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CONTRIBUTORS

Committee on Exploring Linkages Between Soil Health and Human Health; Board on Agriculture and Natural Resources; Food and Nutrition Board; Division on Earth and Life Studies; Health and Medicine Division; National Academies of Sciences, Engineering, and Medicine

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EXPLORING LINKAGES BETWEEN SOIL HEALTH AND HUMAN HEALTH

Committee on Exploring Linkages Between Soil Health and Human Health

Board on Agriculture and Natural Resources

Division on Earth and Life Studies

Food and Nutrition Board

Health and Medicine Division

Consensus Study Report

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KELLY WRIGHTON, Colorado State University, Fort Collins

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KARA N. LANEY, Study Director
ROBERTA A. SCHOEN, Board Director, Board on Agriculture and Natural Resources
ANN L. YAKTINE, Board Director, Food and Nutrition Board
KATHERINE R. KANE, Senior Program Assistant (*until March 2024*)
SAMANTHA SISANACHANDENG, Senior Program Assistant (*as of April 2024*)

---

[1] Member of the National Academy of Sciences
[2] Member of the National Academy of Engineering

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[1] Member of the National Academy of Engineering

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---

[1] Member of the National Academy of Medicine
[2] Member of the National Academy of Sciences
[3] Member of the National Academy of Engineering

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by **JEFFERY L. DANGL (NAS),** University of North Carolina, and **RICHARD M. AMASINO (NAS),** University of Wisconsin–Madison. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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The committee and staff are grateful for the support of the National Academies of Sciences, Engineering, and Medicine's staff who contributed to producing this report. The committee and staff thank Lauren Everett, Radiah Rose-Crawford, and Eric Edkin in the Executive Office of the Division on Earth and Life Studies; Cynthia Getner in the Office of the Chief Financial Officer; Anne Marie Houppert and Rebecca Morgan in the National Academies Research Center; Nancy Huddleston, Reece Meyhoefer, and Sydney O'Shaughnessy in the Office of the Chief Communications Officer; Hannah Fuller in the Office of News and Public Information; and Tucker Nelson in the Office of Congressional and Government Affairs. We would also like to thank Samantha Sisanachandeng and Katherine Dhurandhar for getting the report over the finish line.

In Memory of Diana H. Wall

The committee dedicates this report to Dr. Diana H. Wall, the chair of the report committee, who passed away on March 25, 2024. Diana was a tenacious scientist who shaped the modern field of soil biodiversity. Her research and publications on soil organisms, particularly on nematodes in Antarctica, clarified critical links between climate change and soil biodiversity. In addition to her groundbreaking science, Diana contributed her energy and expertise to National Academies committees for more than 35 years. She was a leader in the field of soil science and a delightful colleague. This report and each member of the committee benefited from her insights and curiosity.

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Preface

Quotes capturing the importance of soil to our existence are not difficult to find. In fact, the U.S. Department of Agriculture has compiled a list on its website, with contributions ranging from Homer to the Indigo Girls. Perhaps not surprisingly, you will find a few of those quotes in this report. What most on the list have in common is the connectivity of the well-being of humanity to the health of soil.

Yet, soil, compared to other earth systems, is understudied. This neglect is partly because what is out of sight is out of mind, and the complexity of soil processes is definitely out of sight. That connects to another problem with soils: what is out of sight is often difficult to study. However, with technological advances, seeing and sensing what goes on below the surface is becoming more feasible and, with each passing day, a little less expensive. These capabilities could not come soon enough to address challenges humanity faces in the 21st century: global warming, food security and malnutrition, and antibiotic resistance. In all these threats, soil has a role to play.

Furthermore, we can use our increasing knowledge of soil processes not just to address these challenges but to restore function and preserve biodiversity in the soils we have largely taken for granted as we have worked to feed the world's growing population over the last century. We can also explore the complexity and connectivity of the microorganisms that live in soil, on plants, and in us and possibly unlock new opportunities to improve health in all three domains.

These are not small topics to tackle, and I want to thank my fellow committee members for their dedication to our task to explore linkages between soil health and human health. Writing this report required more than a year of service. Through numerous in-person meetings and Zoom calls and countless revisions, they stayed focused on their commitment, bringing their diverse expertise and working constructively in groups and as an entire team to address a broad statement of task. I learned a great deal from each one, and I appreciate all the time they volunteered to see this report through to completion.

I also want to thank the presenters and reviewers who gave of their time to make this report better. We learned so much from the many researchers who took time out of their days to share their work with us, and I hope that they see their science in our report. The reviewers' detailed comments helped us take a second look at our evidence and arguments and improve both.

The work of the committee would not have been possible without the support of Kara Laney, study director, and Katherine Kane, senior program assistant. Kara's years of experience as a study director showed as she wrangled our fragments of text and sweeping conversations into a linear report. No one would have guessed that this was Katherine's first time supporting a study; she was a pro from the very start.

On behalf of the committee, I want to say that I hope this report contributes to a focus of attention on the importance of soil health that does not fade. A generation from now, we should be able to say that we have learned a great deal more about soil health and its contributions to our own health, but we will not have to justify its importance. We will prioritize soil health because it is evident, just as it has been evident to those quoted throughout history.

Diana H. Wall, *Chair*
Committee on Exploring Linkages Between Soil Health and Human Health

Acronyms and Abbreviations

ARG	Antibiotic-resistance genes
BSAAO	Biological Soil Amendments of Animal Origin
EPA	U.S. Environmental Protection Agency
FDA	U.S. Food and Drug Administration
GHG	Greenhouse gases
ITS	Internal transcribed spacer
MP	Microplastics
NCP	Nature's Contributions to People
NSF	National Science Foundation
PFAA	Perfluoroalkyl acid
PFAS	Per- and polyfluoroalkyl substances
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonic acid
rRNA	Ribosomal RNA
SCFA	Short-chain fatty acid
SIC	Soil inorganic carbon
SOC	Soil organic carbon
SOM	Soil organic matter
USDA	U.S. Department of Agriculture
UV	Ultraviolet

Summary

The United States is an important food producer globally, in part because of its abundance of agriculturally productive soils. However, management practices that maximize yields have caused losses in soil organic matter, poor soil structure and water-holding capacity, and increased salinity on millions of acres of land. Microbial communities, the drivers of many soil processes, have been adversely affected by excessive use of tillage, nutrient applications, and pesticides. Erosion, accelerated by tillage and lack of ground cover, has caused the loss of over 57 billion metric tons of topsoil from the Midwest alone over the past 150 years. Although U.S. agriculture increased its productivity in the 20th century by adopting new practices and technological advances, these increases are not expected to be repeated in the 21st. Furthermore, the externalized costs to the environment and human health—water and air pollution, biodiversity loss, and increased greenhouse gas (GHG) emissions—caused by many agricultural management practices are apparent and severe.

Considerable efforts are underway to mitigate these problems through management practices that improve soil health, defined by the Food and Agriculture Organization as "the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems". There is also interest in determining whether improved soil health has favorable effects on the nutrient density of foods grown. Recent advancements have sparked exploration into the interconnectedness of microbiomes across soil, plants, humans, and other animals and how microbiomes can support healthy soils as well as humans. These advances may also lead to new discoveries in the soil microbiome that could facilitate drug development and address threats to human health, including antibiotic resistance, contaminants, and soil-borne pathogens.

Given this, the U.S. Department of Agriculture's National Institute of Food and Agriculture asked the National Academies of Sciences, Engineering, and Medicine to convene a committee of experts to explore the linkages between soil health and human health (Box S-1).

THE COMMITTEE'S PROCESS AND SCOPE OF THE STUDY

Members of the Committee on Exploring Linkages Between Soil Health and Human Health were appointed by the National Academies for their expertise relevant to the statement of task. The committee members volunteered for more than a year to write this report, hearing from 33 invited speakers, participating in numerous deliberation sessions, and reviewing and integrating scientific evidence to respond to the statement of task.

The committee approached its task from the viewpoint of the One Health concept—that is, the health of humans, other animals, plants, and the wider environment are linked and interdependent. It noted that the pursuit of One Health has, until recently, neglected the environmental piece of the puzzle and that, of the many poorly understood and unintegrated components of the environment, perhaps the most neglected among them is soil. The committee sought to press the One Health treatment of soil beyond its passing inclusion as a medium for food production or a receptacle of chemical contamination and examine the many ways in which the health of soil connects to the health of humans.

BOX S-1
Statement of Task

A committee appointed by the National Academies of Sciences, Engineering, and Medicine will review the state of knowledge on linkages between soil health, with particular respect to U.S. agricultural soils, and human health and prepare a report describing the potential to increase the human health benefits from microbial resources in the soil.

In the course of its review, the committee will identify current research efforts and examine scientific findings on such topics as:

- Relationships between the human microbiome and soil microbiome including the plant microbiome as part of a continuum.
- Linkages between soil management practices and the nutrient density of foods for human consumption and other effects on food;
- Information on soil microbial compounds used in drug development, such as antioxidants, antibiotics, and compounds with anti-cancer properties;
- Information on soil-borne human pathogens and microbial compounds such as toxins;
- Information on the interactions of the soil microbiome with soil contaminants that pose risks to human health; and
- Soil management practices that enhance health benefits and reduce adverse health impacts.

The committee's report will describe key findings and knowledge gaps, identify promising research directions, and offer recommendations for enhancing the human health benefits of the soil microbiome.

Nevertheless, there are many kinds of soils and environments, and the committee could not address all possible linkages between soil health and human health. The committee’s report reflects its statement of task, which was primarily focused on soil used in crop production in the United States. This summary begins with a discussion of linkages between soil microorganisms and human health, followed by the various ways soils and agricultural management practices connect to human health. It also discusses the interplay between management practices, crop nutritional qualities, and possible connections to human health, and it concludes with opportunities for improving human health by increasing soil health. The recommendations made in the report follow each section in Tables S-1 through S-4.

LINKAGES BETWEEN SOIL MICROORGANISMS AND HUMAN HEALTH

Through their ability to cycle nutrients and carbon, filter water, and build soil structure and organic matter, the most obvious linkage between soil microorganisms and human health rests on the fact that they—and soil biota in general—are integral to the capacity of soils to produce food. Perhaps less recognized is the critical role the soil microbiome plays in climate regulation, including carbon sequestration, and the ability of soil microbes to metabolize many organic contaminants into harmless byproducts, which limits exposure to humans. Likewise, many of today’s antibiotics and other drugs are derived from soil microorganisms. That soil microbes can also be harmful to human health is highlighted by several foodborne pathogen outbreaks in fresh produce in recent decades linked to manure or compost-amended soils.

TABLE S-1 Recommendations to Advance Understanding of Linkages Between Soil Microorganisms and Human Health

Microbiome sampling	Researchers must incorporate sufficient rigor in the sampling design to capture the spatial and temporal heterogeneity of the microbiome to reveal responsive indicators of health. (Recommendation 7-1)
	Researchers should enhance universal methodologies (sampling, documentation) for microbiome analysis across different sample materials. (Recommendation 7-2)
Microbiome data management	Federal funders should require that resources to ensure metadata as well as data on environmental and ecosystem properties or population characteristics be included, properly stored, and reusable, as accessible data are necessary but not enough. (Recommendation 7-3)
Microbiome diagnostics	Funding agencies should support discovery of scalable diagnostics, with the goal that affordable, rapid assays will be developed for use on soil microbiomes in the field and with diverse human populations. (Recommendation 7-4)
	Funding agencies should support research designed to investigate causal relationships in soil and human microbiomes, toward the development of microbial therapeutics. (Recommendation 7-5)
Collaboration	Funding agencies should support microbiome research within disciplines (e.g., community ecology, soil ecology, and soil biogeochemistry or microbiology and medicine) to integrate methodologies to bring together composition and functional assessments of microbiomes. (Recommendation 7-6)
	Funding agencies should support microbiome research among disciplines (e.g., agronomy, plant science, soil ecology, microbiology, immunology, human nutrition, medicine, engineering) to explore the connectivity of the microbiome across systems (e.g., soil, plants, and humans). (Recommendation 7-7)

While the above linkages between soil microorganisms and human health are largely known, the connections between soil microbiomes and human microbiomes remain underexplored. There is indirect evidence of the importance of exposure to environmental microorganisms for human health, notably on the immune, metabolic, and central nervous systems. However, the extent to which exposure specifically to the soil microbiome influences the human microbiome is unknown. From animal models, soil biodiversity appears to be interrelated with the mammalian gut microbiome, with studies finding that animals in contact with soil and dust have gut microbiomes with greater diversity and richness. Whether this also occurs in humans and has potential benefits for human health remains unknown.

Additionally, because microbial actions are responsible for many chemical indices currently used as health indicators, the microbiome may provide early indicators of health changes and act as a canary in the coal mine. However, the ability to define and interpret microbial health indicators is currently limited by a sparse understanding of the ecology and function of microorganisms in both soil and human systems. Sampling and analyzing microbiomes along a continuum of health states and complementary use of multiple molecular (metabolite, proteomic, genomic, and transcriptomic) and non-molecular methods can provide more definitive evidence on microbial metabolic pathways related to health status. This evidence will help researchers incorporate microbiome-related data in future approaches to monitor soil health and human health.

Finally, the reservoir of antibiotics and other medicinal natural products in soils remains largely untapped. Less than 5 percent of the estimated hundreds of thousands of antibiotic substances in soil have been characterized. Continued development of molecular methods and cultivation techniques could offer efficient ways to screen soils for promising medicinal compounds.

LINKAGES BETWEEN AGRICULTURAL MANAGEMENT PRACTICES AND HUMAN HEALTH

Common agricultural management practices have increased crop yield and food security, but this productivity has often come at the expense of soil health, with detrimental effects on the environment and human health. For example, synthetic fertilizer use has greatly increased crop production but has also caused excess nutrients to leach from agricultural fields, sometimes resulting in contaminated groundwater, algal blooms, and production of potent GHGs that contribute to climate change. Although conservation tillage is widely used in the United States, conventional tillage is still employed in many cropping systems and can reduce soil organic matter, suppress biodiversity, and increase erosion. Eroded material can reduce water quality, irritate human respiratory systems, and increase exposure to pesticides and possible contaminants residing in soils. At its most fundamental level, agricultural management practices often create trade-offs between the many services soils provide to people—for example, food production on the one hand and, on the other, the ability of ecosystems to sustain biodiversity, sequester carbon, and perform myriad other functions that are equally, even if less obviously, essential to human health.

Prior to the early 2000s, soils were rarely included in assessments of the services that ecosystems provide to people beyond adequate food and materials for building. Since then, there has been an increasing recognition that soils provide additional important functions. Collectively, these services have been termed Nature’s Contribution to People (NCPs) and include nutrient cycling; water, climate, and air regulation; disease suppression; and habitat creation and maintenance as well as benefits that contribute to cultural, recreational, and spiritual well-being. For example, the world’s soils contain three and four times more carbon than is in the atmosphere and vegetation, respectively, and they play a major role in global carbon cycling through acting as both source and sink.

Management decisions affect whether carbon is stored in or lost from soil. Reduced tillage, increased input of organic matter into soil via crop residues, planting of cover crops or long-lived crops with large root systems, and the use of organic soil amendments (e.g., manure, compost, and biosolids) build soil organic matter and thus carbon in soils. Incidentally, these practices likely also reduce erosion and promote microbial biomass and diversity, nutrient and water holding capacity, and aggregate stability. Such changes increase NCPs with direct and indirect benefits to human health, such as water filtration and improved air quality.

Management practices have the potential to assist soils in suppressing plant disease, another soil-derived NCP. Development of disease-suppressive soil is an example of positive plant–soil feedback that can benefit future plant productivity through the lasting effects of plant–soil interactions. Practices that promote microbial abundance and diversity, such as crop rotations, cover crops, residue retention, minimum tillage, and compost or manure addition, have been shown to promote disease suppression.

TABLE S-2 Recommendations to Advance Understanding of Agricultural Management Practices That Enhance Benefits to and Reduce Adverse Effects on Human Health

Managing trade-offs and enhancing soil-derived Nature's Contributions to People (NCP)	The U.S. Department of Agriculture (USDA) and other agencies should prioritize research to better characterize and monitor NCPs (e.g., nitrogen cycling or the nonmaterial NCPs related to human health), to understand the underlying mechanisms to improve predictions (e.g., disease suppression), and to assess their importance across different scales (e.g., plot to landscape and upward). This research should be translated into tools that can be used by land managers in agricultural and nonagricultural settings to inform decisions that involve trade-offs among NCPs. (Recommendation 3-2)
	USDA, the U.S. Geological Survey, and other agencies involved in land management should support research that explores the mechanisms driving soil-derived regulating NCPs and approaches through which their benefits can be enhanced. (Recommendation 3-4)
	USDA and other agencies should support research that: • Develops novel strategies or management combinations to overcome potential trade-offs from common agricultural management practices. For example, soil health would benefit from non-pesticide dependent ways to address weed, insect, and pathogen pressure or terminate cover crops in no-till systems. Similarly, new plant varieties or strategies that minimize water use from cover crops while maximizing soil protection and soil carbon inputs in arid and semi-arid regions should be studied. These efforts should include research in controlled environments and under field conditions to understand when and how biostimulants can help restore degraded soil and how their use compares biologically and economically with other methods to improve soil health. • Investigates the short-term and long-term impacts of diverse pesticides, including mixtures, on soil biota and their functions, which have implications for soil health. • Increases the safe and effective use of underutilized resources streams (such as biosolids, manure, and compost) as sources of nutrients and organic matter for crop production. These efforts would include developing technologies and waste management practices to improve the feasibility and affordability of assessing nutrient content, screen for and remove contaminants or compounds of concern to human health, and formulate and distribute these recycled resources to producers in ways that are competitive with commercial fertilizers. (Recommendation 4-3)
Food safety	USDA's National Institute of Food and Agriculture and the National Institutes of Health should support research studies conducted in controlled environments as well as in field trials that assess persistence of microbial pathogens under varying climatic conditions in order to better understand factors that may facilitate pathogen survival in soil and transfer onto crops. These studies should incorporate various crops, as well as biostimulants and fertilizer additions, that may alter plant–pathogen interactions and zoonotic pathogen persistence. (Recommendation 5-7)
	USDA should support efforts, such as the USDA–Agricultural Research Service's National Predictive Modeling Tool Initiative, that use soil monitoring data linked with climate and other environmental data to predict and help control mycotoxin risk in crops and forage species. (Recommendation 5-8)

Along with soil moisture and precipitation, agricultural management practices affect foodborne pathogens and mycotoxin production, both of which present risks to human health. Foodborne pathogens can be introduced to the food supply through organic soil amendments, but there are practices and regulations that mitigate risks to human health. Regarding mycotoxins, the health of soils influences nutrient and water-holding capacity of the soil and thus plant stress, which in turn determines the ability of crops to resist colonization. Better understanding of the conditions under which pathogens and mycotoxins thrive will reduce crop losses and human illness by identifying ways to maximize crop growth potential while minimizing practices conducive to pathogen growth or toxin production.

