(1), 17-27.

McFarland, M. J., R B Brobst, G Kester. (2009). Restoring fire ravaged land in California with biosolids. *Water*, 39-40.

McGoodwin, A. (2018). *Mitigating the Municipal Waste Management Crisis in Emerging Markets: A Cost-benefit Analysis of Enhancing Waste Management Interventions* (M-RCBG Associate Working Paper No. 93). https://www.hks.harvard.edu/centers/mrcbg/publications/awp/awp93

McIvor, K., Cogger, C., & Brown, S. (2012). Effects of Biosolids Based Soil Products on Soil Physical and Chemical Properties in Urban Gardens. *Compost Science & Utilization*, *20*(4), 199-206. https://doi.org/10.1080/1065657X.2012.10737049

Meyer-Kohlstock, D., Schmitz, T., & Kraft, E. (2015). Organic waste for compost and biochar in the EU: Mobilizing the potential. *Resources*, *4*(3), 457-475. https://doi.org/10.3390/resources4030457

Meyer, V. F., Redente, E. F., Barbarick, K. A., Brobst, R. B., Paschke, M. W., & Miller, A. L. (2004). Plant and Soil Responses to Biosolids Application following Forest Fire. *Journal of Environmental Quality*, *33*, 873-881.

Meyer, V. F., Redente, E. F., Barbarick, R., & Brobst, R. (2001). Biosolids (compost) Application Affect Runoff Water Quality Following Forest Fire. Journal of Environmental Quality. *Journal of Environmental Quality*, *30*, 1528-1532.

Minasny, B., & McBratney, A. B. (2018). Limited effect of organic matter on soil available water capacity. *European Journal of Soil Science*, *69*(1), 39-47. https://doi.org/https://doi.org/10.1111/ejss.12475

Minnesota Composting Council (2014). *2014 Economic Impact of Composting Study*. http://www.mncompostingcouncil.org/uploads/1/5/6/0/15602762/economic_impact_study_final-2-2-15.pdf

MIT. (2023). *Climate Portal*. Massachusetts Institute of Technology. Retrieved August 1, 2023 from https://climate.mit.edu/

Mohammadshirazi, F., Brown, V. K., Heitman, J. L., & McLaughlin, R. A. (2016). Effects of tillage and compost amendment on infiltration in compacted soils. *Journal of Soil and Water Conservation*, *71*(6), 443-449. https://doi.org/10.2489/jswc.71.6.443

Mohammadshirazi, F., McLaughlin, R. A., Heitman, J. L., & Brown, V. K. (2017). A multi-year study of tillage and amendment effects on compacted soils. *Journal of Environmental Management*, *203*, 533-541. https://doi.org/https://doi.org/10.1016/j.jenvman.2017.07.031

Moinard, V., Levavasseur, F., & Houot, S. (2021). Current and potential recycling of exogenous organic matter as fertilizers and amendments in a French peri-urban territory. *Resources, Conservation and Recycling*, *169*, 105523.

Morris, J., Brown, S., Cotton, M., & Matthews, H. S. (2017). Life-cycle assessment harmonization and soil science ranking results on food-waste management methods. *Environmental Science & Technology*, *51*(10), 5360-5367. https://doi.org/10.1021/acs.est.6b06115

Morris, J., Brown, S., Matthews, H., & Cotton, M. (2014). Evaluation of Climate, Energy, and Soils Impacts of Selected Food Discards Management Systems. *Oregon State Department of Environmental Quality*. https://www.oregon.gov/deq/FilterDocs/FoodWasteStudyReport.pdf

Mu, D., Horowitz, N., Casey, M., & Jones, K. (2017). Environmental and economic analysis of an in-vessel food waste composting system at Kean University in the U.S. *Waste Management*, *59*, 476-486. https://doi.org/10.1016/j.wasman.2016.10.026

Mukhtar, S., L. McFarland, M., A. Gerngross, C., & J. Mazac, F. (2004). *Efficacy of Using Dairy Manure Compost as Erosion Control and Revegetation Material* American Society of Agricultural and Biological Engineers, St. Joseph, MI. https://elibrary.asabe.org/abstract.asp?aid=16786&t=5

Naiman, R. J., & Décamps, H. (1997). The Ecology of Interfaces: Riparian Zones. *Annual Review of Ecology and Systematics*, *28*(1), 621-658. https://doi.org/10.1146/annurev.ecolsys.28.1.621

NEBRA. (2024). *National Biosolids Data Project*. North East Biosolids & Residuals Association. Retrieved December 11, 2024 from https://www.biosolidsdata.org/

Nedelciu, C. E. R., K.V., Schlyter, P., & Stjernquist, I. (2020). Global phosphorus supply chain dynamics: Assessing regional impact to 2050. *Global Food Security*, *26*(100426). https://doi.org/10.1016/j.gfs.2020.100426

Neher, D. A., Hoitink, H. A., Biala, J., Rynk, R., & Black, G. (2022). Chapter 17 - Compost use for plant disease suppression. In R. Rynk (Ed.), *The Composting Handbook* (pp. 847-878). Academic Press. https://doi.org/10.1016/B978-0-323-85602-7.00015-7

Neher, D. A., Weicht, T. R., & Dunseith, P. (2015). Compost for management of weed seeds, pathogen, and early blight on brassicas in organic farmer fields. *Agroecology and Sustainable Food Systems*, *39*(1), 3-18.

Nelson, E. B. (1996). Enhancing turfgrass disease control with organic amendments. *Turfgrass Trends*, *5*(6), 3.

Nelson, K., Thompson, D., Hopkinson, C., Petrone, R., & Chasmer, L. (2021). Peatland-fire interactions: A review of wildland fire feedbacks and interactions in Canadian boreal peatlands. *Science of the Total Environment*, *769*, 145212. https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.145212

Nest, T. V., Ruysschaert, G., Vandecasteele, B., Houot, S., Baken, S., Smolders, E., Cougnon, M., Reheul, D., & Merckx, R. (2016). The long term use of farmyard manure and compost: effects on P availability, orthophosphate sorption strength and P leaching. *Agriculture, Ecosystems & Environment*, *216*, 23-33.

Nest, T. V., Vandecasteele, B., Ruysschaert, G., Cougnon, M., Merckx, R., & Reheul, D. (2014). Effect of organic and mineral fertilizers on soil P and C levels, crop yield and P leaching in a long term trial on a silt loam soil. *Agriculture, Ecosystems & Environment*, *197*, 309-317.

Nicholson, F., Bhogal, A., Cardenas, L., Chadwick, D., Misselbrook, T., Rollett, A., Taylor, M., Thorman, R., & Williams, J. (2017). Nitrogen losses to the environment following food-based digestate and compost applications to agricultural land. *Environmental Pollution*, *228*, 504-516.

Nordahl, S. L., Preble, C. V., Kirchstetter, T. W., & Scown, C. D. (2023). Greenhouse gas and air pollutant emissions from composting. *Environmental Science & Technology*, *57*(6), 2235-2247.

NRCS. (2000). *Part 637 Environmental Engineering National Engineering Handbook.* U.S. Department of Agriculture. Retrieved June 16, 2023 from https://directives.sc.egov.usda.gov/viewerFS.aspx?id=3850

NRCS. (2010). Chapter 2: Composting. In *Environmental Engineering National Engineering Handbook*. United States Department of Agriculture Natural Resources Conservation Service. https://directives.nrcs.usda.gov//sites/default/files2/1720464003/Chapter%202%20-%20Composting.pdf

NRCS. (2022). *Conservation Practice Standard Soil Carbon Amendment Code 336* (336-CPS-1). https://www.nrcs.usda.gov/resources/guides-and-instructions/soil-carbon-amendment-ac-336-conservation-practice-standard

Obrycki, J. F., Basta, N. T., & Culman, S. W. (2017). Management options for contaminated urban soils to reduce public exposure and maintain soil health. *Journal of Environmental Quality*, *46*(2), 420-430.

Oladeji, O., Tian, G., Lindo, P., Kumar, K., Cox, A., Hundal, L., Zhang, H., & Podczerwinski, E. (2019). Nitrogen release and plant available nitrogen of composted and un-composted biosolids. *Water Environment Research*, *92*(4), 631-640. https://doi.org/10.1002/wer.1260

Oladeji, O., Tian, G., Lindo, P., Kumar, K., Cox, A., Hundal, L., Zhang, H., & Podczerwinski, E. (2020). Nitrogen release and plant available nitrogen of composted and un-composted biosolids. *Water Environment Research*, *92*(4), 631-640. https://doi.org/10.1002/wer.1260

Oldfield, E. E., Felson, A. J., Wood, S. A., Hallett, R. A., Strickland, M. S., & Bradford, M. A. (2014). Positive effects of afforestation efforts on the health of urban soils. *Forest Ecology and Management*, *313*, 266-273. https://doi.org/10.1016/j.foreco.2013.11.027

Ontl, T. A., & Schulte, L. A. (2012). Soil Carbon Storage. *Nature Education Knowledge*, *3*(10), 35.

Otuya, R., Slaughter, L. C., West, C. P., Deb, S. K., & Acosta-Martinez, V. (2021). Compost and legume management differently alter soil microbial abundance and soil carbon in semiarid pastures. *Soil Science Society of America Journal*, *85*(3), 654-664. https://doi.org/10.1002/saj2.20215

Owen, D., Davis, A. P., & Aydilek, A. H. (2020). Understanding the Effects of Slope Ratio, Straw Mulching, and Compost Addition to Topsoil to Establish Permanent Vegetation and Reduce Nutrient Runoff [Tech Report]. https://rosap.ntl.bts.gov/view/dot/50917

Owen, D., Davis, A. P., & Aydilek, A. H. (2021). Compost for Permanent Vegetation Establishment and Erosion Control along Highway Embankments. *Journal of irrigation and drainage engineering*, *147*(8), 04021031. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001587

Ozores-Hampton, M. (2019). *Past, present, and future of compost utilization in horticulture*. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85076604259&doi=10.17660%2fActaHortic.2019.1266.43&partnerID=40&md5=b8c77a2db41219578fd87e7e1a26b31f

Ozores-Hampton, M. (2021a). Compost utilization in vegetable production. In *Compost Utilization in Production of Horticultural Crops* (pp. 59-76). CRC Press. https://www.taylorfrancis.com/chapters/edit/10.1201/9781003140412-6/compost-utilization-vegetable-production-monica-ozores-hampton?context=ubx&refId=0571b7fd-bd7d-4268-a8b6-e2e6ba8d5ec4

Ozores-Hampton, M. (2021b). Fertility program using compost in fruit crops, vegetable and field ornamental production. In *Compost Utilization in Production of Horticultural Crops* (pp. 27-44). CRC Press. https://www.taylorfrancis.com/chapters/edit/10.1201/9781003140412-3/fertility-program-using-compost-fruit-crops-vegetable-field-ornamental-production-monica-ozores-hampton?context=ubx&refId=855346c3-ed0b-4712-b8be-b78206e48d3b

Ozores-Hampton, M. (2021c). Impact of compost on soil health. In *Compost Utilization in Production of Horticultural Crops* (pp. 9-26). CRC Press. https://www.taylorfrancis.com/chapters/edit/10.1201/9781003140412-2/impact-compost-soil-health-monica-ozores-hampton?context=ubx&refId=2bdf945c-e471-47ef-be27-7f10405ecd6d

Ozores-Hampton, M. (2021d). Past, present and future of compost in horticulture crop production. In *Compost Utilization in Production of Horticultural Crops* (pp. 1-8). CRC Press. https://www.taylorfrancis.com/chapters/edit/10.1201/9781003140412-1/past-present-future-compost-horticulture-crop-production-monica-ozores-hampton?context=ubx&refId=ba4705c9-48f3-47ee-8a9b-76147d230696

Ozores-Hampton, M., Biala, J., Evanylo, G., Faucette, B., Cooperband, L., Roe, N., Creque, J. A., & Sullivan, D. (2022). Chapter 16 - Compost use. In R. Rynk (Ed.), *The Composting Handbook* (pp. 777-846). Academic Press. https://doi.org/10.1016/B978-0-323-85602-7.00013-3