LINKAGES BETWEEN AGRICULTURAL MANAGEMENT PRACTICES AND THE NUTRITIVE VALUE OF FOOD

Although there is a common perception that healthy, well-managed soils produce healthier foods, the connection is not always clear. Nutrient availability in the soil, environmental conditions, management practices, and plant genetics all play a part in determining the nutritional quality of food. Comparative studies of different production systems (e.g., conventional vs. organic) have tried to assess the interplay of these factors, but variations in experimental design, soil types, crop species, and environmental conditions have yielded divergent results. Unfortunately, as with most complex systems where biotic and abiotic factors are at play, the influence of a given management practice on crop yield or nutritional quality is not always predictable or consistent.

What ultimately determines the nutritional quality of food crops is the amount of essential nutrients with health-promoting potential that are transported to, or synthesized within, the edible portion of the plant. These include minerals and biosynthesized macromolecules such as amino acids/proteins, carbohydrates, lipids, vitamins, and phytochemicals (also referred to as bioactive secondary metabolites). Agricultural management practices that modify mineral or water availability can affect crop nutritional quality. Some studies have also demonstrated that enhanced soil organic carbon and microbial biomass are associated with increased levels of phytochemicals commonly associated with reduced risk of chronic diseases in humans. However, such differences largely disappear when edible plant tissue yield is considered. If yields increase, concentrations of certain nutrients and health-beneficial phytochemicals may actually *decrease* because nutrients do not necessarily all accumulate within edible plant tissues at the same rate. A higher accumulation of yield-increasing macromolecules such as starch or protein may dilute micronutrient concentrations. Nevertheless, an increased crop yield can potentially lead to increased micronutrient content for consumption even if the concentration per unit mass is reduced. Thus, both quality and quantity of harvestable product need to be considered when assessing effects of various management practices.

The lack of a clear relationship between nutritional quality and management practices in studies could also be because the diversity of secondary phytochemicals in plants is complex, and many compounds function as signaling or defensive molecules that can be differentially biosynthesized in response to biotic or abiotic environmental stress. Therefore, a reduction in plant stress may in some instances lead to lower concentrations of these phytochemical compounds in plant foods. Variation in nutritional quality is also highly dependent on plant genetics, and studies of crop genetic diversity have shown broad ranges in nutrient density. Furthermore, plant genetic traits that confer enhanced micronutrient uptake from soils do not always translate into enhanced accumulation in edible parts. Identifying practical strategies to enhance (micro)nutrient density in staple food crops remains a challenge, especially for at-risk populations in developing regions of the world. This is less of an issue in the United States due to low-cost micronutrient supplementation in staple products (e.g., cereals, dairy, and beverages) and overall diversity in the diet, although micronutrient limitations in soils can reduce yield.

Discussion of nutrient density and phytochemical composition in edible plant material is incomplete without acknowledging the processes that harvested crops undergo before consumption. Nearly all commercially harvested plant foods are processed to make them safe to consume and improve their palatability and shelf life, which alters the nutritional and health attributes. For example, milling cereal grains often removes bran and germ tissues that contain many of the health-beneficial phytochemicals, dietary fiber, minerals, and vitamins. Although nutritional and health benefits of these components are known, capturing their benefits to broadly affect human health remains challenging due to low consumer acceptance of such products. Deriving the full benefits of nutritionally beneficial plant commodities requires innovations in methods to minimize losses of such nutrients and bioactive compounds during processing while maintaining consumer acceptance.

Other food-processing technologies, such as thermal treatment or fermentation, can enhance bioaccessibility or bioavailability of some nutrients and phytochemicals. Bacteria in fermented food may even favorably influence the composition of the gut human microbiota in some cases. However, these treatments may also lead to the degradation and loss of nutrients or phytochemicals. Thus, it is always important to consider the final form of edible plant tissue that is consumed when evaluating soil–plant–human health interactions.

TABLE S-3 Recommendations to Advance Understanding of the Linkages Between Agricultural Management Practices and the Nutritive Value of Food

Agricultural management practices and food composition	The U.S. Department of Agriculture's National Institute of Food and Agriculture (USDA–NIFA) and the National Science Foundation (NSF) should support translational research to better understand the effect of different agricultural management practices, when used in specific environments, on the nutrient and bioactive density of crops (in the context of yield) consumed by humans. (Recommendation 5-1)
	USDA–NIFA, NSF, and the National Institutes of Health should cooperate to support research on the biosynthetic pathways and the environmental cues (including soil factors) that influence food composition, so that crops can be managed or bred for higher levels of target compounds (especially bioactives) even in the absence of promotive environmental signals. (Recommendation 5-2)
	USDA–NIFA and NSF should support research, from greenhouse to field scales, to better understand the utility of biostimulants for nutrient uptake and yield under field conditions and considering different ecological factors, including the indigenous soil microbiome. (Recommendation 5-3)
Role of food processing and food choice	USDA–NIFA and private industry should support research in food-processing technologies that enhance the profile of health-beneficial nutrients and bioactive compounds in foods without sacrificing consumer acceptability and that lead to improvements in diet-related indices of public health. (Recommendation 5-4)
	USDA–NIFA and NSF should support efforts to study the survival and microbial fitness of commensal organisms in foods, their response to thermal and nonthermal processes, and their potential impact on host microbiomes. (Recommendation 5-6)
	USDA–NIFA is encouraged to support studies that examine consumer willingness to purchase foods that are more nutrient dense and consumer interest in paying for foods produced with agricultural management practices that support soil health. (Recommendation 5-9)

IMPROVING SOIL HEALTH TO IMPROVE HUMAN HEALTH

A healthy soil sustains biological processes, decomposes organic matter, and recycles nutrients, water, and energy, reducing the need for synthetic fertilizers and irrigation. It helps mitigate exposure to some chemical contaminants and sustains food production. All these functions make the prioritization of soil health for human health benefits even more important in the face of climate change, which will adversely affect soil nutrient cycling and exacerbate the detrimental effects of flooding or drought on soil stability and water-holding capacity.

Yet, assessing a soil as "healthy" is complex and hotly debated. Numerous variables can be measured, and it is not always clear which ones best correspond to the concept of soil health and how they should be compiled and compared. Consensus has been reached that soil health assessments are regional and system specific and require multiple variables, but which soil health indicators are useful to measure in each context remains contested even as tools have advanced. Furthermore, the spatiotemporal heterogeneity of soil means that single point measurements are unlikely to provide meaningful data for informing management actions or for comparisons across soils. Opportunities exist for monitoring, collecting, and analyzing data so that soil health indicators can be validated over time and in their agricultural context to advance their utility. Such approaches could also be applied to gain a better understanding of the underlying mechanisms contributing to soil health and associated benefits to human health.

Nonetheless, some generalities are possible. A healthy soil will possess optimal pH, nutrient levels, and soil organic matter, with low concentrations of harmful chemicals. Physical properties should provide good aeration and water infiltration and storage. It is increasingly apparent that biodiversity maintenance is an essential constituent for soil health, prompting the urgent need to preserve soil microorganisms (as well as meso- and macrofauna). It is also widely acknowledged that agricultural management practices that minimize disturbance and maximize crop biodiversity, maintain continuous living plants, and keep the soil covered, wherever possible, will build soil health. The incorporation into planting rotations of cover crops, perennial crops, or crops bred specifically for root system development or rhizosphere interactions with soil biota are all options for increasing belowground biomass. More research and development will be needed to make these crops viable choices in the diverse soils and climates of the United States.

Although there are many intricacies about soil health to be learned, immediate action should be taken to map and mitigate current soil chemical contamination. The degradation of chemical contaminants is a soil-derived NCP, but contamination can overwhelm the capacity of soil to mitigate risks to human health. High levels of lead and cadmium in soils reduce microbial activity and plant biomass. Microplastics can change soil structure, affect water-holding capacity, and may enrich pathogens and antibiotic resistance genes in soil microbial communities. Per- and poly-fluoroalkyl substances, a large group of synthetic, organofluorine chemicals that are highly persistent in the environment, are of increasing concern as environmental contaminants. These and other soil contaminants have not been strategically mapped in the United States. Thus, there is a lack of comprehensive knowledge regarding the geographic distribution of these contaminants in U.S. soils and the specifics of their co-occurrence in mixed forms. Each contaminant class is diverse with heterogeneous impacts based on the nature and quantity of the material and the characteristics of the soil in question. The reality of soil contamination is even more complex because of the potential for co-contamination with multiple compounds. It is likely that contaminants interact with one another in ways that compound the adverse effects on soil health. This gap in understanding underscores the need for more detailed research and mapping of soil contaminants to better address soil and environmental health challenges.

Finally, there are abundant underutilized organic resources in the United States—food waste, compost, agroindustrial and forestry byproducts, manure, biosolids, and source-separated human excreta—that could be used to increase soil nutrients and organic matter and reduce demand for synthetic fertilizer. However, current challenges involving geographic distribution, quantification of nutrient content, and contaminant removal must be solved to make the most effective use of these resources.

TABLE S-4 Recommendations to Improve Soil Health

Awareness and preservation	Federal agencies and scientific societies should continue their work to promote the public awareness of the importance of soil health and its societal value beyond its immediate material benefits. (Recommendation 3-1)
	Land managers and city planners should manage landscapes in a way that preserves and promotes soil habitat and biodiversity by minimizing disturbance and soil sealing and optimizing plant cover and diversity wherever possible. (Recommendation 3-3)
	Producers and other land managers should adopt practices that increase the organic matter content, biodiversity, and other health parameters of their soils. (Recommendation 6-7)
Agricultural soil management	The U.S. Department of Agriculture (USDA) should develop a coordinated national approach to monitor soil health over time and space. This approach would allow for broad comparisons across locations and an ability to identify areas of concern. Over time, it would also enable comparisons among management practices as well as their context dependency. To achieve this would require: • Learning from monitoring efforts outside the United States (e.g., the European Union and New Zealand). • Developing harmonized methods with known relationships to soil health. • Research to answer questions about the best biological indicators of soil health to measure in a given context. • Continuing to the development and improvement of interpretation and predictive power of soil data from soil sensors and other tools for more rapid and in-situ measurement of abiotic and biotic soil properties and their usefulness to assess soil health. • Support to develop a user-friendly soil data management system to store soil health information in a way that is publicly accessible and comparable over time. (Recommendation 4-1)
	USDA should fund research projects that: • Are designed to identify the underlying mechanisms of soil health and the plant–soil feedbacks that drive changes in soil health and how they affect long-term ecosystem outcomes. Such projects may require factorial experiments where management practices are tested in isolation. • Involve longer-term studies where slow processes can be studied under realistic settings as well as account for climate variability and exposure to environmental stressors such as drought. • Support collaborative on-farm research with scientists, farmers, and industry to identify the underlying mechanisms of soil health. Such research should take into consideration historical and current land management practices. (Recommendation 4-2)

continued

TABLE S-4 *continued*

	USDA's Agricultural Research Service should pursue and USDA's National Institute of Food and Agriculture (NIFA) should support plant breeding research that improves: • The suitability of cover crops in all farming systems, including those in low precipitation locations. • Belowground crop traits, such as root system development and rhizosphere interactions with soil biota. • Perennial crops and polycultural systems. (Recommendation 4-4)
	USDA farm-support programs should consider the benefits of soil health as a context-specific metric of success in restoring degraded soils and as a tool to monitor vital soil functions rather than solely focusing on yield outcomes from management practices and should provide assistance for land managers to support transition to more complex systems. Such assistance could include: • Incentives and insurance for adopting practices that could improve soil health and are designed to contend with certain risks in some areas (e.g., cover cropping in arid or semi-arid regions). • Incentives to increase spatial and temporal diversification. (Recommendation 4-5)
Contamination concerns	Federal agencies should work collaboratively to support surveys of soil chemical contaminants informed by systematic risk assessments to identify where contaminant levels in soil may be particularly high (e.g., locations around, downwind, or downstream of PFAS point sources). These surveys can be used to build contaminant maps (e.g., of lead, arsenic, persistent organic pollutants) that can be viewed individually or overlaid to assess the status of contamination, identify locations of concern, and, over time, evaluate the effectiveness of interventions. (Recommendation 6-1)
	Federal agencies should support interdisciplinary research to reduce gaps in knowledge about exposure pathways from soil and the compounding health effects on soil biota, plants, and people from exposure to multiple chemical contaminants. (Recommendation 6-2)
	The United States should mitigate the entry of plastic and PFAS contaminants into soil by reducing their overall production and use. (Recommendation 6-3)
	The U.S. Environmental Protection Agency (EPA) should continue pursuing research and technology to remove PFAS from wastewater and biosolids. (Recommendation 6-4)
	EPA should pursue research to establish a threshold for plastics in land-applied soil amendments. Revisiting heavy metal thresholds would also be in order. (Recommendation 6-5)
Recycled resources	USDA–NIFA and the National Science Foundation should support research on technologies that enhance usability of food-processing byproducts as functional food ingredients, sources of valuable bioactive compounds and nutrients, or substrates for production of novel high-value compounds. (Recommendation 5-5)
	Public sector investment should be made to develop affordable technologies for converting biosolids into biochar that can be applied to agricultural land and/or used for wastewater treatment. (Recommendation 6-6)
	Public and private entities should invest in Green and Sustainable Remediation techniques, including the application of designer biochars and biosolids biochar, to manage soil contamination effectively. (Recommendation 6-8)

GOING FORWARD

The concept of One Health posits that soil should be valued as an ecosystem that, when healthy, contributes to the health of other ecosystems, plants, humans, and other animals and that contains a microbiome that not only connects to plants but likely to people as well. To promote sustainability and resilience, the way soil is viewed must be altered from that of a widget in a production system to that of a component of a holistic system that includes but extends far beyond agriculture. Soil biodiversity must be preserved, both to ensure current soil functions and to safeguard genetic diversity to enable discoveries of future medicines.

This shift in our perception of soil will be guided by a better knowledge of underlying mechanisms contributing to soil health and its connectedness to plant and human health and a continued optimization of ways to quantify and compare health. It will require changes in farm-support programs to value soil health as a metric of success and to transition toward more complex and perennial cropping systems as well as increased circularity where waste streams are turned into safe resources. Finally, societal awareness of the role soil health plays in human health beyond food production must increase, which will require the involvement of many federal agencies, scientific societies, companies, and international organizations.

1

Introduction

The United States is a large producer of food on the global stage. Its volume of production has many contributing factors, but one of the foundations of the U.S. agricultural sector is the abundance of agriculturally productive soil found within its borders. More than a third of U.S. soils are categorized as Mollisols or Alfisols, the two soil orders considered to be most productive in terms of crops (Eswaran et al. 2012).[1] Mollisols are rich in organic matter from the growth and decomposition of deep-rooted perennial grasses that grow in them, while the clay content of Alfisols, which formed under deciduous forests, holds water and nutrients in the root zone (USDA–NRCS 1999; Eash et al. 2008; Eswaran et al. 2012; Parikh and James 2012). Mollisols comprise the Palouse region of the Pacific Northwest, whereas much of the soils of California's Central Valley are Alfisols. Soils of both orders dominate the Great Plains and Midwest. The fertility of these soils, assisted by irrigation, drainage, or both in some areas, is a substantial component in the success of the U.S. agricultural sector (U.S. Bureau of the Census 1952).

Yet, the productivity of U.S. agriculture since the mid-20th century is, to a large extent, decoupled from the historic richness of the soil. Erosion—accelerated by tillage and from leaving the land bare for parts or all of the year—is estimated to have caused the loss of more than 57 billion metric tons of topsoil (and the nutrients and organic matter therein) from the north central states since the 1870s (Pimentel 2006; Thaler et al. 2022).[2] Following decades of tillage with moldboard plows, monoculture cropping patterns, and the regular removal of crop residues from harvested land, Donigian et al. (1994) calculated that, by the 1950s, the amount of organic carbon in soils in the middle of the country—from North Dakota and Nebraska in the West to Pennsylvania in the East and south to Oklahoma, Arkansas, and the northeast corner of Alabama—was half what it had been in 1907. Reduced water-holding capacity of soil due to the loss of soil structure and organic carbon from erosion, tillage, and removal of crop residue also adversely affects crop productivity (Pimentel et al. 1995; Evanylo and McGuinn 2000). Furthermore, by the 1980s, soil salinity affected 27 percent of irrigated land, nearly 13 million acres, in the United States (Postel 1989).

Soil microbial communities, the drivers of many soil processes, have also been affected. For example, studies conducted on research plots in Michigan and Illinois have found reduced microbial diversity in agricultural soils. A study on the Michigan plots compared uncultivated land and plots under different agricultural management treatments and found that microbial communities in uncultivated land were different in structure from cultivated land, regardless of treatment (Buckley and Schmidt 2001). The experiment conducted in Illinois, at the oldest continuously maintained agricultural research plots in the United States, found that fewer rare bacterial taxa, less diversity and richness in bacteria, and more bacteria adapted for low-nutrient

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[1] The U.S. Department of Agriculture has categorized soil into 12 orders based on measurable and observable soil properties. See USDA–NRCS (1999) for more information.

[2] Parts of North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Missouri, Wisconsin, Illinois, Indiana, and all of Iowa.

conditions were found in the soil of plots that either received no fertilizer or were treated with inorganic fertilizer in continuous corn plantings versus soil in plots treated with cattle manure (Soman et al. 2017). Likewise, frequent tillage and high inorganic nutrient inputs have suppressed the abundance of beneficial mycorrhizal fungi that colonize plant roots, build soil structure, and aid in plant nutrient acquisition, pathogen protection, and drought tolerance (Johansson et al. 2004; Delavaux et al. 2017).

U.S. agriculture overcame this soil degradation and accelerated its productivity in the 20th century by adopting new practices and taking advantage of technological advances. Further declines in soil organic matter content following the 1950s were mitigated by the integration of soybeans in crop rotations even as planting of clover and other leguminous crops declined or plateaued (U.S. Bureau of the Census 1952; Allmaras et al. 1998; Grey et al. 2012), the mid-century switch to mechanized combine harvesters (which left more crop residue on the field than binders or pickers; Allmaras et al., 1998), and the application of synthetic fertilizer, for which the amount used tripled between 1940 and 1960 and steadily increased until 1981 (Hignett 1956; Collier et al. 2017; Hellerstein et al. 2019). The transition from animal power to machines, already underway well before 1950, increased farm productivity and labor efficiency, and investment in and adoption of crops bred to produce high yields when supplemented with applied fertilizer bolstered productivity (U.S. Bureau of the Census 1952; Allmaras et al. 1998; Pardey and Alston 2021). Pesticide use also began to take off in the 1950s, replacing the labor needed to mitigate crop damage from weeds, insects, and pathogens (Osteen and Szmedra 1989). After hitting a plateau in 1920, the number of irrigated acres in U.S. agriculture increased from 1940 until the late 1970s (Hrozencik and Aillery 2021), and new technology—particularly the development of corrugated plastic tubing in the 1960s—lowered the costs associated with draining land (Fouss and Reeve 1987). Between 1948 and 2021, the volume of U.S. crop production increased 190 percent while the amount of labor and land used in agriculture fell (USDA–ERS 2024).