Ozores-Hampton, M., Stansly, P. A., & Salame, T. P. (2011). Soil Chemical, Physical, and Biological Properties of a Sandy Soil Subjected to Long-Term Organic Amendments. *Journal of Sustainable Agriculture*, *35*(3), 243-259. https://doi.org/10.1080/10440046.2011.554289

Pai, S., Ai, N., & Zheng, J. (2019). Decentralized community composting feasibility analysis for residential food waste: A Chicago case study. *Sustainable Cities and Society*, *50*, Article 101683. https://doi.org/10.1016/j.scs.2019.101683

Pan, P., Qi, Z., Zhang, T., & Ma, L. (2023). Modeling phosphorus losses to subsurface drainage under tillage and compost management. *Soil and Tillage Research*, *227*, 105587.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49-57. https://doi.org/10.1038/nature17174

Peltre, C., Christensen, B. T., Dragon, S., Icard, C., Kätterer, T., & Houot, S. (2012). RothC simulation of carbon accumulation in soil after repeated application of widely different organic amendments. *Soil Biology and Biochemistry*, *52*, 49-60.

Penha, L. A. O., Khatounian, C. A., & Fonseca, I. C. B. (2012). Effects of early compost application on no-till organic soybean. *Planta Daniha*, *30*(1), 1-8.

Pennsylvania Department of Environmental Protection. (2021). *PA Department of Environmental Protection Nutrient Credit Trading Program Manure Treatment Technology Nutrient Credit Calculation Methodology*. https://files.dep.state.pa.us/Water/BPNPSM/NutrientTrading/TradingResources/Manure%20Treatment%20Technology%20Nutrient%20Credit%20Calculation%20Methodology.pdf

Peregrin, G., & Hinesley, L. E. (2011). *Effects of Compost on the Growth of Fraser Fir Christmas Trees in North Carolina*. https://p2infohouse.org/ref/11/10220.pdf

Pierzynski, G. M. (2000). *Methods of phosphorus analysis for soils, sediments, residuals, and waters*. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=c3713db4ecdc1f92ca2ea685ef940117bcfd27f2

Pimentel, D., Houser, J., Preiss, E., White, O., Fang, H., Mesnick, L., Barsky, T., Tariche, S., Schreck, J., & Alpert, S. (1997). Water resources: agriculture, the environment, and society. *BioScience*, *47*(2), 97-106.

Pitt, R., Lantrip, J., Harrison, R., Henry, C. L., Xue, D., & O'Connor, T. (1999). *Infiltration through disturbed urban soils and compost-amended soil effects on runoff quality and quantity*. National

Risk Management Research Laboratory Duluth, GA, USA. http://www.dynsystem.com/netstorm/docs/epa600r00016.pdf

Platt, B., Bell, B., & Harsh, C. (2013). *Pay dirt. Composting in Maryland to reduce waste, create jobs, and protect the bay*. https://ilsr.org/wp-content/uploads/2013/05/ILSR-Pay-Dirt-Report-05-11-13.pdf

Platt, B., Ciplet, D., Bailey, K. M., & Lombardi, E. (2008). *Stop trashing the climate*. https://ilsr.org/wp-content/uploads/2008/06/fullreport_stoptrashingtheclimate.pdf

Pluske, W., Murphy, D., & Sheppard, J. (2024). *Total Organic Carbon: Fact Sheet*. https://www.soilquality.org.au/factsheets/organic-carbon

Potschin, M., & Haines-Young, R. (2016). Defining and measuring ecosystem services. In *Routledge handbook of ecosystem services* (pp. 25-44). Routledge. https://unstats.un.org/unsd/envaccounting/workshops/ES_Classification_2016/Potschin_Haines-Young_2016.pdf

Powlson, D., Bhogal, A., Chambers, B., Coleman, K., Macdonald, A., Goulding, K., & Whitmore, A. (2012). The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: a case study. *Agriculture, Ecosystems & Environment*, *146*(1), 23-33.

Pozzebon, E. A., & Seifert, L. (2023). Emerging environmental health risks associated with the land application of biosolids: a scoping review. *Environmental Health*, *22*(1), 57.

Qian, S., Zhou, X., Fu, Y., Song, B., Yan, H., Chen, Z., Sun, Q., Ye, H., Qin, L., & Lai, C. (2023). Biochar-compost as a new option for soil improvement: Application in various problem soils. *Science of the Total Environment*, *870*, 162024. https://doi.org/https://doi.org/10.1016/j.scitotenv.2023.162024

Rath, D., Bogie, N., Deiss, L., Parikh, S. J., Wang, D. Y., Ying, S., Tautges, N., Berhe, A. A., Ghezzehei, T. A., & Scow, K. M. (2022). Synergy between compost and cover crops in a Mediterranean row crop system leads to increased subsoil carbon storage. *SOIL*, *8*(1), 59-83. https://doi.org/10.5194/soil-8-59-2022

Raun, W. R., & Johnson, G. V. (1999). Improving nitrogen use efficiency for cereal production. *Agron. J.*, *91*, 357-363.

Readyhough, T., Neher, D. A., & Andrews, T. (2021). Organic amendments alter soil hydrology and belowground microbiome of tomato (Solanum lycopersicum). *Microorganisms*, *9*(8), Article 1561. https://doi.org/10.3390/microorganisms9081561

Reddy, N., & Crohn, D. M. (2012). Compost induced soil salinity: A new prediction method and its effect on plant growth. *Compost Science and Utilization*, *20*(3), 133-140. https://doi.org/10.1080/1065657X.2012.10737038

Reeve, J. R., Endelman, J. B., Miller, B. E., & Hole, D. J. (2012). Residual effects of compost on soil quality and dryland wheat yield sixteen years after compost application. *Soil Science Society of America Journal*, *76*(1), 278-285. https://doi.org/10.2136/sssaj2011.0123

ReFED. (n.d.). *The Business and Societal Case for Reducing Food Waste*. https://refed.org/downloads/Economic_Analysis.pdf

Regni, L., Nasini, L., Ilarioni, L., Brunori, A., Massaccesi, L., Agnelli, A., & Proietti, P. (2017). Long term amendment with fresh and composted solid olive mill waste on olive grove affects carbon sequestration by prunings, fruits, and soil. *Frontiers in Plant Science*, *7*, 2042. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5220087/pdf/fpls-07-02042.pdf

Reider, C. R., Herdman, W. R., Drinkwater, L. E., & Janke, R. (2000). Yields and nutrient budgets under composts, raw dairy manure and mineral fertilizer. *Compost Science & Utilization*, *8*(4), 328-339.