However, the rate of productivity increases in the 20th century are not expected to be repeated in the 21st. Efficiencies in labor, advances in genetics, and technological innovations will continue, but the degree to which they increase productivity will likely be smaller (Pardey and Alston 2021). Furthermore, the externalized costs to the environment caused by current agricultural production systems, such as water and air pollution and biodiversity loss, are apparent (Broussard and Turner 2009; EPA 2011; Tibbett et al. 2020).

Many of these externalities, which have implications not only for the environment but for human health as well, connect back to the soil. Nutrients applied to the soil that are not taken up by plants or microorganisms leach into groundwater, contaminating drinking water supplies (Capel et al. 2018). Excess nutrients, pesticides, and sediment as well as antibiotics and other contaminants from livestock manure and biosolids leave the field through surface drainage systems or because of extreme rain events, polluting surface waters that are places of recreation for people or that supply drinking water to communities (Capel et al. 2018). More than half of the emissions in the United States of nitrous oxide—one of the greenhouse gases causing global warming—come from cropland, due in large part to the application of synthetic fertilizer and the mineralization of soil organic matter, which increases the amount of mineral nitrogen in the soil (EPA 2023). Loss of function in soil microbial communities, which can be connected to decreases in soil microbial biodiversity (Wagg et al. 2021), affects the biogeochemical cycling of nutrients and the growth of plants, with concomitant deleterious effects on food production and the climate (Saleem et al. 2019). Loss of soil microbial diversity may also affect human health as evidence increasingly supports the importance of environmental exposure to microorganisms in the development of the immune system (Hanski et al. 2012; von Mutius 2021).

There are considerable efforts underway to decrease these external costs and the subsequent adverse effects on human health through management practices that improve soil health while maintaining or even increasing the supply of food produced by U.S. agriculture (e.g., Wolfe 2019; Hills and Benedict 2021; USDA 2022, 2023). At the same time, there is interest in determining whether changing agricultural management practices to improve soil health has a favorable effect on the nutrient density of foods grown in the United States (Carr et al. 2013; Reeve et al. 2016; Montgomery and Biklé 2021; Bourne et al. 2002; White House 2022). Scientific advances in the past 10–20 years that have increased the ability and reduced the cost of exploring the microbiome—across soil, plants, and humans and other animals—are also spurring interest in how microbial communities are connected among species and how attention to microbiomes can support soil health, food quality, and human health. These advances may also lead to new discoveries in the soil microbiome that could facilitate drug development and address threats to human health such as antibiotic resistance, new and emerging contaminants, and soil-borne pathogens (Hover et al. 2018; Gambarini et al. 2021).

With these possibilities in mind, the U.S. Department of Agriculture's National Institute of Food and Agriculture (USDA–NIFA) asked the National Academies of Sciences, Engineering, and Medicine (hereafter referred to as the National Academies) to convene a committee of experts to explore the linkages between soil health and human health.

THE COMMITTEE AND ITS CHARGE

The committee was asked to review the state of knowledge on linkages between soil health and human health, giving particular attention to the linkages involving the United States' agricultural soils. Several components of the statement of task called for exploration of the soil microbiome and possible connections to human health. The committee was also charged with providing information about soil-borne pathogens and toxins as well as microbial compounds that could be used in drug development. The sponsoring agency, USDA–NIFA, asked the committee to identify promising research directions and offer recommendations for enhancing the human health benefits of the soil microbiome. The study's full statement of task is in Box 1-1.

The National Academy of Sciences appointed a committee with the diverse expertise and experience needed to address this specific statement of task. The committee contained experts in agronomy, plant pathology, food science, microbiomes, human nutrition, microbial ecology, soil science, toxicology, and human health. As with all National Academies committees, members were appointed for their individual expertise, not their affiliation to any institution, and they volunteered their time to serve on this committee. The biography of each committee member can be found in Appendix A.

THE COMMITTEE'S PROCESS

The committee carried out its task between April 2023 and April 2024. It held 11 information-gathering meetings between April and October 2023, hearing from 33 invited speakers. All information-gathering meetings, whether conducted online or in a hybrid format, were open to the public, live streamed, and recorded and posted on the study's website. Agendas for these meetings can be found in Appendix B.

BOX 1-1
Statement of Task

A committee appointed by the National Academies of Sciences, Engineering, and Medicine will review the state of knowledge on linkages between soil health, with particular respect to U.S. agricultural soils, and human health and prepare a report describing the potential to increase the human health benefits from microbial resources in the soil.

In the course of its review, the committee will identify current research efforts and examine scientific findings on such topics as:

- Relationships between the human microbiome and soil microbiome including the plant microbiome as part of a continuum;
- Linkages between soil management practices and the nutrient density of foods for human consumption and other effects on food;
- Information on soil microbial compounds used in drug development, such as antioxidants, antibiotics, and compounds with anti-cancer properties;
- Information on soil-borne human pathogens and microbial compounds such as toxins;
- Information on the interactions of the soil microbiome with soil contaminants that pose risks to human health; and
- Soil management practices that enhance health benefits and reduce adverse health impacts.

The committee's report will describe key findings and knowledge gaps, identify promising research directions, and offer recommendations for enhancing the human health benefits of the soil microbiome.

The committee reviewed relevant scientific literature as well as written comments provided by the public. All materials submitted to the committee by members of the public were archived in the study's public access file.

Over the course of several months, the committee drafted a report in response to the statement of task. This draft was then reviewed anonymously by experts with knowledge complementary to those serving on the committee. The committee members revised the report on the basis of the reviewers' comments. This process was overseen by the National Academies' Report Review Committee. The report was made publicly available after the Report Review Committee determined that the committee had appropriately addressed the reviewers' comments.

SCOPE AND ORGANIZATION OF THE REPORT

This report is not the first time a National Academies committee has been asked to explore soil health in the context of agriculture. The most direct antecedents include *Alternative Agriculture* (NRC 1989), *Soil and Water Quality: An Agenda for Agriculture* (NRC 1993), *Toward Sustainable Agricultural Systems in the 21st Century* (NRC 2010), and *Science Breakthroughs to Advance Food and Agricultural Research by 2030* (NASEM 2019). These reports all touched on the human health implications of agricultural soil management, but the linkages between soil health and human health were not directly in their remit. Other reports have examined the connection between specific soil management practices (in agriculture and beyond agriculture) and human health.[3] This report reiterates many conclusions and recommendations made in the past reports.

The committee's statement of task also builds on previous National Academies' reports on the microbiome and the technologies that can be used to understand it. In particular, the 2007 report *The New Science of Metagenomics* presaged the opportunities of new technologies to understand microbial life (NRC 2007). This report is the first by the National Academies to focus explicitly on the microbial life in soil since the -omics revolution.

Given the emphasis placed on the soil microbiome in the statement of task, the committee devoted substantial discussion in Chapter 2 to the biological properties of soil, the microbial diversity found in soil, and the interactions between soil microbial communities and plant microbial communities. This discussion is placed within a wider context of the importance of soil in the objectives of One Health and the influence that global change events, such as land use change and global warming, have on soil properties (lower right corner of Figure 1-1).

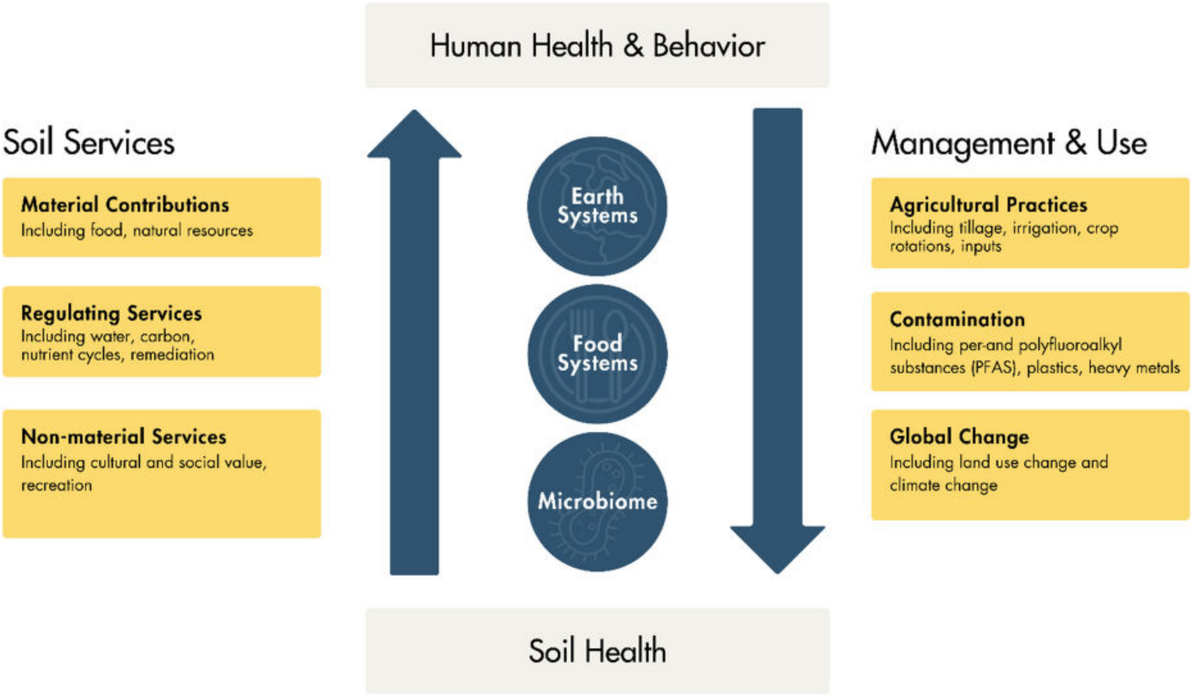

FIGURE 1-1 Soil health, its connection to ecosystem services and human management and use, and its interaction with earth systems, food systems, and the microbiome.

The statement of task asked the committee to examine linkages between soil management practices and the nutrient density of foods as well as how these practices could enhance human health benefits and reduce adverse health impacts. Therefore, Chapter 3 reviews the contributions that soil makes to human health in terms of the ecosystem services it provides. These include material and nonmaterial contributions as well as regulating services, such as water filtration and carbon cycling (left side of Figure 1-1). Interpreting soil management

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[3] See, for example, *Use of Reclaimed Water and Sludge in Food Crop Production* (NRC 1996), *Biosolids Applied to Land* (NRC, 2002), and *Bioavailability of Contaminants in Soils and Sediments* (NRC 2003).

practices to involve those related to crop agriculture, the committee describes the effects of agricultural management practices on soil health in Chapter 4. Tillage, irrigation and drainage, crop choice and land cover, synthetic fertilizer use, organic soil amendment application, and pesticide use are specifically reviewed (top right corner of Figure 1-1). This chapter also reviews indicators used to assess soil health. This discussion of agricultural management practices then sets up the exploration in Chapter 5 of the evidence for the linkages between agricultural management practices and the nutrient density of food. It also examines how food-processing technologies and consumer dietary choices complicate efforts to trace a line from healthy soil to healthy food.

Soil-borne human pathogens are numerous and not limited to agricultural settings. The committee did not deal with them extensively. Soil-borne human pathogens merit their own treatment, but they are not directly relevant to agricultural management practices in farming systems, aside from those that cause food-safety issues. The effects of agricultural management practices and soil health on food-borne pathogens and mycotoxins are addressed in Chapter 5.

Similarly, the committee recognizes that human health is affected by chemical contaminants found in soil through exposure in situations other than agricultural settings or food consumption and that agricultural management practices are not the only source of soil contaminants. Soil contamination has been addressed by the National Academies in previous reports (NRC 1996, 1997, 2003, 2005). In this report, the committee limits its analysis, for the most part, to examples of heavy metal contaminants that may affect human health through food consumption in Chapter 6. Microplastics and per-and polyfluoroalkyl substances (PFAS) are also reviewed as they are emerging contaminants of soils (middle right of Figure 1-1). However, the committee notes that these emerging contaminants are ubiquitous in households and in the environment and that soils are not the only route of exposure.

The field of microbiome science is rapidly advancing. Chapter 7 looks at what the tools available today can reveal about the soil microbiome, the human microbiome, and connections between the two. It identifies the steps needed to turn the immense amount of data available about microbiomes into actions to improve soil health and human health. Chapter 8 summarizes the committee's conclusions and recommendations for research directions.

The committee recognizes that agriculture in the United States is comprised of diverse farming systems that exist in a variety of soil types in different scales, climates, and topographies. It is not possible for the committee to address agricultural management practices for all systems or all crops. Therefore, this report is primarily concerned with soil health in larger cropping systems. Urban agriculture is addressed briefly in Chapter 4; however, the issues of soil health and its relationship to human health in urban agricultural systems and in urban soils generally in the United States are unique enough to deserve their own treatment. Similarly, soil health in forage systems is discussed in Chapters 4 and 5, but livestock and pasture systems are not covered extensively. The committee also is aware that soil management practices can have adverse effects on human health for those who work with soil (e.g., farmers, farm workers, and landscapers), but this report does not address occupational health concerns.

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2
The Connectivity of Health

The interdependence of the health of humans, other animals, and ecosystems has long been apparent. The written record includes observations by Hippocrates and Aristotle of the connections between human health and the health of the environment and between human disease and that of other animals, respectively (Evans and Leighton 2014). In the last three centuries, the recognition that maintaining health in humans, other animals, and ecosystems "constitute[s] a single objective, because to achieve all three at once is the only means of achieving any one of them" has steadily gained traction in academic, scientific, and political institutions (Evans and Leighton 2014, 414). Over the course of the 20th century, increasing awareness among scientists, conservationists, and policy makers of the need to address health collectively and holistically resulted in a series of meetings in the late 1990s and early 2000s that led to the coining of the term One Health in 2004 (Cook et al. 2004; Gibbs 2014).

One Health has been defined many ways in the subsequent years. In 2021, the Food and Agriculture Organization (FAO), the World Organisation for Animal Health (WOAH, founded as OIE), the World Health Organization (WHO), and the United National Environment Programme (UNEP) endorsed the following interpretation of the concept:

> One Health is an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals, and ecosystems. It recognizes the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and interdependent.
>
> The approach mobilizes multiple sectors, disciplines, and communities at varying levels of society to work together to foster well-being and tackle threats to health and ecosystems, while addressing the collective need for healthy food, water, energy, and air, taking action on climate change and contributing to sustainable development. (OHHLEP 2022, 2)

This definition captures the multitude of organisms whose health needs to be maintained. It also acknowledges the importance of the health of Earth itself, as functional Earth processes are fundamental to sustaining an environment that can support life with clean water and air and with an adequate food supply.

Attention to the health of Earth—to local, regional, and planetary environmental systems—within the pursuit of One Health is overdue (Barrett and Bouley 2015). In 2010, FAO, WOAH, and WHO came together to publish a Tripartite Concept Note that proposed "a long-term basis for international collaboration aimed at coordinating global activities to address health risks at the human-animal-ecosystems interfaces" (FAO, OIE, and WHO 2010). Although ecosystems were mentioned, the document and subsequent work of the three organizations focused heavily on the control of diseases, especially diseases that move from animals to people (Gibbs 2014). It was only in 2022 that UNEP joined the others to establish the Quadripartite Collaboration for One Health, "reaffirming the importance of the environmental dimension of the One Health collaboration" (FAO et al. 2022, 1). That year, the Quadripartite Organizations published a joint plan of action "to drive the change and transformation required to mitigate the impact of current and future health challenges at the human–animal–plant–environment interface at global, regional and country level" (FAO et al. 2022, x).

Integrating the environment into One Health is one of the six tracks within the action plan. In the plan, the Quadripartite Organizations acknowledge that:

> The environmental sector, which consists of areas such as natural resource management, wildlife management and conservation, biodiversity conservation, management and sustainable use, pollution and waste management, is not always routinely incorporated into the One Health approach and there has been limited engagement in cross-sectoral initiatives. The role of the environmental determinants of health has not been well understood by other sectors and there is good potential to integrate environmental considerations more consistently" (FAO et al. 2022, 11)

Of the many poorly understood and unintegrated components of "the environmental sector," perhaps the most neglected among them is soil (Singh et al. 2023). When it comes to the effect of soil on the health of other organisms, the joint plan of action only discusses the need to address chemical contamination of soil. Yet, the biological, chemical, and physical health of soil is integral to the balanced and optimized health of people, other animals, and ecosystems beyond just the mitigation of contaminants. Leonardo da Vinci is credited with saying "We know more about the movement of celestial bodies than the soil underfoot," an observation that is still true five centuries later. This chapter briefly describes the fundamental role soil plays in the pursuit of One Health and the impact land use change has had on soil's ability to contribute to One Health objectives. It then describes the properties of soil that define soil health. Components of the definition of human health are also reviewed. The importance of microbiomes as a conduit between soil health and human health are highlighted in the last section.

SOIL AND ONE HEALTH

Attention to the state of soils is essential to the objectives of One Health. Healthy ecosystems cannot exist without soils that successfully contribute to Earth's biogeochemical cycles, which move the atoms of key elements between living and non-living things and make life possible. Many of these cycles are reliant on the organisms that live in soil. People, other animals, and plants depend on the products generated by these cycles and organisms (see Chapter 3 for further discussion). When these cycles are functioning properly, soil and the organisms that live in it contribute to the One Health objectives of optimizing the health of all organisms while supplying clean air and water and supporting the production of food.

However, the state of soils today suggests that their ability to contribute to One Health objectives is impaired. It is estimated that at least 15 percent of Earth's land surface suffers from human-induced soil degradation, largely caused by erosion, nutrient loss, salinization, pollution, and compaction (Oldeman et al. 1991). Much of that degradation is due to the conversion of wildland from native ecosystems into managed agricultural systems (Box 2-1).

BOX 2-1
Land Use Trends

Land use management regimes—from natural landscapes to managed forests, cropland, and rangeland to urban environments—profoundly influence soil health. On the one hand is the historical and ongoing degradation of soil quality, which threatens to undermine soil ecosystem services critical to One Health such as food production, habitat provisioning, contaminant remediation, climate regulation, and the cycling of nutrients, carbon, and water (see Chapter 3). On the other hand, changes from soil-degrading land uses to those that preserve and protect the soil have the potential to preserve or build soil health and sequester carbon (Guo and Gifford 2002; Lal 2004; Borrelli et al. 2017), holding significant potential to enhance agricultural sustainability and food security and contribute to climate change mitigation (IPCC 2022).

Agriculture is by far the most extensive form of human land management. Currently, over one-third of global land area—roughly half of all habitable land on the planet—is used for agriculture (Ellis et al. 2010; Ritchie and Roser 2013; FAO, UNEP, WHO, and WOAH 2022). The same is true for the United States: agricultural use accounts for more than one half of the land (Figure 2-1; Bigelow and Borchers 2017). Conversion of wildland from native ecosystems into managed agricultural systems increased sharply during the 18th–20th centuries both globally and in the United States (Ellis et al. 2010; Klein et al. 2017). Although in recent decades this conversion has slowed or even reversed in some regions of the world (including in the United States), significant expansion of agricultural land continues in some places, notably parts of South America and Africa (Ritchie and Roser 2013, Klein et al. 2017).