Ribaudo, M. O., Gollehon, N. R., & Agapoff, J. (2003). Land application of manure by animal feeding operations: Is more land needed? *Journal of Soil and Water Conservation*, *58*(1).

Risse, M., & Faucette, B. (2023). *Compost Utilization for Erosion Control* (University of Georgia Cooperative Extension Bulletin 1200). https://secure.caes.uga.edu/extension/publications/files/pdf/B%201200_6.PDF

Roe, N. E., & Cornforth, G. C. (2000). Effects of dairy lot scrapings and composted dairy manure on growth, yield, and profit potential of double cropped vegetables. *Compost Science & Utilization*, *8*(4), 320-327.

Rollins, C. A., & Koenig, J. (2010). Modifications to existing codes and ordinances: Bioassay of microbial diversity in compost. In *Low Impact Development 2010: Redefining Water in the City* (pp. 962-979). https://doi.org/10.1061/41099(367)84

Ross, D. (2012a). How To Generate Tradable Nutrient Reduction Credits. *BioCycle*, 48. https://www.biocycle.net/how-to-generate-tradable-nutrient-reduction-credits/

Ross, D. (2012b). Understanding Value Of Nutrient Credits. *BioCycle*, 57. https://www.biocycle.net/understanding-value-of-nutrient-credits/

Ryals, R., & Silver, W. L. (2013). Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands. *Ecological Applications*, *23*(1), 46-59. https://doi.org/10.1890/12-0620.1

Rynk, R., Cooperband, L., Oshins, C., Wescott, H., Bonhotal, J., Schwarz, M., Sherman, R., & Brown, S. (2022). Chapter 1 - Why compost? In R. Rynk (Ed.), *The Composting Handbook* (pp. 1-26). Academic Press. https://doi.org/10.1016/B978-0-323-85602-7.00001-7

Rynk, R., Jeff Ziegenbein, Cary Oshins, Nanci Koerting, James Hardin, Jeff Gage. (2022). *Chapter 11 - Process management*. https://doi.org/10.1016/B978-0-323-85602-7.00011-X

Rynk, R., Schwarz, M., Richard, T. L., Cotton, M., Halbach, T., & Siebert, S. (2022). Chapter 4 - Compost feedstocks. In R. Rynk (Ed.), *The Composting Handbook* (pp. 103-157). Academic Press. https://doi.org/10.1016/B978-0-323-85602-7.00005-4

Saer, A., Lansing, S., Davitt, N. H., & Graves, R. E. (2013). Life cycle assessment of a food waste composting system: Environmental impact hotspots. *Journal of Cleaner Production*, *52*, 234-244. https://doi.org/10.1016/j.jclepro.2013.03.022

Saha, B., Ateia, M., Fernando, S., Xu, J., DeSutter, T., & Iskander, S. M. (2024). PFAS occurrence and distribution in yard waste compost indicate potential volatile loss, downward migration, and transformation. *Environmental Science: Processes & Impacts*, *26*(4), 657-666.

Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *PNAS*, *114*(36), 9575-9580. https://doi.org/https://doi.org/10.1073/pnas.1706103114

Sanders, J., Waliczek, T. M., & Gandonou, J. M. (2011). An economic analysis of a university educational cafeteria composting program-bobcat blend. *HortTechnology*, *21*(5), 639-646. https://doi.org/10.21273/horttech.21.5.639

Sarinsky, M., & Weatherford, K. (2024). *The Social Cost of Greenhouse Gases: An Overview*. https://policyintegrity.org/files/publications/SCCGHG_Overview_Policy_Brief_vF.pdf

Sax, M. S., Bassuk, N., Van Es, H., & Rakow, D. (2017). Long-term remediation of compacted urban soils by physical fracturing and incorporation of compost. *Urban Forestry & Urban Greening*, *24*, 149-156.

Scharenbroch, B. C. (2009). A meta-analysis of studies published in Arboriculture & Urban Forestry relating to organic materials and impacts on soil, tree, and environmental properties. *Arboriculture & Urban Forestry (AUF)*, *35*(5), 221-231.

Schultze-Allen, P. (2010). *Urban LID using compost*. https://www.scopus.com/record/display.uri?eid=2-s2.0-77954932190&doi=10.1061%2f41099%28367%2991&origin=inward&txGid=4c45a3a73c53cb9d9a377c01dc8bf13e

Schwarz, M., Bonhotal, J., & Rozeboom, D. (2010). The Space It Takes-Footprint Calculator for Composting Butcher Waste. https://cwmi.css.cornell.edu/spaceittakes.pdf

Semple, K., Reid, B., & Fermor, T. (2001). Impact of composting strategies on the treatment of soils contaminated with organic pollutants. *Environmental Pollution*, *112*(2), 269-283.

Sherman, R. (2018). *The Worm Farmer's Handbook: Mid-to Large-Scale Vermicomposting for Farms, Businesses, Municipalities, Schools, and Institutions*. Chelsea Green Publishing.

https://dela.ent.sirsi.net/client/en_US/default/search/detailnonmodal/ent:$002f$002fSD_ILS$002f0$002fSD_ILS:2140790/ada

Shiralipour, A. (Ed.). (1998). *The effects of compost on soil*. https://www.hinkleycenter.org/pdfs/1998-15_Stratton.pdf.

Shrestha, P., Small, G. E., & Kay, A. (2020). Quantifying nutrient recovery efficiency and loss from compost-based urban agriculture. *PLoS ONE*, *15*(4), Article e0230996. https://doi.org/10.1371/journal.pone.0230996

Silver, W. L., Vergara, S. E., & Mayer, A. (2018). Carbon sequestration and greenhouse gas mitigation potential of composting and soil amendments on California's rangelands. *California Natural Resources Agency*, *62*.

Solís-Domínguez, F. A., Valentín-Vargas, A., Chorover, J., & Maier, R. M. (2011). Effect of arbuscular mycorrhizal fungi on plant biomass and the rhizosphere microbial community structure of mesquite grown in acidic lead/zinc mine tailings. *Science of the Total Environment*, *409*(6), 1009-1016. https://doi.org/10.1016/j.scitotenv.2010.11.020

Soong, J. L., Fuchslueger, L., Marañon-Jimenez, S., Torn, M. S., Janssens, I. A., Penuelas, J., & Richter, A. (2020). Microbial carbon limitation: The need for integrating microorganisms into our understanding of ecosystem carbon cycling. *Global Change Biology*, *26*(4), 1953-1961.

Stehouwer, R., Cooperband, L., Rynk, R., Biala, J., Bonhotal, J., Antler, S., Lewandowski, T., & Nichols, H. (2022). Chapter 15 - Compost characteristics and quality. In R. Rynk (Ed.), *The Composting Handbook* (pp. 737-775). Academic Press. https://doi.org/10.1016/B978-0-323-85602-7.00012-1

Stoffella, P. J., Dong, Y., Jiang, D., Zhang, S., & He, Z. L. (2016). Use of compost to mitigate the salt effect of sediment from Taylor Creek in south Florida. *Acta Horticulturae*, *1146*, 157-164. https://doi.org/10.17660/ActaHortic.2016.1146.21

Stoffella, P. J., He, Z. L., Wilson, S. B., Ozores-Hampton, M., & Roe, N. E. (2014). Compost utilization in subtropical horticultural cropping systems. *Acta Horticulturae*, *1018*, 95-108. https://doi.org/10.17660/ActaHortic.2014.1018.7

Stratton, M. L., & Rechcigl, J. (1998). *Compost application to ryegrass*. https://p2infohouse.org/ref/12/11576.pdf

Sullivan, D., Bary, A., Nartea, T., Myrhe, E., Cogger, C., & Fransen, S. (2003). Nitrogen availability seven years after a high-rate food waste compost application. *Compost Science & Utilization*, *11*(3), 265-275.

Sullivan, D., Bary, A., Thomas, D., Fransen, S., & Cogger, C. (2002). Food waste compost effects on fertilizer nitrogen efficiency, available nitrogen, and tall fescue yield. *Soil Science Society of America Journal*, *66*(1), 154-161.

Sullivan, D. M., & Miller, R. O. (2001). Compost quality attributes, measurements and variability. In *Compost utilization in horticultural cropping systems*. CRC Press. https://ir.library.oregonstate.edu/concern/defaults/h702qd72m

Sundquist, E. T., Ackerman, K. V., Bliss, N. B., Kellndorfer, J. M., Reeves, M. C., & Rollins, M. G. (2009). *Rapid assessment of US forest and soil organic carbon storage and forest biomass carbon sequestration capacity* (2331-1258). https://pubs.usgs.gov/publication/ofr20091283

Tautges, N. E., Chiartas, J. L., Gaudin, A. C. M., O'Geen, A. T., Herrera, I., & Scow, K. M. (2019). Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. *Global Change Biology*, *25*(11), 3753-3766. https://doi.org/10.1111/gcb.14762

The World Bank. (2022).

Timshina, A. S., Robey, N. M., Oldnettle, A., Barron, S., Mehdi, Q., Cerlanek, A., Townsend, T. G., & Bowden, J. A. (2024). Investigating the sources and fate of per-and polyfluoroalkyl substances (PFAS) in food waste compost. *Waste Management*, *180*, 125-134.

Traversa, A., Loffredo, E., Palazzo, A. J., Bashore, T. L., & Senesi, N. (2014). Enhancement of switchgrass (Panicum virgatum L.) early growth as affected by composts. *Journal of Soil Science and Plant Nutrition*, *14*(2), 471-482. https://doi.org/10.4067/S0718-95162014005000037

Trlica, A., & Brown, S. (2013). Greenhouse gas emissions and the interrelation of urban and forest sectors in reclaiming one hectare of land in the Pacific Northwest. *Environmental Science & Technology*, *47*(13), 7250-7259.

Tyler, R. W. (2021). Compost utilization and the economic impact in crop production. In M. Ozores-Hampton (Ed.), *Compost Utilization in Production of Horticultural Crops* (pp. 135-156). CRC Press. https://www.taylorfrancis.com/chapters/edit/10.1201/9781003140412-12/compost-utilization-economic-impact-crop-production-rodney-tyler?context=ubx&refId=e8351957-2b8d-4176-b46b-eb9004291d3f

Tyler, R. W., Marks, A., & Faucette, B. (2011). *The Sustainable Site: the design manual for green infrastructure and low impact development.* Forester Press. https://www.abebooks.com/9780970768780/Sustainable-Site-Design-Manual-Green-0970768788/plp

UCAR. (2020). *How Do We Reduce Greenhouse Gases?* Retrieved October 16, 2024 from https://scied.ucar.edu/learning-zone/climate-solutions/reduce-greenhouse-gases

Ugarte, C. M., & Taylor, J. R. (2020). Chemical and biological indicators of soil health in Chicago urban gardens and farms. *Urban Agriculture and Regional Food Systems*, *5*(1), Article e20004. https://doi.org/10.1002/uar2.20004

Una, T., Hernandez, J., Beebe, A., & Brown, S. (2022). How does your garden grow? Impact of residuals-based amendments on urban soil health, vegetable yield and nutritional density. *Urban Forestry & Urban Greening*, *77*, 127742.