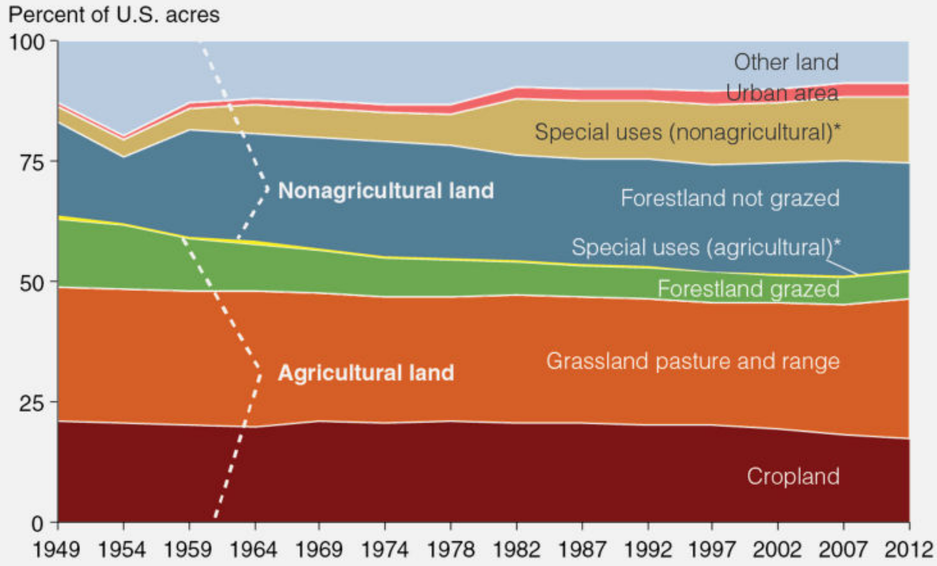

FIGURE 2-1 Major U.S. land uses, by percent of acres, 1949 to 2012.
NOTE: Special uses include rural parks and wilderness areas, rural transportation areas, defense/industrial lands (all nonagricultural uses), and farmsteads/farm roads (agricultural uses).
SOURCE: U.S. Department of Agriculture–Economic Research Service. "Major Land Uses in the United States, 1949–2012." Accessed April 26, 2024. https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=58260.

continued

BOX 2-1 *continued*

Such historical and ongoing land use change has significant implications for soil health. In temperate regions, conversion from natural to agricultural systems has been observed to cause depletion of the soil organic carbon pool—an important indicator of soil health—by as much as 60 percent, with losses sometimes exceeding 75 percent in tropical regions (Guo and Gifford 2002; Lal 2004). Land use change is also associated with an acceleration in soil erosion and subsequent topsoil loss, with rates of loss from agricultural lands now frequently exceeding natural rates of soil formation, making this a major concern for global food security (Pimentel and Burgess 2013; Borrelli et al. 2017).

Within the broad classification of agricultural land use, management systems vary widely and include cropland, pasture, rangeland, and grazed forest uses. Approximately one third of U.S. agricultural land—392 million acres in 2012—is cropland (Figure 2-1; Bigelow and Borchers 2017). This category of land use is most frequently subjected to tillage, irrigation, and soil amendments, and the intensity of these management practices can vary greatly across cropping systems and have significant bearing on soil health (see Chapter 4). When land use is viewed through the lens of human health—specifically human dietary health—it is notable that the vast majority of U.S. cropland is currently devoted to growing crops such as corn and soybeans used principally for animal feed, yet projections for diets that are both sustainable and healthy indicate a need to reduce the proportion of animal-sourced foods in the American diet while increasing intake of nutrient-rich plant-based foods such as whole grains, pulses, fruits, nuts, and vegetables (Bigelow and Borchers 2017; Willett et al. 2019). Despite the importance of dietary diversity to human health, only 2 percent of U.S. cropland is currently used to grow fruits and vegetables (Bigelow and Borchers 2017; USDA–NASS 2019). Prevailing U.S. vegetable cropping systems are typically high intensity, receiving frequent tillage, irrigation, and relatively high levels of inputs, and managing soil health in such systems presents notable challenges. In combination with their relatively minor land use footprint, there has been a dearth of research and practical management strategies that promote soil health in vegetable cropping systems (Norris and Congreves 2018). Yet, as land used for vegetable cropping increases to support human health via dietary diversity, the soil health of these systems will be of increasing importance, underscoring the connectivity of soil health and human health via land use.

Urbanization is another form of land use change that is important when considering the links between soil health and human health. Urban area accounts for 3 percent of total U.S. land (Bigelow and Borchers 2017). According to the U.S. Census Bureau, as of 2020, 80 percent of the U.S. population now resides in urban areas, which they define as “densely developed residential, commercial, and other nonresidential areas” (U.S. Census Bureau 2022). Urban soils are intensively managed and used for recreation, gardening, and many other purposes, and they provide ecosystem services such as soil filtration (De Kimpe and Morel 2000). Urban soils have distinctive properties, such as higher levels of heavy metal contamination, even in soils within urban forest stands (Pouyat et al. 2008).

The global pattern of conversion holds true for the United States. Between the 1780s and 1980s, more than 50 percent of the wetlands in the conterminous United States were lost, mostly due to agricultural conversion (Dahl 1990). The loss of wetland soils’ contributions to One Health—for example, the cleaning of water through filtration—has been amplified by other degradations linked with agricultural production. The excess application of nitrogen to U.S. agriculture fields increases crop yields but directly works against the One Health objectives of clean air and clean water by contributing to air and water pollution (Ribaudo et al. 2011). Soil’s fertility—that is, its part in addressing the collective need for healthy food—as well as its ability to serve as a filter for contaminants can be altered by the accumulation of pesticides, metals, plastics, and other compounds (Wang et al. 2022; Rashid et al. 2023).

Although U.S. agriculture continues to provide abundant food, the degradation of U.S. agricultural soils due to erosion, compaction, biodiversity loss, mineralization of soil organic matter, and contamination has highlighted the urgent need to ensure that soil function is maintained for food production and other One Health objectives. The next section reviews the different properties of soil that contribute to soil function, which, when maintained, defines soil health.

SOIL HEALTH

Terms used to describe the state of soil have proliferated in the field of soil science as researchers and stakeholders have debated definitions that vary in the weight given to static properties versus dynamic ones (e.g., soil texture versus organic matter content), reflect a point of view (e.g., soil scientist versus farmer), or place a system of interest in context (e.g., agricultural versus unmanaged) (Bünemann et al. 2018; Lehmann et al. 2020). The committee uses the term *soil health* as it is the term in current use by the study's sponsor and the term used in the statement of task.

FAO defines soil health as "the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems" (FAO 2020). To achieve this ability, healthy soil should possess important characteristics such as good structure, nutrient availability, water-holding capacity, and biological activity. These characteristics depend on the interaction of a soil's physical, chemical, and biological properties (Figure 2-2). Soil properties are heavily influenced by the parent material from which the soil formed (e.g., mineral rock or organic matter), the organisms living in the soil, and the topography and climate of the soil's location as well as the interaction of all these factors over a period of time. Therefore, soil health is highly context dependent.

Soil physical properties include its texture (the size of soil particles) and structure (how closely and in what shape soil particles are bound or aggregated) (Brady 1984). These features relate to a soil's porosity (the volume of space within soil for air or water) or, conversely, its compaction. Porosity in turn affects the extent to which water can infiltrate and permeate the soil. Thus, physical properties influence the amount of water held within soil pores and a soil's vulnerability to erosion. Of particular interest in terms of agriculture, soil physical properties affect the ease with which plant roots can grow and access soil water and the ease with which seedlings can emerge. Soil temperature also influences plant growth and soil respiration, that is, the release of carbon dioxide (CO_2) from the soil.

Every soil has a pH, that is, a degree of acidity, alkalinity, or neutrality. The soil pH affects the amount and availability of plant nutrients, the solubility and motility of heavy metals, microbial growth and diversity, and the soil's cation exchange capacity (CEC) (Brady 1984). CEC involves the smallest soil particles, colloids, which are formed from weathering and subsequent chemical processes. Colloids can be organic or inorganic and contain a mix of positively or negatively charged exchange sites that can attract negatively or positively charged particles, respectively. Generally, agricultural soils have an overall negative charge that allows them to mostly attract and hold on to positively charged particles, or cations, and mostly repel negatively charged ones, or anions. The degree to which a soil can attract and hold cations is its CEC, while a soil's ability to attract and hold anions is its anion exchange capacity. Both are regulated by soil properties such as clay content and clay type, soil organic matter levels, and soil pH. Particles that are repelled into the soil solution are available for plant roots and microbes to access and readily take up. CEC and other soil properties such as mineral nutrients, organic matter content, and soil extracellular enzyme activities can offer insights into the biochemical properties of soil.

The biological properties of soil consist of the life found within it. Soil is one of the largest reservoirs of biodiversity on Earth and home to 59 ± 15 percent of all species (Fierer 2017; Anthony et al. 2023). Mammals, plants, and millions of much smaller organisms found in soil (Figure 2-3) all contribute to the biological properties.

Biological processes are responsible for most of the functions that are integral to soil health. Soil megafauna and macrofauna—for example, moles, earthworms, and arthropods—burrow through soil, creating pore space and decomposing and redistributing organic matter through bioturbation (Menta 2012). The cutaneous mucous of earthworms and mollusks adds stability and structure to soil (Menta 2012). Soil arthropods regulate biological populations, nutrient cycling, and decomposition (Setälä and McLean 2004). Certain soil arthropods and nematodes (a phylum of roundworms) prey on microbial populations and affect processes such as biogeochemical engineering (Bongers and Bongers 1998; Setälä and McLean 2004).

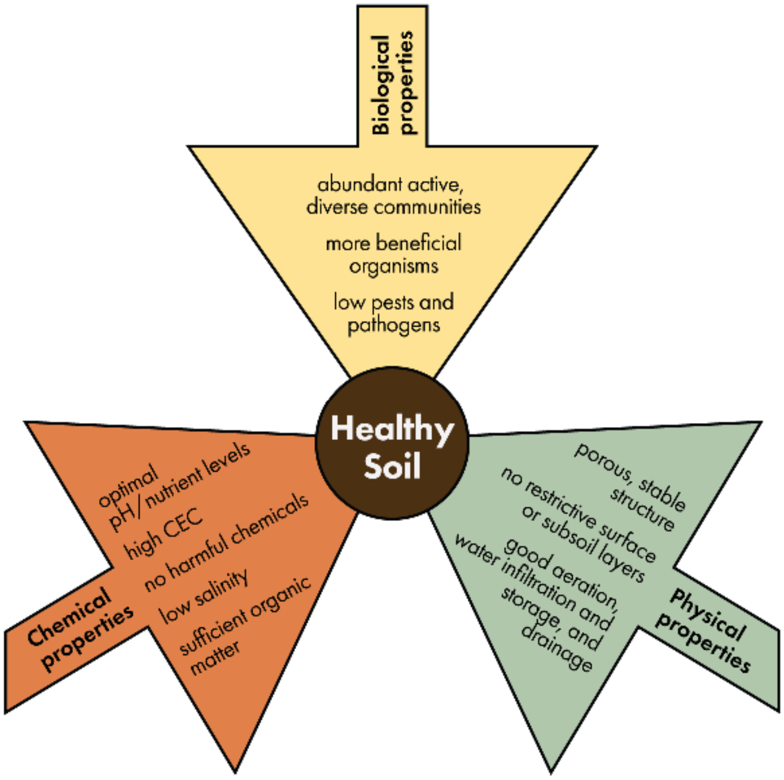

FIGURE 2-2 Optimal physical, chemical, and biological properties that promote healthy soils for cropping systems.
NOTE: CEC=cation exchange capacity.
SOURCE: Adapted from Magdoff and van Es (2021).

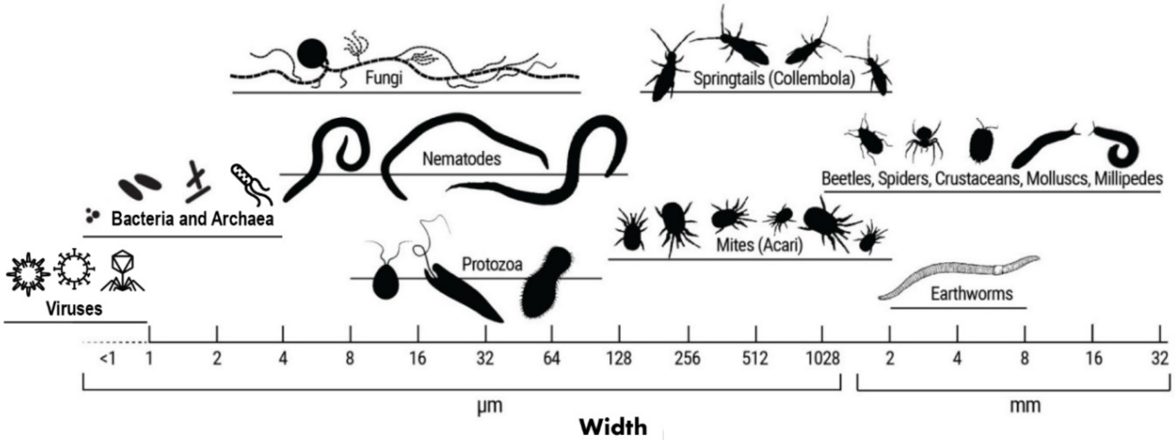

FIGURE 2-3 Soil viruses, microorganisms, and meso- and macrofauna grouped by size.
SOURCE: Adapted from Brackin et al. (2017).

Plants, with approximately half their biomass belowground, also influence soil biodiversity and soil health by exuding carbon compounds for soil biota in the rhizosphere (Steinauer et al. 2016), providing litter for decomposers, and acting as hosts for symbionts, such as mycorrhizal fungi and rhizobia (Bartelt-Ryser et al. 2005). Because different plant species often occupy unique niches and perform different functions, more diverse plant communities have been associated with higher nutrient uptake, soil carbon storage, and ecosystem resilience (Lange et al. 2015). In addition, plants offer a range of habitats to microorganisms in and above the soil. The complex interactions between plants and soil physical, chemical, and biological properties thus shape the soil habitat and biota in a way that affects subsequent plant growth cycles, which is known as plant–soil feedback.

Microorganisms living in the soil—bacteria, archaea, protists, and fungi—punch above their weight in terms of their size in relationship to the role they play in soil processes.[1] Along with driving biogeochemical cycles, bacteria control soil redox, decompose organic matter, and help in disease suppression (Fierer et al. 2012). Knowledge of the presence and diversity of archaea in soil has recently expanded with discovery of archaea engaged in nitrogen fixation, phosphorus solubilization, siderophore production, sulfur cycling, nitrification, and other processes in soil (Naitam and Kaushik 2021). Fungi, including mycorrhizal fungi, decomposers, and many other groups, are important for nutrient cycling (Veresoglou et al. 2012), causing and preventing plant disease, improving plant drought tolerance, and contributing to soil structure formation (Delavaux et al. 2017; Bahram et al. 2018). Protists (which include several groups of protozoa, unicellular algae, and fungi) participate in decomposition, nutrient cycling, soil structure formation, pest and disease control, and many other processes (Geisen et al. 2016). Additionally, the potential role of viruses in soils is just starting to be appreciated. Emerging evidence suggests that these obligate parasites can sustain soil biodiversity and influence a range of processes including nutrient cycling, carbon dynamics, and plant health (Liang et al. 2024).

Few species of soil biota act alone; instead, most are intimately interconnected in complex food webs. Their interactions—including predation and parasitism, cooperation and

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[1] The committee considered soil microorganisms to consist of living microorganisms in the soil, per discussion found in Berg et al. (2020). Further discussion of this term in relation to the microbiome is found below in the section "Microbiomes and One Health."

symbiosis, and competition (Scheu 2002; Thakur and Geisen 2019)—affect nutrient cycling, plant health, and overall ecosystem functioning.

Soil organisms' distribution and access to nutrients is very much shaped by their physical environment, for example, aggregation and pore size (Erktan et al. 2020; Hartmann and Six 2023), and by soil pH (Crowther et al. 2019). Soil organisms, in turn, help construct their habitat by binding soil particles with extracellular polymeric substances and hyphae into stable aggregates (Rillig and Mummey 2006), creating pores and channels (Lavelle et al. 2016), and providing microenvironments for building soil organic matter (Figure 2-4; Six et al. 2004). Thus, all the properties of soil work together to complete the picture of soil health.

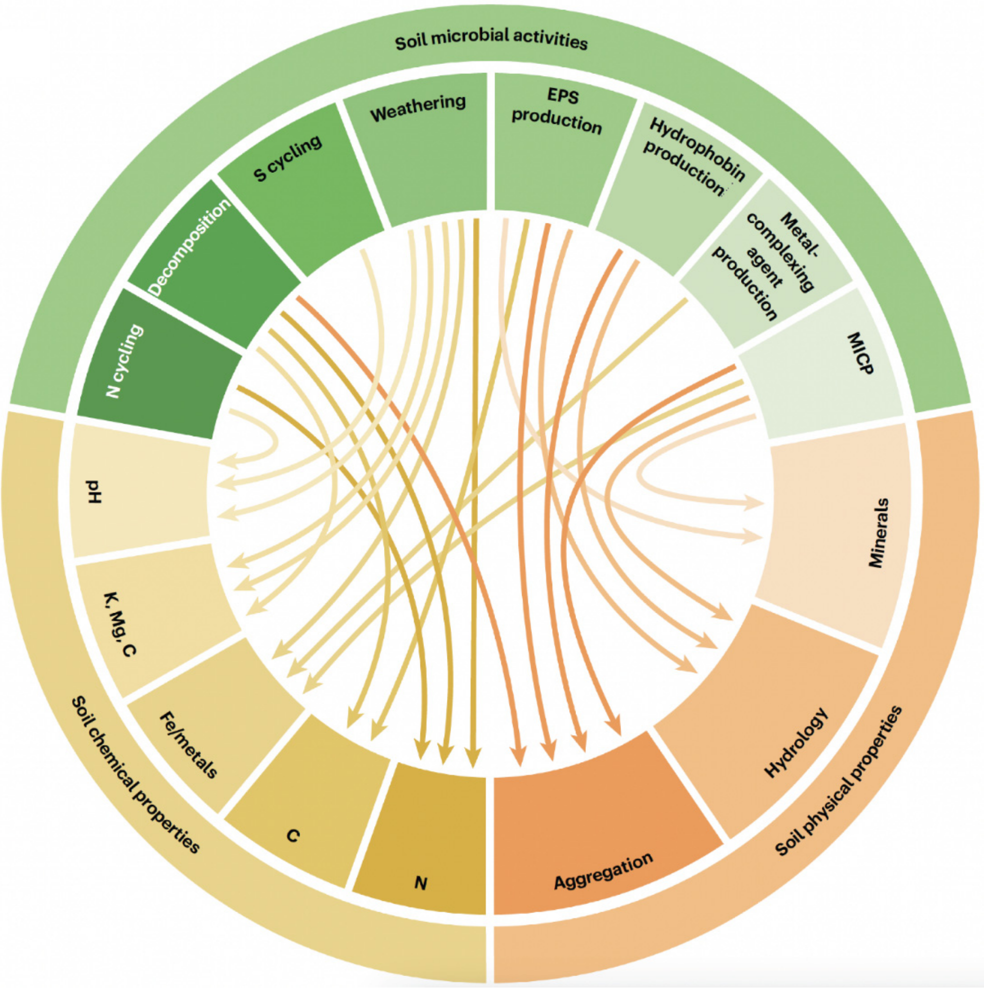

FIGURE 2-4 The various microbial processes affecting soil chemical and physical properties.
NOTES: Green=various microbial processes. Yellow=soil chemical properties. Orange=physical properties. The color of the arrow indicates the affected soil properties. EPS=extracellular polymeric substance. MICP=microbially induced carbonate precipitation.
SOURCE: Used with permission of Springer Nature BV, from "The Interplay Between Microbial Communities and Soil Properties", Philippot et al., *Nature Reviews Microbiology*, 2023; permission conveyed through Copyright Clearance Center, Inc.