USCC. (2002). *Test Methods for the Examination of Compost and Composting*. U.S. Composting Council. https://www.compostingcouncil.org/page/tmecc

USCC. (2008). *USCC Factsheet: Compost and Its Benefits*. https://hrra.org/wp-content/uploads/2020/04/Compost-and-Its-Benefits.pdf

USCC. (2021). USCC Compost Manufacturer's Environmental Impact Analysis. Retrieved January 18, 2023, from https://www.compostingcouncil.org/news/573020/USCC-Compost-Manufacturers-Environmental-Impact-Analysis.htm

USCC. (2022a). *Benefits of Compost*. US Composting Council. Retrieved December 21, 2022 from https://www.compostingcouncil.org/page/CompostBenefits

USCC. (2022b). *PFAS Positioning and Guidance Document*. https://cdn.ymaws.com/www.compostingcouncil.org/resource/resmgr/documents/pfas/USCC-Position-on-PFAS-Final.pdf

USDA. (2019). *PART 205 - NATIONAL ORGANIC PROGRAM: 205.203 Soil fertility and crop nutrient management practice standard.* https://www.govinfo.gov/content/pkg/CFR-2019-title7-vol3/xml/CFR-2019-title7-vol3-part205.xml

https://nca2018.globalchange.gov/

USGS. (2023). *PEAT*. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-peat.pdf

van der Wiel, B. Z., Weijma, J., van Middelaar, C. E., Kleinke, M., Buisman, C. J. N., & Wichern, F. (2021). Restoring nutrient circularity in a nutrient-saturated area in Germany requires systemic change. *Nutrient Cycling in Agroecosystems*, *121*, 209-226.

Vitosh, M. L. (1996). *N-P-K Fertilizers* (E-896). https://www.canr.msu.edu/field_crops/uploads/archive/E0896.pdf

Vouillamoz, J., & Milke, M. (2001). Effect of compost in phytoremediation of diesel-contaminated soils. *Water Science and Technology*, *43*(2), 291-295.

Walling, E., & Vaneeckhaute, C. (2020). Greenhouse gas emissions from inorganic and organic fertilizer production and use: A review of emission factors and their variability. *Journal of Environmental Management*, *276*, 111211.

Wang, D., Lin, J. Y., Sayre, J. M., Schmidt, R., Fonte, S. J., Rodrigues, J. L. M., & Scow, K. M. (2022). Compost amendment maintains soil structure and carbon storage by increasing available carbon and microbial biomass in agricultural soil – A six-year field study. *Geoderma*, *427*, Article 116117. https://doi.org/10.1016/j.geoderma.2022.116117

Wang, L. (2014). Food processing wastes as an energy feedstock: Availability and sustainability. In *Sustainable Bioenergy Production* (pp. 283-306). CRC Press. https://doi.org/10.1201/b16764

Ward, E. B., Doroski, D. A., Felson, A. J., Hallett, R. A., Oldfield, E. E., Kuebbing, S. E., & Bradford, M. A. (2021). Positive long-term impacts of restoration on soils in an experimental urban forest. *Ecological Applications*, *31*(5), Article e02336. https://doi.org/10.1002/eap.2336

Whalen, J. K., Hu, Q., & Liu, A. (2003). Compost applications increase water-stable aggregates in conventional and no-tillage systems. *Soil Science Society of America Journal*, *67*(6), 1842-1847.

White, K. E., Brennan, E. B., Cavigelli, M. A., & Smith, R. F. (2020). Winter cover crops increase readily decomposable soil carbon, but compost drives total soil carbon during eight years of intensive, organic vegetable production in California. *PLoS ONE*, *15*(2), Article e0228677. https://doi.org/10.1371/journal.pone.0228677

Wilson, C., Zebarth, B. J., Burton, D. L., & Goyer, C. (2018). Short-Term Effects of Diverse Compost Products on Soil Quality in Potato Production. *Soil Science Society of America Journal*, *82*(4), 889-900. https://doi.org/10.2136/sssaj2017.10.0345

Winfield, E. (2020). Climate-Smart Agriculture: Compost Amendments. https://www.climatehubs.usda.gov/sites/default/files/WLIC%20Fact%20Sheet%202_Compost.pdf

Witzgall, K., Vidal, A., Schubert, D. I., Höschen, C., Schweizer, S. A., Buegger, F., Pouteau, V., Chenu, C., & Mueller, C. W. (2021). Particulate organic matter as a functional soil component for presistent soil organic carbon. *Nature Communications*, *12*(4115). https://doi.org/https://doi.org/10.1038/s41467-021-24192-8

WORC. (2023). *Soils for Salmon: Building Soil*. Washington Organic Recycling Council. Retrieved July 27, 2023 from https://www.soilsforsalmon.org/

Wuebbles, D. F., DW; Hibbard, KA; DeAngelo, B; Doherty, S; Hayhoe, K; Horton, R; Kossin, JP; Taylor, PC; Waple, AM; Weaver, CP. (2017). *Executive summary. In Climate Science Special Report: Fourth National Climate Assessment, Volume I*. https://science2017.globalchange.gov/downloads/CSSR2017_PRINT_Executive_Summary.pdf

Wuest, S. B., & Reardon, C. L. (2016). Surface and root inputs produce different carbon/phosphorus ratios in soil. *Soil Science Society of America Journal*, *80*(2), 463-471. https://doi.org/10.2136/sssaj2015.09.0334

Yu, H., Ding, W., Luo, J., Geng, R., Ghani, A., & Cai, Z. (2012). Effects of long-term compost and fertilizer application on stability of aggregate-associated organic carbon in an intensively cultivated sandy loam soil. *Biology and Fertility of Soils*, *48*, 325-336.

Zhang, H., & Schroder, J. (2014). Animal Manure Production and Utilization in the US. *Applied Manure and Nutrient Chemistry for Sustainable Agriculture and Environment*, 1-21. https://doi.org/10.1007/978-94-017-8807-6_1

# Appendix

## Literature Search Methodology

***Literature Search Strategy***

To inform the development of this report, a literature search and screen of publications was conducted to identify and retrieve publications relevant to the following six research questions:

1. What are the national and U.S. regional environmental benefits of compost application?
2. What environmental impacts can be avoided by using compost?
3. What is the economic value of the environmental benefits of applying compost?
4. How do the environmental and economic benefits of applying compost vary based upon the type of soil to which the compost is applied?
5. How do benefits vary depending on the feedstocks used to produce the compost?
6. What would the environmental and economic benefits of compost application be “at scale”?

The aim was to compile approximately 30 publications per research question, including both peer reviewed and grey literature. This summary describes the literature search strategy, including the search criteria and search strings that were be applied. Figure A illustrates this stepwise process.

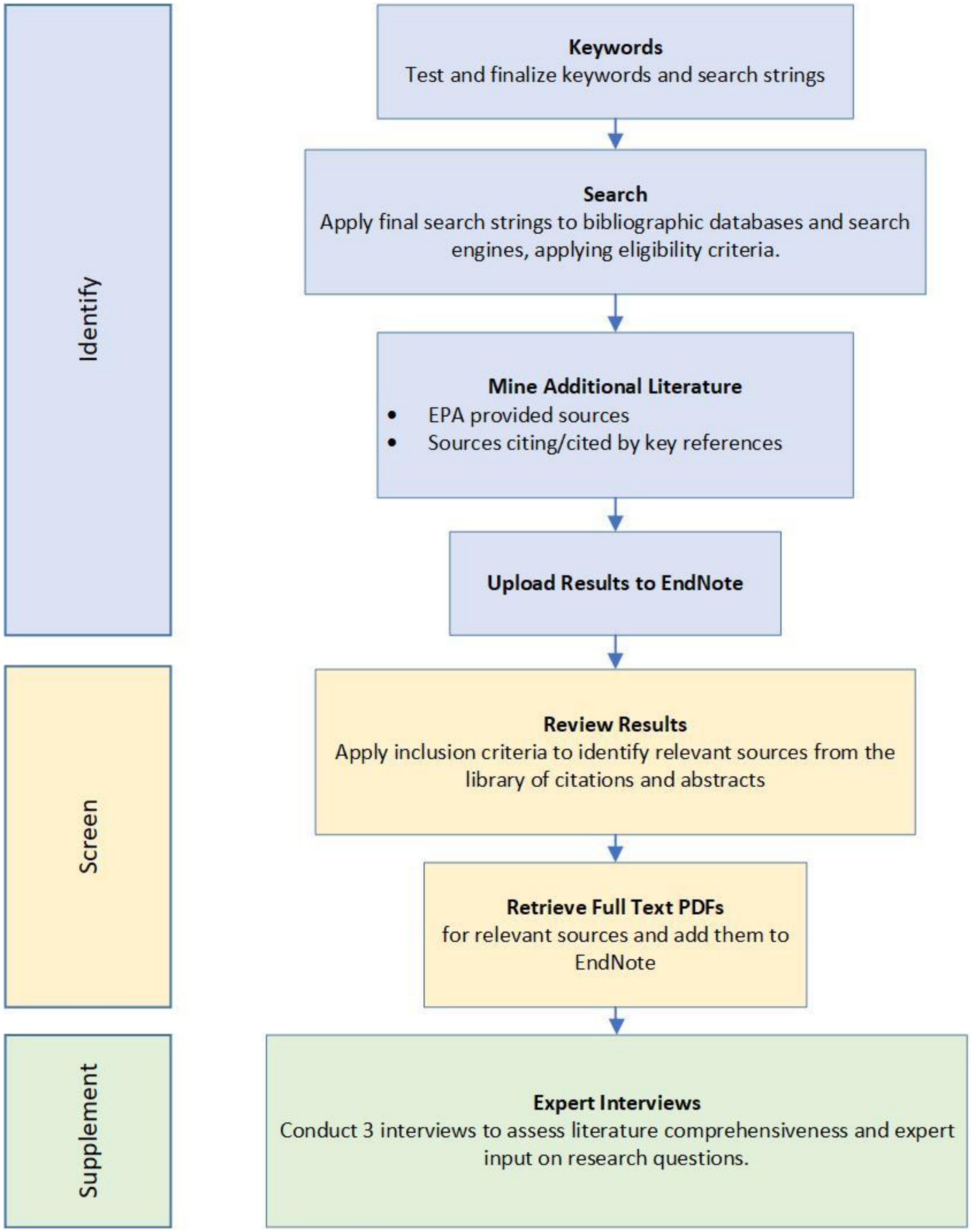


*Figure A-1. Summary of the literature search process that was applied to identify relevant publications and information.*

### *Literature Search Terms*

**Search Strings.** Information sources were queried using Boolean search strings to address each of the six research questions. Example search strings are presented in Table A below. Search strings and keywords were adapted as needed during the search process to target the right literature.

*Table A-1. Draft search strings to address research questions.*

| Research Question | Draft Search String |
|---|---|
| a) What are the national and U.S. regional environmental benefits of compost application? | "compost" AND ("green infrastructure" OR "erosion" OR "stormwater" OR "water quality" OR "water retention" OR "soil" OR "remediation" OR "revegetation" OR "fire" OR "hazard" OR "climate" OR "carbon sequestration") AND ("benefit" OR "ecosystem service") |
| b) What environmental impacts can be avoided by using compost? | Results from the search above were used. Additional searches about the environmental impacts of traditional or typical strategies (e.g., inorganic fertilizers) conducted. |
| c) What is the economic value of the environmental benefits of applying compost? | "compost" AND ("economic" OR "financial") AND ("value" OR "cost") AND "ecosystem service" AND ("green infrastructure" OR "erosion" OR "stormwater" OR "water quality" OR "water retention" OR "soil" OR "remediation" OR "revegetation" OR "fire" OR "hazard" OR "climate" OR "carbon sequestration") |
| d) How do the environmental and economic benefits of applying compost vary based upon the type of soil to which the compost is applied? | "compost" AND ("environment" OR "economic") AND ("benefit" OR "value") AND ("soil" OR "mineral" OR "land use") |
| e) How do benefits vary depending on the feedstocks used to produce the compost? | "compost" AND ("feedstock" or "food waste") AND "benefit" |
| f) What would the environmental and economic benefits of compost application be "at scale"? | "compost" AND ("environment" OR "economic") AND ("demand" OR "revenue" OR "benefit") AND ("scale" OR "widespread" OR "availability") AND ("national" OR "state" OR "county" OR "community") |

*Note:* Searches were adapted as needed to account for variations in how different databases handle search strings.