Soil health is not uniform. Because the physical, chemical, and biological properties of soil vary by geography, topography, and parent material, all soils can meet the definition of soil health to sustain productivity, diversity, and environmental services even if they are extremely different in composition from one to the next. Whether a soil meets the definition of soil health depends, in large part, on human activities at the local scale (e.g., management practices in agricultural systems, Chapter 4) and at the global scale (e.g., climate change, Box 2-2).

HUMAN HEALTH AND WELLNESS

The One Health concept posits that as the health of one system or organism suffers, the health of humans is also adversely affected. How the state of soil health affects human health is the question of interest in this report. However, as with soil, health and wellness in humans have many facets.

BOX 2-2
Climate Change and Soil Health

Climate affects the multiple and coupled physical, chemical, and biological processes involved in soil health through changes in atmospheric carbon dioxide (CO_2), temperature, and precipitation patterns (FAO 2015; Talukder et al. 2021). Higher CO_2 levels enhance plant photosynthesis and carbohydrate production, leading to increased carbon deposition in the root zone, which in turn affects the biological processes that govern the soil carbon cycle (Preece and Peñuelas 2016; Toreti et al. 2020; Sun et al. 2021; Usyskin-Tonne et al. 2021). Consequences of these shifts include alterations in coupled biogeochemical cycles such as increases in rates of nitrogen mineralization and cycling (Wardle et al., 2004; Horwath and Kuzyakov 2018). Climate change is significantly intensifying the frequency and severity of droughts in soils, with rising global temperatures contributing to increased evaporation rates, decreased soil moisture, and altered precipitation patterns (Trenberth 2011). Extreme floods and droughts cause significant soil erosion and degradation, affecting the soil's ability to store carbon and support plant growth (FAO 2015), and more generally, agricultural productivity and ecosystem health (Dai 2011; Cook et al. 2014). While droughts reduce soil moisture, affecting plant growth and soil microbial activity, excessive rainfall can result in soil erosion and nutrient leaching and degrade soil structure (Doran and Zeiss 2000; Lal 2020). Changes in weather patterns vary regionally, with some areas facing more intense and prolonged droughts, and others experiencing increased precipitation (Sheffield and Wood 2011), thus highlighting the complexity of climate change impacts on soil health.

Shifts in atmospheric CO_2 levels, temperature, and precipitation patterns caused by climate change also affect the soil microbiome (Rillig et al. 2019; Zhou et al. 2020). Elevated CO_2 can enhance plant growth, thus increasing and/or changing root exudates and plant residues, which in turn influence microbial diversity and function (Cavicchioli et al. 2019). Temperature shifts directly affect rates of microbial metabolism; warmer temperatures typically accelerate microbial activity, decomposition, and potentially greenhouse gas (GHG) emissions (Classen et al. 2015; Jansson and Hofmockel 2020). Furthermore, precipitation determines soil moisture, crucial for microbial survival and activity (Classen et al. 2015). Changes in soil water—such as saturation during flooding or desiccation during droughts—profoundly shift microbial community structure and nutrient cycling dynamics, with cascading effects on carbon storage, GHG emissions, and soil food webs. Climate change−induced alterations in the soil microbiome directly translate into changes to soil health, nutrient availability, and overall ecosystem functioning, underscoring the importance of understanding these interactions in the context of global climate change (Cavicchioli et al. 2019; Jansson and Hofmockel 2020).

In 1948, the World Health Organization (WHO) amended its constitution to define health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (WHO 1992). This definition was groundbreaking at the time because it shifted the emphasis to a positive state of wellbeing that included physical, mental, and social domains (Figure 2-5). Although it is still in use today, this definition of health has been criticized because it is difficult to delineate and maintain a "complete" state of well-being (Huber et al. 2011). For example, with technology, thresholds for disease diagnosis and intervention have changed, making it easier to identify earlier stages of disease that may not have previously been identifiable or impactful. Moreover, patterns in the global burden of disease have shifted from acute infectious conditions to higher rates of noncommunicable chronic illnesses.

Some groups have therefore advocated for a shift toward a conceptual framework of health that emphasizes social and personal resources in addition to physical capacity that enables individuals to adapt and self-manage. The Ottawa Charter, an international agreement signed at the First International Conference on Health Promotion organized by the WHO in 1986, states that health is "a resource for everyday life, not the objective of living" (WHO 1986). In this conceptualization, health promotion moves beyond the health sector to include fundamental conditions and resources for health—that is, peace, shelter, education, food, income, a stable ecosystem, sustainable resources, social justice, and equity. It is notable that multiple One Health objectives related to soil health, including food (see further discussion in Box 2-3), a stable ecosystem, and sustainable resources, are among the fundamental conditions and resources for health defined by the WHO Ottawa Charter.

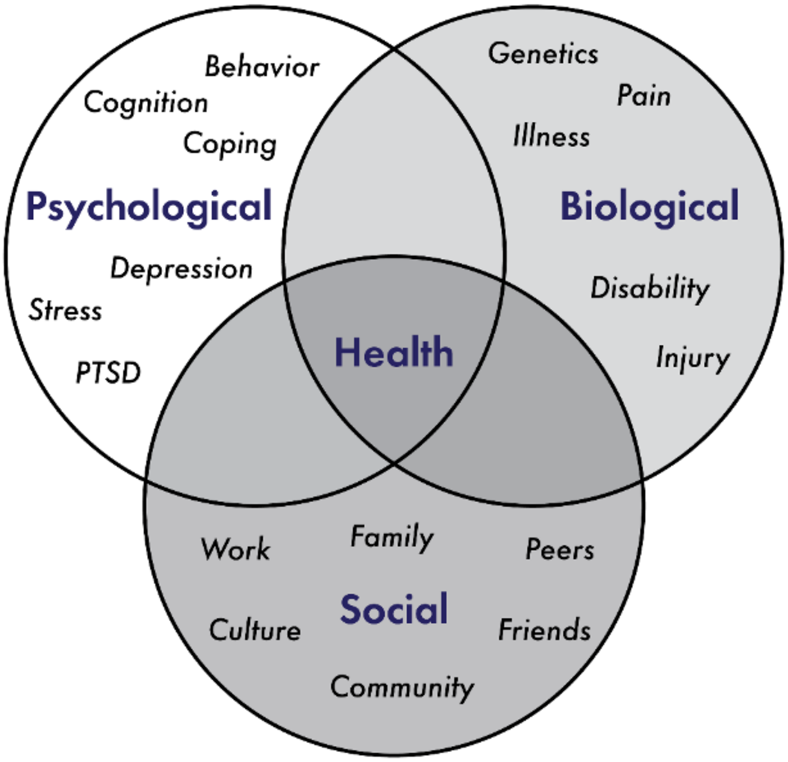

FIGURE 2-5 A biopyschosocial model of health and illness.
SOURCE: Bolton et al. (2018). Reprinted by Permission of SAGE Publications.

BOX 2-3
Food as a Prerequisite for Health

Food is one of the WHO's prerequisites for health. Presumably, the charter authors intended food as a resource for health to be safe, available, affordable, and nutritious. Food security is a state of adequate and consistent access to foods that sustain health and well-being (Coleman-Jensen et al. 2021). While food quantity is a primary component of food security, other dimensions including nutritional quality, food safety, and suitability to dietary preferences are equally important. Further, a state of food security ensures that foods are accessed in socially acceptable ways, free from psychological burden. The dimensions of availability, access, and utilization are recognized.

Food security is deeply intertwined with nutrition access. Usher (2015) developed a framework for this concept that includes acceptability, accessibility, accommodation, affordability, and availability as dimensions of access. This model postulates that true access to healthy foods should account for acceptable interactions between consumers and retailers (acceptability); healthy foods being accessible in terms of location, mode of transportation, and distance (accessibility); compatible hours during which healthy foods can be purchased (accommodation); pricing that is compatible with household income level and food assistance resources (affordability); and healthy foods being available in sufficient quantity and variety (availability). It is important to account for potential discrepancies between observed metrics of nutrition access, such as food retailer density, and perceived nutrition access.

Food and nutrition insecurity lead to increases in infectious and cardiometabolic disease risk among adults (Seligman and Schillinger 2010; Seligman et al. 2010; Berkowitz et al. 2014; Seligman and Berkowitz 2019; Myers et al. 2020). The long-term health impacts of food insecurity in childhood later in life are not yet fully understood (Te Vazquez et al. 2021). In 2022, the prevalence of U.S. households with food insecurity (combining low and very low food security) was 17.3 percent (44.2 million people, including 7.3 million children) (Figure 2-6). This burden is not experienced equally across the whole population. Whereas poverty is the primary underlying cause of food insecurity (Laraia et al. 2017), other household and individual characteristics are strongly associated. The risk for food insecurity is higher among households with children and with women as the primary income earner, older adults, racial/ethnic minorities, Southern states, rural areas and inner cities, and individuals with mental disabilities.

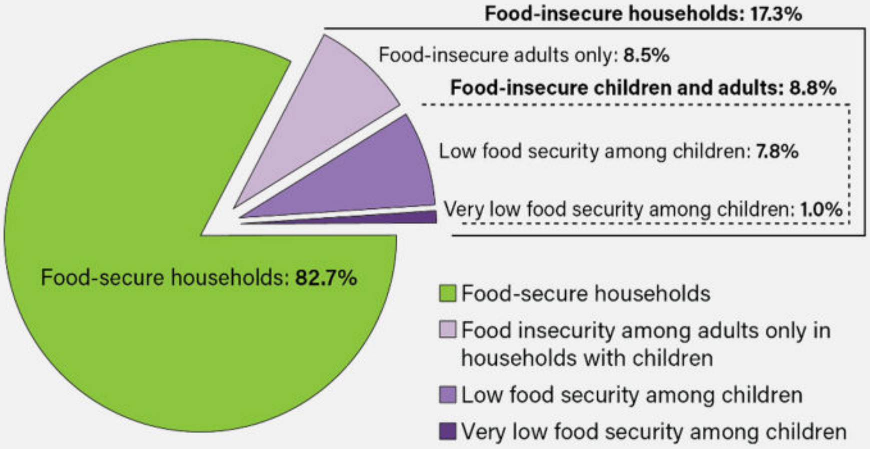

FIGURE 2-6 U.S. households with children by food security status of adults and children, 2022. SOURCE: U.S. Department of Agriculture–-Economic Research Service. "Food Security in the U.S., Key Statistics & Graphics." Accessed April 29, 2024. https://www.ers.usda.gov/topics/food-nutrition-assistance/food-security-in-the-u-s/key-statistics-graphics/.

Health Equity

The WHO constitution states that "the enjoyment of the highest attainable standard of health is one of the fundamental rights of every human being without distinction of race, religion, political belief, economic or social condition." Health equity means that everyone has an opportunity to be as healthy as possible. To achieve this, health disparities must be identified and addressed. A health disparity or inequity has been defined as a particular type of difference in health in which disadvantaged social groups—such as those living in poverty, racial or ethnic minorities, women, or other groups who have persistently experienced social disadvantage or discrimination—systematically experience worse health or greater health risks than more advantaged social groups (Braveman 2006). Measurement of health disparities therefore requires an indicator or modifiable determinant of health, an indicator of social position or way of categorizing people into different groups, and a method for comparing the health or health determinant indicator across groups.

Social Determinants of Health

Social determinants of health are the non-medical factors that influence health outcomes across the lifespan (Figure 2-7). They include the physical environment (see Box 2-4) but also the economic policies and systems, social norms, social policies, and political systems that shape daily life. Social determinants of health can be even more important than health care in ensuring a healthy population and contribute to a relatively large proportion of inequities in health (Bunker et al. 1994). There is often a tendency to focus on how individual behaviors, such as diet, smoking, and alcohol, lead to health inequities and ignore the upstream drivers of these behaviors—the causes of the causes. Healthy People 2030 groups social determinants of health into five domains: economic stability (which includes a focus on food security and healthy eating), education access and quality, health care access and quality, neighborhood and built environment, and the social and community context (U.S. Department of Health and Human Services n.d.).

MICROBIOMES AND ONE HEALTH

As with soil, microorganisms are not explicitly identified in the definition of One Health. A growing recognition of their importance to the health of ecosystems and organisms and the connective role they play between organisms and between organisms and ecosystems has led to calls for greater visibility within the concept of One Health (Trinh et al. 2018; van Bruggen et al. 2019; Berg et al. 2020; Singh et al. 2023).

Microbiome

Microorganisms interact with each other to form communities, which occupy habitats with "distinct physico-chemical properties" (Whipps et al. 1988). However, microorganisms are not alone in these habitats. Along with the structure and conditions of the environment, microorganisms also affect and are affected by viruses, relic DNA, and metabolites. For example, soil viruses, both those targeting eukaryotic and single-celled microorganisms, are increasingly appreciated for their capacities to alter composition and functioning (Emerson et al. 2018; Albright et al. 2022; Jansson and Wu 2023). Therefore, microorganisms live in a microbiome, which consists of the microbial community, the environment, and microbial structural elements and metabolites with which they interact (Whipps et al. 1988; Berg et al. 2020).

FIGURE 2-7 Social determinants of health.
SOURCE: Healthy People 2030, U.S. Department of Health and Human Services, Office of Disease Prevention and Health Promotion. Accessed November 8, 2023. https://health.gov/healthypeople/objectives-and-data/social-determinants-health.

In addition to existing in a particular environment, studies in recent years suggested that different microbiomes are perhaps interconnected and form a circular loop (Figure 2-8; Singh et al. 2020; Banerjee and van der Heijden 2023; Sessitsch et al. 2023). Microbiomes exist in all eukaryotic organisms and in diverse ecosystems; the committee focused on the microbiomes and connectivity thereof for soil, plants, and humans, as per its charge.

BOX 2-4
Influence of the Environment on Human Health

Environmental health is the branch of public health focused on how the built and the natural environment influence human health. There are many indirect and direct ways in which the environment can influence human health (Barton and Grant 2006). Together, environmental influences can have a large impact on health. Large studies have attributed 15−23 percent of global deaths and 12−22 percent of global morbidity (measured as disability adjusted life years [DALYs]) to environmental risks (Global Burden of Disease Risk Factors Collaborators et al. 2015; Prüss-Ustün et al. 2017).

continued

BOX 2-4 *continued*

Most of the research on environmental factors and health has focused on the impacts of pollutants and chemicals, especially in the air and water. Federal laws in the United States, such as the Clean Air Act and Safe Drinking Water Act, that regulate air and water quality have helped to reduce the harmful health effects of pollutants (Weinmeyer et al. 2017; Nethery et al. 2020), but continued reduction of exposures remains a priority. The U.S. Department of Health and Human Service's Healthy People 2030 initiative specifically lists reduction of exposure to harmful pollutants in soil, in addition to air, water, and materials in homes and workplaces as a key objective (U.S. Department of Health and Human Services n.d.).

There are also data on the health benefits of the natural environment. Living in or near to greener and more biodiverse environments reduces mortality rates and improves mental well-being (Bowler et al. 2010; Haahtela 2019). Some of the effect appears to be related to increased activity levels and social cohesion, and exposure to soil microbes is also likely to play a role (Rook 2013). Microbes in soil, dust, and on foods impact immune system development, function, and even human behavior. For example, early exposure to microbes is likely to promote allergen tolerance (Rook 2013; Ottman et al. 2019).

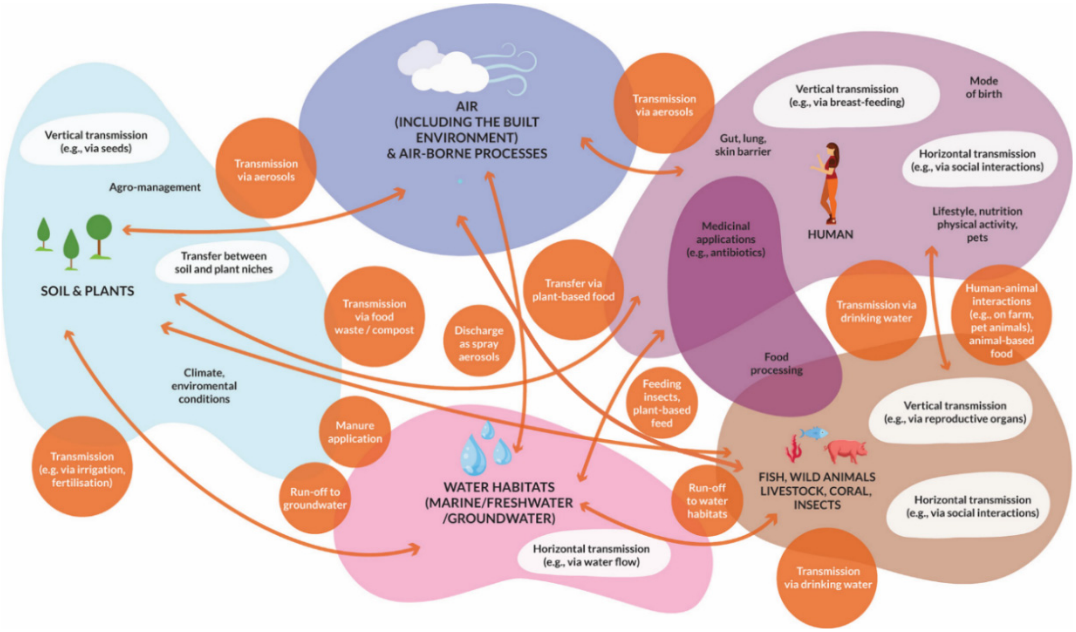

FIGURE 2-8 Microbiome transfer between environments and modes of transfer.
SOURCE: Adaptation used with permission of American Society of Microbiology–Journals, from "Microbiome Interconnectedness throughout Environments and with Major Consequences for Healthy People and a Healthy Planet", Sessitsch et al., *Microbiology and Molecular Biology Reviews* 87 (3), 2023; permission conveyed through Copyright Clearance Center, Inc.

Soil and Plant Microbiomes

Just as soil health does not look the same across soils, there is not one soil microbiome or a soil microbiome archetype (Fierer 2017). Spatial variability can create enough difference in the environment that two samples taken within a foot of each other have different microbiomes (Fierer 2017; Berg et al. 2020). It is estimated that there are, at a minimum, 6 million microbial species that live in soil (Anthony et al. 2023), an estimate that does even not include viruses. As is discussed in Chapter 3, these microorganisms are the workhorses of the biogeochemical cycles on Earth. It is likely that each step in a cycle is carried out by diverse soil taxa working together and that many taxa perform redundant functions. However, precisely which microorganisms do what, with which other microorganisms, and under what conditions is not yet known (Fierer 2017; Singh et al. 2023). What is known is that this abundant diversity in soil microbiomes is critical to optimal function (Singh et al. 2014, Wagg et al. 2021).

This diversity is also critical because soil supplies much of the microbiota to other organisms, including plants (Figure 2-9; van Bruggen et al. 2019; Banerjee and van der Heijden 2023). Plants have their own microbiomes, including the rhizosphere, the root endosphere, and the phyllosphere (van Bruggen et al. 2019; Trivedi et al. 2020). Each sphere is home to a unique microbiome (Edwards et al. 2015; Trivedi et al. 2020; Figure 2-10). For example, the rhizosphere microbiome—the narrow zone of soil close to plant roots and influenced by root exudates—modulates immunity and nutrient acquisition. Rhizosphere communities and soil mutualists (e.g., mycorrhizal fungi) are in part responsible for a plant's tolerance to drought, salinity, nutrient deficiencies, pathogens, and high temperatures (Delavaux et al. 2017; Yang et al. 2018).

Plant roots also harbor a diverse microbiota, including mycorrhizal fungi (fungi that live on or in plant roots) and rhizobia (nitrogen-fixing bacteria that live in legume root nodules). The root endosphere, that is, the microorganisms living within the plant roots, are recruited to the plant from the rhizosphere (Bulgarelli et al. 2015). The response of plant metabolism to stress changes the composition of the microbial community that is recruited (Pepper and Brooks 2021).

The phyllosphere microbiome is found on leaf and stem surfaces. Despite the oligotrophic environment and harsh environmental factors such as high temperature, precipitation, and solar radiation, a thriving microbial community can be seen in the phyllosphere (Vorholt 2012). Studies have found that soil microbial communities are even a source of microbiota to this aboveground microbiome (Trivedi et al. 2020). Thus, soil microbial communities play a critical role in shaping the structure, composition, and functioning of plant-associated microbiota (Fierer 2017).

Human Microbiomes

Similar to plants, animals evolved symbiotic microorganisms, with different body parts comprising distinct assemblages of microbiota (Ley et al. 2008). Compared to about 23,000 genes in the human genome, the number of microbial genes can be over three million, producing thousands of metabolites that shape human immunity, nutrition, growth, and health (Gilbert et al. 2018; Valdes et al. 2018). For example, as many as 100 trillion microorganisms reside in the human gastrointestinal tract (Lozupone et al. 2012). Gut microbes are known to confer fermentation capacities of nondigestible substrates such as dietary fibers and endogenous intestinal mucus, facilitating microbes able to produce short-chain fatty acids and gases. The gut microbiota also influences human health through modulating immune, metabolic, and behavioral traits (Valdes et al. 2018). The oral microbiome is also incredibly diverse and is the second largest microbial community in the human body (Deo and Deshmukh 2019). Remarkably, each part of the human tongue has its distinct microbial community (Wilbert et al. 2020). Other human body parts, such as skin, nostrils, and genital organs, also comprise consistently abundant microbial communities.

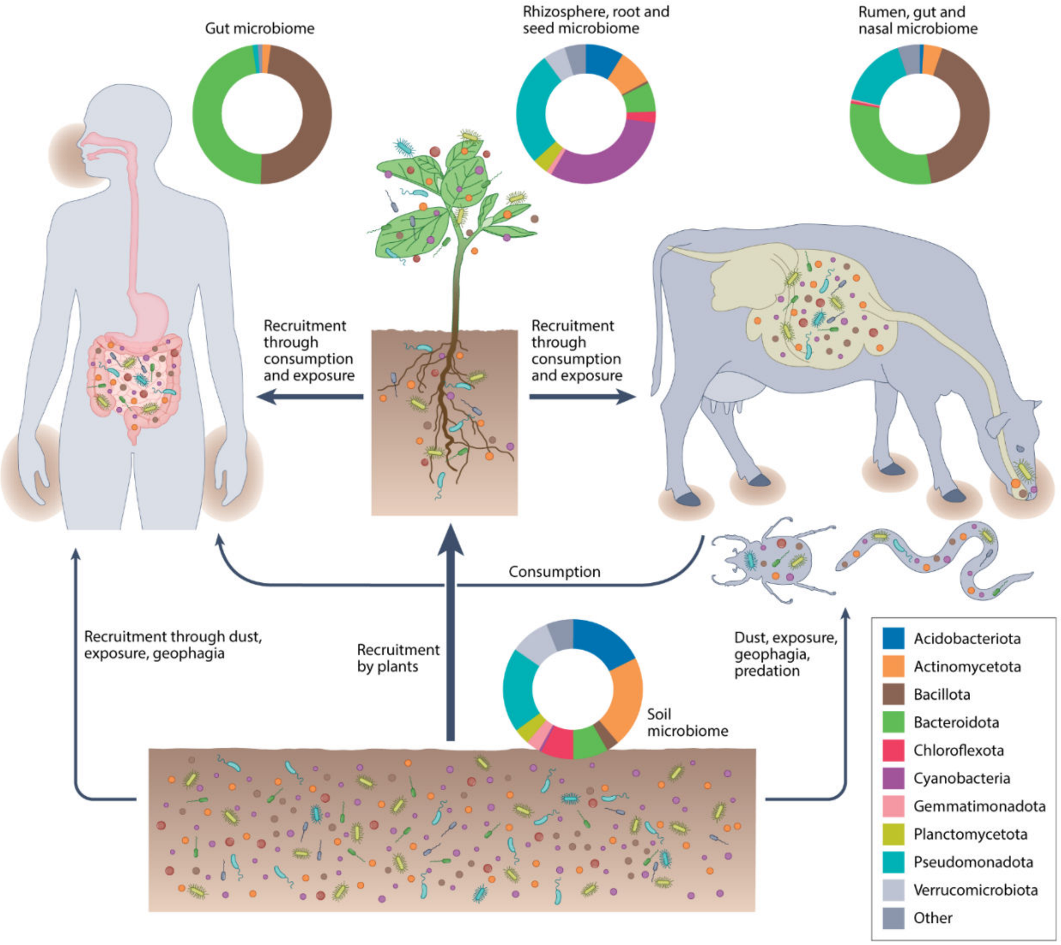

FIGURE 2-9 Soil as a microbial reservoir for plant, animal, and human microbiomes.
SOURCE: Used with permission of Springer Nature BV, from “Soil Microbiomes and One Health”, Banerjee and van der Heijden, *Nature Reviews Microbiology* 21 (1), 2023; permission conveyed through Copyright Clearance Center, Inc.

Microbiomes as a Conduit Between Soil Health and Human Health

Making direct connections between soil health and human health can be challenging. Although similar characteristics can be measured in humans and soils, they also provide evidence of the difficulty in defining healthy soils as well as healthy humans, due to the lack of standards, detectable biomarkers, and comparable metrics in some cases (Table 2-1). One opportunity for solving this challenge is identifying connectivity between microbiomes; however, establishment of microbes in humans from soil and plant microbiomes is still underexplored. Although there seems to be little overlap between the microbiomes of soils and humans, there are compositional and functional similarities between the plant rhizosphere and the human gut microbiome (Blum et al. 2019). As discussed previously and in greater detail in Chapters 4 and 5, soil microorganisms heavily influence plants. How the relationship of soil microbiomes to plant microbiomes may in turn affect human microbiomes is less evident. This ambiguity includes the degree to which agricultural management practices have an effect on the nutrient density of foods.

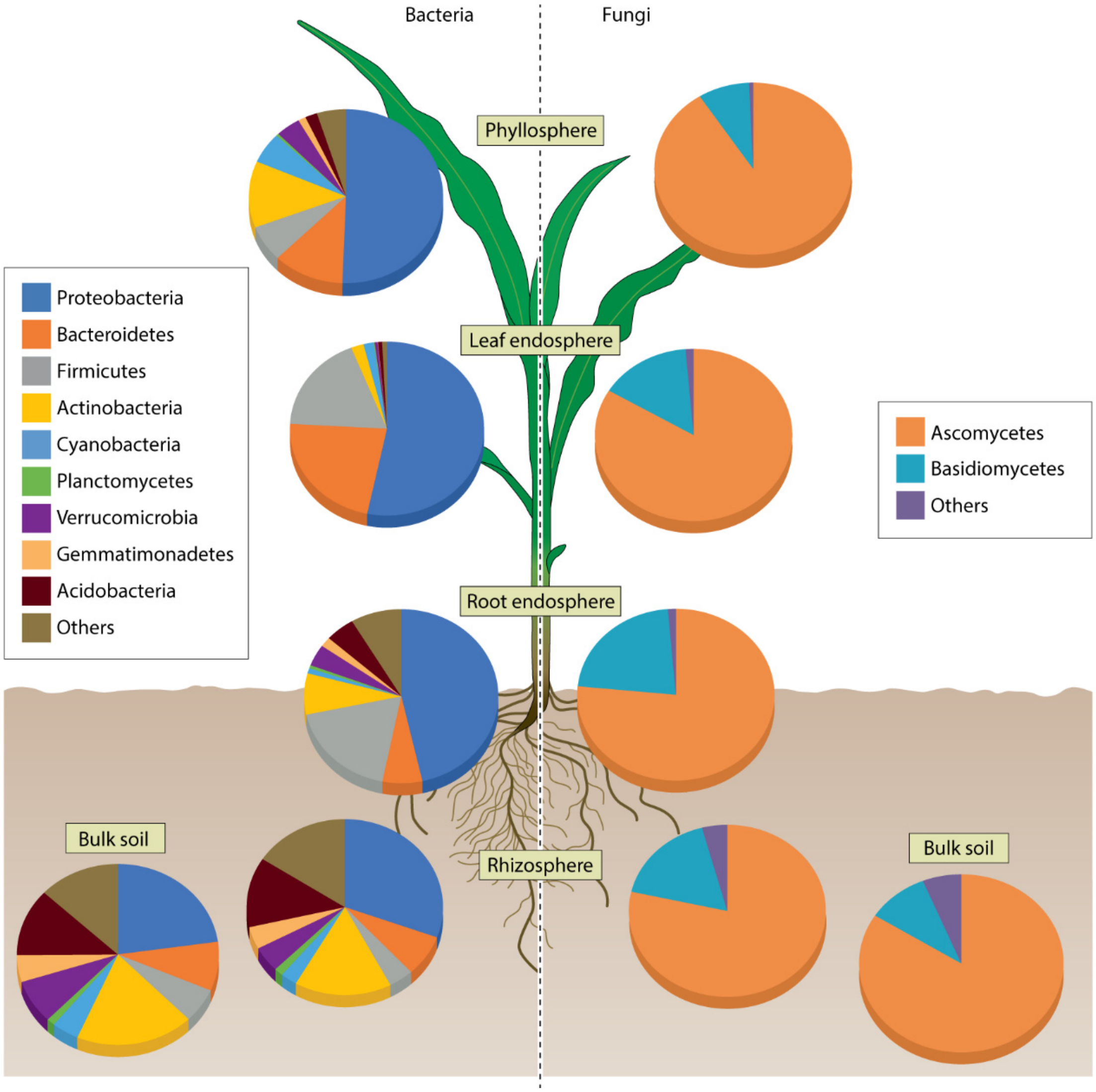

FIGURE 2-10 General structure of the bacterial and fungal communities from various plant-associated traits.
SOURCE: Used with permission of Springer Nature BV, from "Plant-Microbiome Interactions: From Community Assembly to Plant Health", Trivedi et al., *Nature Reviews Microbiology* 18 (11), 2020; permission conveyed through Copyright Clearance Center, Inc.

As the One Health approach is predicated on interdependence, there could perhaps be no more obvious integrator across the health of all organisms than the soil microbiome. The activity (or lack thereof) that occurs within soil microbiomes—for example, nutrient cycling, soil structure, and carbon sequestration—has profound implications for the health of ecosystems and people, including the needs prioritized in the definition of One Health (i.e., healthy food, water, and air and action on climate change; Chapter 3). The ability of microorganisms to suppress plant disease or sorb or breakdown contaminants affects the environmental hazards and soil-borne pathogens to which people may be exposed (Chapters 3–6), and the One Health Joint Plan of Action specifically recognizes pollution and waste management as an area in need of more attention (Chapters 4 and 6). Even though there is much more to learn about the connection between soil health and human health, there is mounting evidence that exposure to environmental microorganisms can have positive impacts on human health, as discussed in Chapter 7. Clearly, greater attention to the activity and health of soil microbiomes would be pragmatic in the pursuit of One Health.

TABLE 2-1 Examples of Measurable Characteristics of Healthy Soils and Healthy Humans

	Soil	Human
Biochemical compositional analysis	Nutrient composition (carbon, nitrogen, phosphorous, potassium), contaminants	Blood tests measuring metabolism, homeostasis, organ function, cell counts
Physical characteristics that can be measured	Depth of topsoil, physical structure of soil	Body temperature, heart rate, blood pressure, autonomic tone, body weight, reflexes
Functional measures of systems and their performance	Water holding capacity, mutualistic and pathogenic organisms, bioaccessibility of nutrients in soil	Mobility, disease, frailty/vigor, cognitive performance, physical strength/performance, cardio-respiratory fitness
Other	Microbiome composition including prospective pharmaceuticals	Microbiome, subjective well-being, pain

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3

The Importance of Soil Health to Nature's Contributions to People

"While the farmer holds the title to the land, actually it belongs to all the people because civilization itself rests upon the soil," Thomas Jefferson once said. These words resonate because the health of soil determines human health through a variety of mechanisms. The linkage that is perhaps easiest to appreciate is the production of food, but soils also filter and regulate the flow of water, including drinking water. In addition, soils provide habitat and nutrients for diverse soil biota, cycle nutrients, and harbor genetic resources that can result in new medicines, including antibiotics (Figure 3-1). Soils are best seen as ecosystems, defined as "a dynamic complex of plant, animal and microorganism communities and their non-living environment interacting as a functional unit" (United Nations 1992, Article 2). Many of the benefits, or services, to humans from those interactions are organized around biogeochemical processes and the various functions carried out by soil biota (Kibblewhite et al. 2008; Smith et al. 2015).

In 2005, the Millennium Ecosystem Assessment (MEA) categorized services provided by ecosystems into four groups including provisioning, regulating, supporting, and cultural (MEA 2005). More recently, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) reclassified and reconceptualized many of such services as Nature's Contributions to People (NCP; Díaz et al., 2018). In doing so, IPBES de-emphasized the attribution of economic value to ecosystem services under the MEA, recognizing the potential pitfalls of simplistic application of financial models to complex environmental systems. Instead, the NCP framework underscores the importance of involving a broader spectrum of disciplines and cultures—particularly those from the social sciences and humanities—in the generation of new knowledge, environmental discourse, and policy formulation.

Recognizing the importance of these modifications to the MEA, as well as the clear linkages between soil NCPs and the United Nations' Sustainable Development Goals (P. Smith, Keesstra et al. 2021), the committee has chosen to use the concept of NCPs in this report. This chapter reviews the contributions soils make to people, placing particular emphasis on the contributions made to human health.

WHICH OF NATURE'S CONTRIBUTIONS TO PEOPLE ARE DERIVED FROM SOIL?

Prior to the early 2000s, soils were rarely included in assessments of ecosystem services (Brevik et al. 2018). Since then, the number of scientific papers involving soil multifunctionality has increased exponentially (Adhikari and Hartemink 2016). Soil-derived NCPs are divided here into three main categories: material NCPs, regulating NCPs, and nonmaterial NCPs (Table 3-1). Material NCPs refer to goods and resources that are harvested or extracted from soils and include food and feed, fuel and building materials, and genetic resources (MEA 2005; Brevik et al. 2018; Díaz et al. 2018). Regulating NCPs are natural processes that help modulate and maintain the balance of ecosystems and earth systems, including soil formation, habitat creation, water and air regulation, and the ability of soils to suppress disease and degrade pollutants. Nonmaterial NCPs include benefits obtained from soils that contribute to cultural, recreational, and spiritual well-being. Material and regulating NCPs are discussed in detail below, along with a brief discussion of nonmaterial NCPs. Cross-cutting NCPs—a fourth category of NCPs described by IPBES—are not discussed here.

Nutrient cycling, which facilitates multiple ecosystem services, had previously been considered a supporting service in the MEA but was not assigned to a specific NCP in the new framework; it was instead separated to highlight how this process works together for multiple soil NCPs. Because of the important roles nitrogen and carbon play in food production, the committee opted to specifically discuss these nutrient cycles in the "Regulating NCP" section.