**Testing and Refinement.** A preliminary search of available literature was conducted to optimize search strings before initiating a comprehensive search of literature databases. During this preliminary search, Scopus was used to search combinations of the initial keywords and search strings proposed in Table A above. The general availability of relevant literature and the effectiveness of proposed search terms provided information needed to inform and refine the search strategy, including combinations of search strings to address multiple research questions. The accuracy of the search strategy was evaluated using a predetermined *test set* of approximately five references.

**Information Sources.** The following potential literature sources were used to identify relevant literature. Note that this list is not exclusive and was modified as needed, depending on the search returns.

**Initial Resources.** An initial list of potentially applicable literature resources for consideration was generated (see below). These resources were searched and mined for relevant literature to include. Content and cited references in the report titled "From Prevention to Landfill: The Environmental Impacts of Food Waste (Part 2)" were also considered initially.

**Initial Resource List.** Resources included:

- The U.S. Composting Council has collaborated with Association of American Plant Food Control Officials (AAPFCO) to create a **list of benefits of compost backed up by research**:
    - https://cdn.ymaws.com/www.compostingcouncil.org/resource/resmgr/images/use_compost/AAPFCO_Uniform_Product_Claim.pdf
- U.S. Composting Council (USCC) website:
    - https://www.compostingcouncil.org/page/CompostBenefits
- Target Organics, A Compost Program Research Hub:
    - https://hub.compostingcouncil.org/

- USCC Compost Research and Education and Foundation website:
    - Research—https://compostfoundation.org/Research/CREF-Research
    - The Composting Handbook—https://www.compostfoundation.org/Education/The-Composting-Handbook
    - "The Climate and Compost Connection" by Sally Brown, Ph.D. (https://www.compostfoundation.org/Education/Publications)
    - Look at work/book by Britt Faucette, Ph.D. (https://www.compostfoundation.org/Education/Publications) – an academic who works on the soil/water connection. May be able to get books on Google for free.
- Research and publications by Robert Michitsch, Ph.D. – University of Wisconsin (rmichits@uwsp.edu)
- Research being done at University of CA, Davis on carbon sequestration.
- Publications from Soil Science Society of America:
    - https://www.soils.org/
- Rodale Institute:
    - https://rodaleinstitute.org/?s=compost
- Composting Collaborative (a project of BioCycle, GreenBlue and USCC):
    - https://www.compostingcollaborative.org/

**Bibliographic Databases.** Elsevier's Scopus abstract and citation database was the primary search tool. Scopus coverage comprises about 23,452 active journal titles, 120,000 conferences and 206,000 books from more than 5,000 international publishers. Publication types covered in Scopus include peer-reviewed articles and reports. EconLit was used to supplement Scopus searches as needed to identify publications addressing research questions related to economics issues.

**Search Engines and Specialist Websites.** Searches of websites (Google, state environmental websites, etc.) were also carried out to identify grey literature that may not be returned in other databases (e.g., Scopus, EconLit).

***Literature Eligibility Criteria***

**Publication type.** Initially, searches were focused on peer-reviewed published literature, such as published journal articles and book chapters. Subsequently, grey literature (scientific reports and assessments typically authored or sponsored by federal, state or local government agencies or nonprofit organizations that have a clear title, identified writer or organization, and publication year) was targeted.

**Time period.** The search was restricted to publication dates post-2010 (to gather timely information). However, pre-2010 references were also considered if the initial searches did not produce sufficient information or if highly relevant sources that predated the 2010 cutoff were identified through citation mapping or other means (e.g., expert interviews).

**Geographic range.** Searches were limited to literature published in English from the United States (priority focus), Canada, the United Kingdom and the European Union (secondary focus). The geographic extent was expanded if search returns for specific research questions were found to be limited.

**Citation Mapping.** If database searches returned insufficient results for any research questions, citation mapping of highly relevant papers was conducted. Highly relevant papers were selected based on relevance to the research question(s) and best professional judgment.

***Screening References***

**Data Management and Compilation.** Reference citations returned from the search strategy were uploaded to EndNote, creating a library of available literature. The literature was cataloged by research question within the Endnote library.

**Inclusion Criteria.** The criteria in Table B were applied to screen the reference results.

*Table A-2. Inclusion criteria for screening references for relevance.*

| Categories | Inclusion criteria |
|---|---|
| Geographic location | Primary focus: United States<br>Secondary focus: Canada, United Kingdom, European Union |
| Timeframe | Primary focus: 2010 or newer<br>Secondary focus: Pre-2010 references if the initial searches do not produce sufficient information or if a highly relevant source that predates the 2010 cutoff is identified through citation mapping or other means (e.g., expert communication) |
| Publication types | Peer-reviewed published literature; grey literature (scientific reports and assessments typically authored or sponsored by federal, state or local government agencies or nonprofit organizations that have a clear title, identified writer or organization, and publication year) |
| Potential keywords | See initial search strings in Table A; to be refined as necessary during the search process. |

Any returns not meeting the criteria were excluded at this stage. Returns that met the inclusion criteria were included for title/abstract screening and further consideration and categorization based on the individual research questions.

**Title/Abstract Screening.** Inclusion criteria were considered at the title/abstract level using EndNote Online. Resources that did not inform the research questions were excluded from further consideration. All excluded references were moved to a separate, exclusion EndNote library for each research topic or combined research topics. Full-text pdf files were obtained for included references through available resources.

***Assessing Search Comprehensiveness: Expert Interviews***

Searches were augmented by interviewing three composting experts for (1) insights and perspectives on the report content and (2) to ensure the literature review was comprehensive, especially regarding grey literature, which includes literature published by government, not-for-profit and other organizations that may not appear in literature databases.

U.S. Environmental Protection Agency
Office of Research and Development