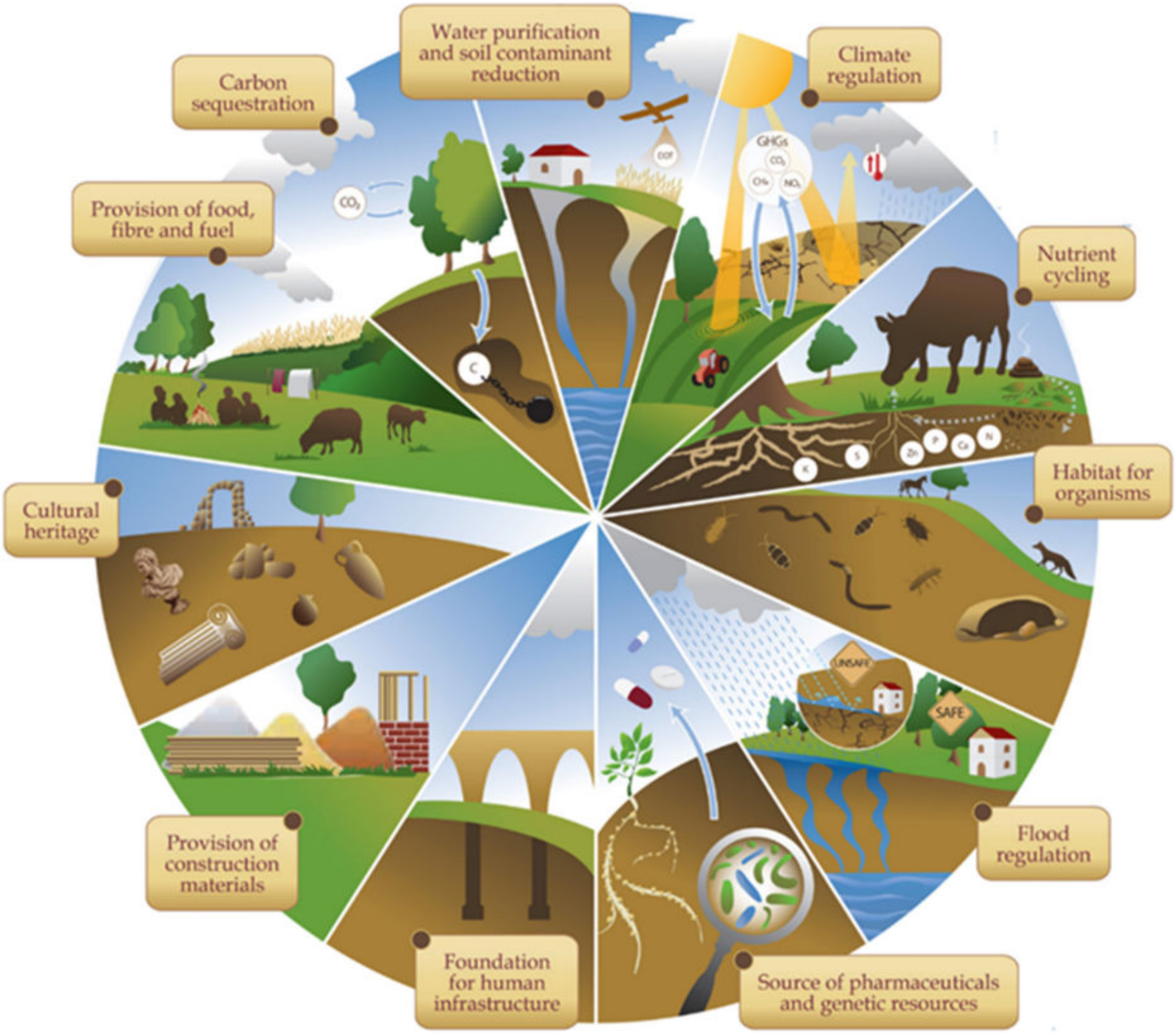

FIGURE 3-1 The multiple functions of soil.
SOURCE: Food and Agriculture Organization of the United Nations. Reproduced with permission.

TABLE 3-1 Three Main Categories of Soil-Derived Nature's Contributions to People (NCPs)

Material NCPs	Food supply, sustainability, and security Genetic, medicinal, and biochemical resources Materials and energy
Regulating NCPs	Soil formation, protection, and degradation of contaminants Habitat creation and maintenance Nutrient cycling[a] Climate regulation[a] Water regulation Air quality regulation[b] Disease suppression
Nonmaterial NCPs	Learning and inspiration Physical and psychological experiences Supporting identities

[a] This chapter specifically reviews the nitrogen and carbon cycles in the section "Nutrient Cycling and Climate Regulation."

[b] Air quality regulation is discussed in the sections "Soil Formation and Protection" and "Nutrient Cycling and Climate Regulation."

SOURCE: Modified from P. Smith, Keesstra et al. (2021).

MATERIAL NATURE'S CONTRIBUTIONS TO PEOPLE

Food Supply, Sustainability, and Security

Soils provide the majority of chemical, physical, and biological requirements for the production of food and feed crops, as well as those grown for fiber, fuel, and building materials. Globally, an estimated 95 percent of food is produced on soil, either directly or indirectly (FAO 2015). The fundamental linkage between soil and human health is thus straightforward: soil provides the nutrients, water, physical matrix, and biological community necessary to grow the crops on which humans rely for sustenance. Soil is absolutely essential for the production of sufficient amounts of food to support humanity.

Food security is defined as the state in which "all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO 1996). To achieve this goal, food production must adhere to the principles of sustainability as originally articulated by the Brundtland Commission, "meet[ing] the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations 1987). Achieving both food security and food sustainability is a complex challenge, to which soil is central (Oliver and Gregory 2015). Soil and land are finite resources, and as global population grows, the amount of productive land per person decreases, threatening food security (Bruinsma 2011; Ramankutty et al. 2018). At the same time, increases in food production have too often come at the expense of soil health, threatening food sustainability (see Chapter 4; Bagnall et al. 2021).

Genetic, Medicinal, and Biochemical Resources

Because soils contain diverse microbial communities that collectively encode unparalleled functionally catalytic properties, these environments represent a critical resource source for natural products. For instance, soils can be mined for enzymes to support industrial applications and the production of medicinal products. There are many examples where biocatalysts derived from soils have either been used themselves or exploited to aid in the optimization of existing enzymes for accelerated reaction rates, enhanced or relaxed enzyme specificities, and operation under nonstandard conditions (Ahmad et al. 2019), which has led to use of soil-derived lipases, amidases, cellulases, chitinases, proteases, and alcohol oxidoreductases, to name a few, for industrial and commercial uses (Salwan and Sharma 2018; Thiele-Bruhn 2021). The use of functional metagenomic screening is aiding in the discovery of novel genes coding for enzymes, enabling the sampling of enzymes from uncultivated microorganisms (Zhang et al. 2021). Although these discoveries have yielded commercial products, there is still much work to be done to fully uncover the wealth of enzymes and catalyzed reactions that remain hidden in soils. The ongoing exploration of soil for biochemical resources holds the potential for novel and environmentally friendly ways to synthesize industrial chemicals.

In addition to biochemical provisioning, soil biota produce a variety of small molecules with bioactivity (Lee and Lee 2013). Soil biota are important sources of antibiotics, defined as large group of organic compounds produced by microorganisms that are deleterious to other microorganisms. Furthermore, soil biota also synthesize secondary metabolites with pharmaceutical activities, such as hypocholesterolaemic, anti-cancer drugs, and immunosuppressants (Thiele-Bruhn 2021). Table 3-2 showcases representative commercial antibiotics and pharmaceuticals derived from soil microbial natural products. Together these natural products highlight how soils have been bioprospected for products with human-health-derived benefits.

Although the use of synthesized substances in medicinal products is on the rise, most clinical substances rely on natural chemotypes or are even derived from natural agents themselves (Peláez 2006). An examination of 162 antibiotics marketed between 1982 and 2019 revealed that 7 percent were natural products and 48 percent were derived from natural sources, with the rest being prophylactic agents or synthetic drugs (Newman and Cragg 2020). Unfortunately, most antibiotics in use today were discovered more than 40 years ago, and further growth in this area has stagnated, largely due to limited financial incentives for pharmaceutical industries (Genilloud 2019). This global scarcity of new antibiotics, coupled with escalating accumulation of antibiotic resistance genes in pathogens, poses a severe threat, with an anticipated 10 million annual deaths by 2050 from antibiotic resistance (Hurley et al. 2021; Lessa and Sievert 2023). Despite various international partnerships and government-supported initiatives addressing the value chain gap for new compounds, there remains a notable dearth of efforts focused on early discovery programs (Rex 2014; Cooper 2015; NASEM 2022). International frameworks governing genetic resources also complicate the discovery of new compounds (Box 3-1).

TABLE 3-2 Examples of Marketed Compounds Originating from Soil Microbial-Derived Natural Products[a]

Drug class	Compound (selected list)	Commercial product (examples)	Soil microbial source (genus only)
Antibiotic	Penicillin	Penicillin G, Ampicillin, Methicillin, Carbenicillin, Amoxicillan	*Penicillium, Aspergillus*
	Cephalosporin	Ceclor, Mefoxin, Ceftin	*Acremonium, Eericellopsis, Streptomyces*
	Streptomycin	Estreptomicina, Devomycin	*Streptomyces*
Immunosuppressant	Cyclosporin	Sandimmune	*Tolypocladium*
	tacrolimus (FK506)	Prograf	*Streptomyces*
	Mycophenolic	Cellcept	*Penicillum, Verticicladiella, Septoria*
Anti-tumor	Bleomycin		*Streptomyces*
	Doxorubicin	Adriamcyin, Doxil	*Streptomyces*
Cholesterol lowering	Lovastatin	Mevacor, Zocor (Simvastatin)	*Aspergillus, Monascus*
	Mevastatin	Prvachol	*Penicillum*
Anti-migraine	Ergotamine	Ergostat, Cafergot	*Claviceps*
Lipase inhibitor	Lipstatin	Xenical (Orlistat)	*Streptomyces*

[a] Most medicinal secondary metabolites derived from soils are produced by Actinobacteria and fungi. Among these, 70 percent of all medicinal products are ascribed to a single Actinobacterial genus, *Streptomyces*, while medicinal-producing fungal genera include *Penicillium*, *Aspergillus*, *Trichoderma*, and *Fusarium*.
SOURCE: Based on Thiele-Bruhn (2021).

BOX 3-1
Soil Bioprospecting within the Framework of the Nagoya Protocol

The Nagoya Protocol on Access and Benefit-sharing, which went into effect in 2014, is part of the Convention on Biological Diversity, an international treaty on conservation. The protocol serves as important legal guide for the fair sharing of benefits from using genetic resources, such as plants, animals, and microbes (Secretariat of the Convention on Biological Diversity 2011). Implementing measures to adopt and access genetic resources can enable countries to reap the benefits arising from research and development products mined from soil, while exercising their sovereign rights over these resources. However, execution of the Nagoya Protocol (and of the Convention on Biological Diversity before the protocol went into effect) for soil microbial antibiotic discovery poses several challenges. Microbial genetic resources in soil are often not clearly owned by any specific individual or community, and thus determining rightful owners and obtaining informed consent can be complex, especially when dealing with naturally occurring and widely distributed microorganisms. Obtaining necessary permits for soil sampling and addressing traditional knowledge associated with microbial resources can further hinder the exploration of microbial diversity. Differences in national regulations related to the protocol can create challenges for researchers and industries involved in soil microbial product discovery, hindering regulatory harmonization. Efforts to address these challenges may involve international collaboration, clear communication and engagement with local communities, and the development of frameworks that balance the objectives of the Nagoya Protocol with the needs of scientific research for soil microbial product discovery.

Nevertheless, soils remain an untapped reservoir for antibiotics. Despite the estimation of hundreds of thousands of antibiotic substances in soil, less than 5 percent have been characterized (Genilloud 2017; Crits-Christoph et al. 2018). Modern cultivation and molecular screening methods, replacing conventional culturing methods that resampled the same microorganisms and compounds, offer efficient ways to interrogate soils for promising medicinal compounds. Alternative cultivation techniques that better simulate soil conditions bring to light the functional capacities of the uncultured majority residing in soils (Carini 2019; Murray et al. 2019; Bartelme et al. 2020). These methods have recovered new natural products such as antibiotics from soil biota ranging from nematodes to microorganisms (Lewis et al. 2010; Imai et al. 2019; Shukla et al. 2023). Likewise, genomics and paired functional screens also expanded the identification of new antibiotics and medicinal products from various lineages of soil microbiota (Brady 2007; Piel 2011; C. Li et al. 2022). Therefore, soils represent an underutilized reservoir for medicine, with modern screening methods offering promising avenues to tap into this vast and largely unexplored resource.

Material and Energy

Peatlands, soils with partially decomposed vegetation, are a direct source of energy as these soils are harvested as fuel. Crops can also be grown for use as biofuel (J. Smith et al. 2021), and trees are grown for energy uses and construction purposes. Some types of soil are important sources of raw materials essential for construction (Brevik et al. 2018; Morel et al. 2021). Clay-rich soils are used for ceramics and the creation of bricks; other soil resources such as sand and gravel are raw materials for production of concrete and cement. Soil is also the primary constituent of adobe, rammed earth, and cob buildings.

REGULATING NATURE’S CONTRIBUTIONS TO PEOPLE

Regulating services from soil include benefits derived from soil functions that modify and control ecosystem characteristics such as maintaining water and air quality, cycling nutrients, regulating greenhouse gas (GHG) flux and climate, and disease suppression. This section describes in more detail several of the key soil functions related to regulating NCPs. Degradation of contaminants is addressed in Chapter 6.

Soil Formation and Protection

Soil formation provides the foundation for all other services derived from soil. This process is regulated by multiple factors including climate; the types and activities of organisms such as plants, animals, and humans; topographical characteristics; originating or parent materials of soil particles; and timescales over which soil formation takes place (Jenny 1946). The combined influence of these factors determines critical soil properties such as texture, structure, porosity mineralogy, capacity for water movement and storage, and the depth to bedrock or other root-limiting layers. These properties in turn define the environmental context and thresholds for how the resulting soils function and respond to management.

Soil biota and microbiomes contribute to soil formation and development through organic residue decomposition and aggregate stabilization and production of organic acids from microbial activities that weather rocks and minerals (Oades 1993; Schulz et al. 2013). Burrowing organisms engineer physical passages that enhance aeration, drainage, and water movement, and root systems strongly influence soil structure, chemistry, and moisture content, thereby shaping soil formation and habitats (Ramette and Tiedje 2007).The strong inherent link between factors that influence soil formation and the resulting soil properties, including most soil health indicators such as soil carbon dynamics and the characteristics and functioning of soil biota, is also the reason why soil health management outcomes and assessments are regionally specific (Zuber et al. 2020; see the section "Indicators of Soil Health" in Chapter 4).

One of the biggest threats to NCPs that derive from soil, in addition to contamination (see Chapter 6), is the functional or physical loss of soil itself. The physical loss of topsoil through erosion directly removes the richest soil layer for plant growth and carries lost sediments and nutrients as runoff to nearby waterbodies or as windblown dust that can travel anywhere from a few hundred miles to neighboring states or thousands of miles to distant continents. A recent study estimated that the midwestern United States has lost nearly a foot of topsoil in the past 150 years; tillage practices that disrupt the landscape and expose the soil to wind and water erosion have contributed heavily to these losses (Thaler et al. 2022). The National Resources Inventory of the U.S. Department of Agriculture (USDA) shows that national rates of soil erosion slowed considerably between the late 1980s and 1990s, likely due to greater awareness of soil erosion and implementation of conservation management practices, but more than 500 million tons of soil are lost from croplands per year due to wind and water erosion (USDA–NRCS 2017).

Soil erosion can affect human health in many ways, including through loss of soil resources that support stable food production. Sedimentation of water resources through soil erosion adversely affects human health directly or indirectly by reducing water quality and altering aquatic ecosystems (Heathcote et al. 2013; Chen et al. 2016). Dust particulates carried from exposed or unstable soils and agricultural operations to other urban, agricultural, and natural systems can irritate human respiratory systems and pose direct or indirect health risks (Opp et al. 2021) and transport other contaminants and irritants such as pesticides and microplastics (Middleton 2017; Aparicio et al. 2018; Rezaei et al. 2019). Particulate matter aerosols less than 2.5 and 10 μm in diameter are a major component of wind-blown sediments and dust storms that pose a significant risk for human health when inhaled (Li et al. 2015). In addition to the known harmful chronic respiratory and cardiovascular effects of inhaling sediments from dust storms due to land degradation, erosion, and increased aridity (Goudie 2020), researchers have also detected increased nonaccidental and cardiovascular mortality following dust storms (Crooks et al. 2016).

Soils can be functionally removed from many of their contributions to human ecosystems through soil sealing. Coverage by impervious surfaces such as with concrete, pavement, or compaction is increasing as a result of urbanization and development. Soil sealing creates human health and infrastructural problems in cities by preventing the soil from absorbing water after precipitation events, which can cause disastrous flooding after storms. Sealing also prevents soil and vegetation from naturally regulating heat and atmospheric exchange, thereby exacerbating the "urban heat island" effect (Scalenghe and Marsan 2009).

Threats to both the physical availability and the functional capacity of soil to perform NCPs has prompted the need to ensure "soil security." Soil security encompasses "the maintenance and improvement of soils worldwide so that they can continue to provide food, fiber and fresh water, contribute to energy and climate sustainability and help to maintain biodiversity and protect ecosystem goods and services" (Koch et al. 2012, 186). A key component of ensuring soil security is implementing soil management practices that provide continuous soil cover and improve soil structure to help protect and stabilize soils against water and wind erosion and prevent or mitigate land degradation and associated human health risks.

Strategies that prioritize living root systems and residue coverage are effective in reducing wind and water erosion, with fibrous root systems providing the greatest protection (De Baets et al. 2011) even in sandy soils (Vannoppen et al. 2017). Revegetating bare areas or increasing vegetation along waterways and slopes can also help prevent soil movement and loss due to landslides after extreme precipitation events (Sujatha et al. 2023). In agricultural settings, reducing or stopping tillage can help mitigate erosion by reducing physical soil disturbance and maintaining structural soil development (Seitz et al. 2020). In vulnerable arid and semi-arid ecosystems where soil formation and biological activities are already limited by water scarcity, building and protecting deeper topsoil layers are even more critical to support plant productivity and soil resilience to climate extremes (Zhang et al. 2023). Soil sealing and NCP restriction under impervious surfaces can be addressed in urban systems through innovative city planning and design of greenspaces and porous surfaces (Artmann 2014), which can further help mitigate urban heat islands (Spyrou et al. 2023) and enhance hydrologic management (De Noia et al. 2022).

Habitat Creation and Maintenance

The vast biodiversity found in soil is due to soils' considerable physical and chemical heterogeneity (Ranjard et al. 2013; Curd et al. 2018; Lehmann et al. 2020; Nunan et al. 2020), which creates hotspots, or localized areas, within the soil with heightened activity such as nutrient turnover and microbial interactions. Hotspots develop around roots, decaying organic matter, and other organic-rich pockets. Distinct moisture, oxygen, and nutrient gradients in soils—as well as unique exudation profiles, chemical properties, and root architecture of individual plants—create specialized niches for diverse microbial communities, fostering the proliferation of species with specific adaptations and promoting niche specialization within the soil ecosystem (Ramette and Tiedje 2007; Vos et al. 2013). Linkages between soil habitats and soil biodiversity are crucial for maintaining a diverse gene pool in soil organisms, which facilitates resilience with respect to changing environmental conditions (Box 3-2) and affects various material NCPs such as genetic, medicinal, and biochemical resources. Likewise, the feedback between plants, soil physical and chemical properties, and soil biota can influence the composition and biodiversity of soil biota with consequences for nutrient cycling, productivity, and plant diversity (van der Putten et al. 2013). These plant–soil feedbacks underpin many of the NCPs discussed in this chapter as well as the linkages between soil health and agricultural management practices reviewed in Chapter 4. Although much research has focused on how plant–soil feedbacks affect plant growth in both natural and agricultural systems (Mariotte et al. 2018), current and future studies can help delineate the mechanisms by which interactions between plant and soil microbiomes can affect each other's response to increases in stress, such as from drought, within the context of the soil habitat (de Vries et al. 2023).

Nutrient Cycling and Climate Regulation

In addition to the ecosystem contexts defined by soil-forming factors and processes and providing habitat for diverse soil biota, soils are a critical medium through which nutrients cycle. Extensive research focusing on the biological, geological, and chemical cycling of nutrients in soil systems has revealed the immense complexity of how biotic and abiotic factors regulate the transformations of carbon and nitrogen, other nutrients such as phosphorus and sulfur, and other compounds including heavy metals and synthetic molecules. Within the physical and chemical controls of the soil habitat, soil microbes and microbiomes drive processes that determine the amount of plant-available nutrients such as nitrogen; loss or retention of nutrient and water resources; recycling and remediation of organic wastes, contaminants, and pollutants; and the formation and stabilization of soil organic matter (SOM) (Box 3-3). The relative balance between carbon incorporation into microbial biomass, soil organic matter, and respiration as carbon dioxide (CO_2) during decomposition of organic residues by microbes, known as "carbon use efficiency" (CUE), is also an important regulator of soil nutrient cycling, organic matter formation, and carbon sequestration (Oliver et al. 2021). Given the particular interest in the committee's charge on agriculture, the committee elected to emphasize the carbon and nitrogen cycles because of their critical roles in crop production.

BOX 3-2
Resilience and Soil-Derived Nature's Contributions to People

Stressors that affect soil derived nature's contributions to people (NCPs) can be physical (e.g., extreme temperature, moisture, or compaction), chemical (e.g., extreme pH, excess or shortage of nutrients, salinity, heavy metals, and pesticides) or biological (e.g., loss of biodiversity and introduction of exogenous organisms). They often operate in concert (van Bruggen and Semenov, 2000), which makes responses difficult to predict (Rillig et al. 2019). As such, the concept of resilience has become an increasingly central concept in ecology and in the understanding of social ecological systems including agricultural and food systems (Tendall et al. 2015; Moser et al. 2019; Van Meerbeek et al. 2021). Since the seminal work of Holling (1973), resilience has been defined in many ways, but the term is generally understood to refer to the ability of a system to continue to function (within some given set of acceptable parameters) despite shocks or disruptions. Resilience may be driven by a system's *robustness*—its ability to absorb impact and resist change (though whether this truly constitutes resilience is debated, see Walker 2020), a system's *adaptability*—its ability to flex and shift in order to maintain function under stress, or a system's *transformability*—its ability to create a fundamentally new system when necessary to maintain overall function (Folke et al. 2010; Tendall et al. 2015; Meuwissen et al. 2019). Many attributes or characteristics of systems can contribute to resilience, including redundancy, diversity, connectivity, modularity, and a capacity for self organization (Moser et al. 2019 and references therein). In the context of soil systems, biological diversity emerges as a central attribute influencing a soil's ability to function (i.e., continue to provide NCPs) in the face of a wide variety of stressors.

Ecosystem multifunctionality is greater where assemblages of bacteria, fungi, protists, and invertebrate communities are more diverse (Wagg et al. 2014; Delgado Baquerizo et al. 2020). This diversity effect results from functional complementarity, or a selection effect, where more diverse communities have higher likelihood of harboring taxa performing key functions (Loreau and Hector 2001). Resilience can also result from the presence of many taxa that perform similar functions but vary in their environmental tolerances/preferences; this functional redundancy is referred to as an 'insurance effect' (Yachi and Loreau 1999). In the context of agriculture, management practices can affect resilience, with lower resilience expected where external inputs are high and crop diversity is low compared with systems that promote crop diversity and maintain habitat heterogeneity (van Bruggen and Semenov 2000; Oliver et al. 2015). Soil organic matter plays a role in maintaining resilient ecosystems by promoting microbial diversity as well as soil aggregation and structure that is more resistant to erosion caused by high intensity rainfall or wind events (Lehmann and Kleber 2015).

BOX 3-3
Soil Organic Matter

The formation and stability of soil organic matter (SOM) are important both because of its behavior as a physical and chemical component of soil and its role as a reservoir of nutrients for plants such as nitrogen, phosphorus, and sulfur that can be released by soil microorganisms during decomposition. Carbon is also an energy source for microorganisms. SOM is a broad category of organic soil components that originate from plant and animal residues that enter the soil and exist in varying stages of decomposition and use by soil biota, including as dead microbial cells (Sokol et al. 2022). Some SOM is protected from further decomposition by being physically protected within soil aggregates, by being chemically adhered to soil mineral particles, or simply by possessing a high molecular diversity and stochastic co-occurrence with soil microbes that make it energetically too costly to decompose (Lehmann and Kleber 2015; Lehmann et al. 2020). SOM components range in size from dissolved organic molecules less than 0.045 mm to larger particulate organic matter up to 2 mm and range in composition from individual amino acids or sugars to larger and more complex compounds such as lignin, cellulose, and polyphenols. Depending on the location and chemical complexity of SOM in soil, they can cycle in relatively short (e.g., “active pool,” < 10 years) to more persistent or recalcitrant (e.g., “passive pool,” many decades to centuries) timescales (Lavallee et al. 2020).

Although SOM is a small and often intangible component of soil compared to the mineral sand, silt, and clay particles, its physical, chemical, and biological impacts are disproportionally larger. Small, chemically charged SOM particles contribute substantially to soil chemical properties and ion (e.g., nutrient) exchange and retention capacity (Curtin and Rostad 1997). Pyrolyzed forms of SOM from plant and animal residues such as biochar amendments or “black carbon” also increase nutrient exchange and retention in soils due to their high surface area and complex, chemically charged structures (Liang et al. 2006; Tomczyk et al. 2020). The enormous capacity for ion exchange and retention of SOM also helps buffer soil against sudden changes in pH (Curtin and Rostad 1997). SOM further contributes to aggregate stabilization and building soil structure, which aids in carbon sequestration alongside improved air and water movement and provides spatially diverse habitats for soil biota (Six et al. 2000).

Soils also play a critical role in climate regulation, as both a source and sink of GHGs. The relative degree of production versus consumption of GHGs is heavily regulated by the innate properties of a soil and by management practices. Soils are also a globally significant carbon pool with substantial potential for carbon sequestration (Padarian et al.2022). Additionally, the nature of the soil surface can influence climate through affecting albedo (the fraction of sunlight that is reflected). This section discusses the nitrogen and carbon cycles, highlighting some key GHGs and human health aspects as well as impacts of albedo for climate regulation.

Nitrogen Cycling

Nitrogen, an element essential to building amino acids and nucleic acids, is abundant in the atmosphere in the gaseous form N_2. However, plants and animals cannot make use of N_2. Plants need nitrogen in the forms of ammonium (NH_4^+) or nitrate (NO_3^-) for uptake and subsequent growth. Animals get the nitrogen they need from consuming organic matter that contains nitrogen. Soil is the conduit through which terrestrial plants get the nitrogen they need (Figure 3-2). Nitrogen in the atmosphere, primarily in the form of N_2, can be “fixed” into forms of inorganic nitrogen available to organisms either by tremendous amounts of energy or through microorganisms. Lightning can provide the energy needed to split N_2 molecules that then bind with oxygen to create nitrogen oxides. Nitrogen oxides dissolve in water to form nitrates, which enter soil through precipitation. However, most N_2 is converted into a plant-available form through biological nitrogen fixation, which can occur in different ways (Vitousek et al. 2013). Some bacteria and archaea in the soil can convert N_2 into ammonia (NH_3). Bacteria that live in the root nodules of legumes (rhizobia) can also carry out this conversion and provide biologically available nitrogen to these plants through a symbiotic relationship in which the bacteria in turn receive carbohydrates from the plants. Nitrogen usable by plants can also become available in soil when bacteria and fungi decompose dead plants and animals, converting nitrogen in the dead organisms into ammonium (NH_4^+) through a process called mineralization (Li et al. 2019).

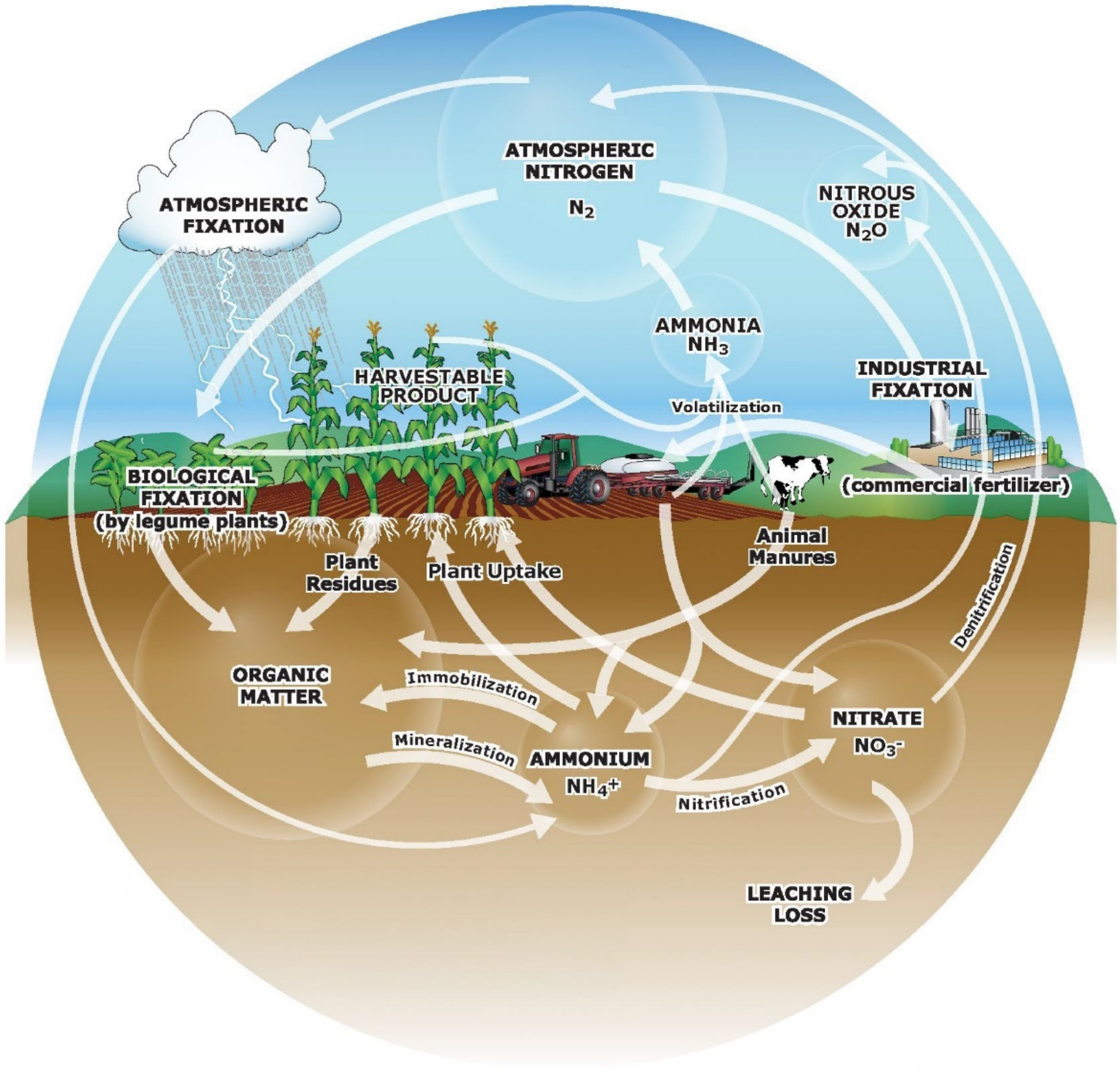

FIGURE 3-2 The nitrogen cycle.
SOURCE: The Fertilizer Institute.

Plants can use ammonia and ammonium, but some plants prefer nitrate (NO_3^-) as their nitrogen source. Ammonia and ammonium can be converted to NO_3^- through the process of nitrification, in which certain types of bacteria and archaea alter NH_3 and NH_4^+ into nitrite (NO_2), and other bacteria convert the nitrite to nitrate. Nitrate not taken up by plants can return to the atmosphere, either by directly volatizing from soil or by leaching into waterways and then volatizing from the water's surface, through denitrification, the process by which other types of bacteria convert nitrate back into N_2 or into nitrous oxide (N_2O) (Z. Li et al. 2022).

An essential regulating service that helps with the production of food and oxygen through plant growth, the nitrogen cycle also presently causes harm to human health because of anthropogenic additions of nitrogen to the environment. In the context of U.S. agriculture, nitrogen is frequently applied to cropland in forms such as synthetic fertilizer, manure, and biosolids (see Chapter 4). However, only 25 percent of the nitrogen applied is taken up by crops on average (Lehman et al. 2015). The excess nitrogen cascades into the environment, harming environmental and human health as it moves from farms to waterways and into the atmosphere (Galloway et al. 2003). In the form of nitrate, nitrogen can leach from agricultural fields, enter groundwater, and contaminate drinking water. High levels of nitrate in drinking water can cause health problems such as methemoglobinemia, or "blue baby" syndrome, which occurs most often in infants who drink formula made with nitrate-rich water. The nitrate reduces the oxygen-carrying capacity of the blood (Ward et al. 2018). Excess nitrogen (and phosphorus) in surface water causes eutrophication, that is, the overabundant growth of algae and aquatic plants. The plant overgrowth can change sediment deposition in streams, adversely affecting habitat for fish and invertebrates whereas the decomposition of algal biomass depletes oxygen, killing fish and other aquatic life forms (Munn et al. 2018). Harmful algal blooms fed by excess nitrogen and phosphorus can also pollute drinking water, reduce availability of aquatic food sources to harvesters and consumers, and constrain people's access to water for productive and health-enhancing recreational activities.

Furthermore, soils are the largest natural source of N_2O, a potent greenhouse gas. Agriculture (from synthetic fertilizer use and manure management) is the largest anthropogenic source of N_2O (Butterbach-Bahl et al. 2013; Canadell et al. 2021). Soils can sometimes act as a sink, consuming N_2O, but the magnitude and impact are not significant (Schlesinger 2013). Overall, soils are a source of N_2O, with flux dynamics strongly influenced by soil nutrient and other management practices in combination with natural factors such as temperature and rainfall. Along with its contributions to global warming, airborne nitrogen pollution can affect human health by reacting with other pollutants, leading to the formation of particulate matter (Wyer et al. 2022), and contributing to acid rain and eutrophication (Sutton et al. 2009).

Carbon Cycling

Carbon dioxide continually cycles between the atmosphere and soils (Figure 3-3). Atmospheric CO_2 is taken up by plants during photosynthesis, and a portion of this carbon ultimately reaches soils in the form of organic compounds released from roots, root exudates, plant litter, and animal droppings. Carbon dioxide is emitted back to the atmosphere when organic compounds decompose and as the product of respiration by soil-dwelling micro- and macroorganisms as well as plant roots. Land use and land use change strongly influence soil carbon dynamics.

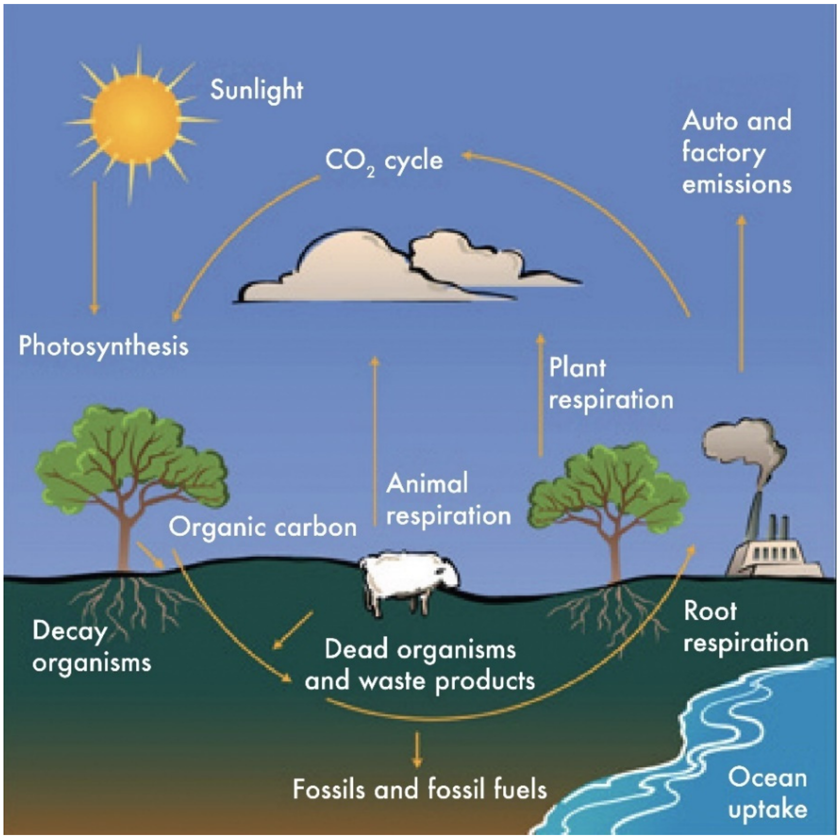

FIGURE 3-3 The carbon cycle.
SOURCE: © UCAR 2024.

Soils regulate climate through their role as a globally significant carbon sink. The top 1m of the world's soils is estimated to contain up to 2,500 gigatons of carbon (GtC)—nearly three times more carbon than is in the atmosphere and four times more than in vegetation globally (Friedlingstein et al. 2020; Lal et al. 2021). Another 800 GtC of organic carbon are estimated to be stored in the second and third meters of soil (Jobbágy and Jackson 2000). Soil carbon stocks are composed of both organic and inorganic forms, each with bearing on climate regulation.

Soil organic carbon (SOC), the carbon contained in organic compounds within the soil, accounts for approximately 60 percent of the total global soil carbon pool (Lal 2008) and is highly susceptible to human perturbation. Most carbon lost from soils to the atmosphere is in the form of CO_2. Land use change (primarily deforestation and conversion to agriculture) is thought to have been a significant source of anthropogenic CO_2 emissions for the past 8,000 years—far preceding the industrial revolution (Ruddiman 2003). Current rates of CO_2 emissions due to land use, land use change, and forestry are estimated at 1.3 GtC per year (compared to the 9.6 GtC per year from combustion of fossil fuels) for the period 2013–2021 (Friedlingstein et al. 2023).

Soil inorganic carbon (SIC) refers to soil carbon in mineral form, primarily as calcium and magnesium carbonates. SIC, like SOC, is also a globally significant carbon pool (approximately 940 GtC), and its spatial distribution tends to vary inversely with SOC. SOC concentrations are typically higher in humid regions and SIC concentration typically higher in arid and semiarid regions, although positive correlation between the two has also been reported (Lal et al. 2021; Naorem et al. 2022). SIC is formed via several pathways, including the chemical weathering of calcium and magnesium silicates, which consumes CO_2 (Lal et al. 2021; Naorem et al. 2022). As arid soils age, carbon may be sequestered as SIC over thousands to tens of thousands of years, making soil age an important factor when considering global carbon sequestration. In contrast to SIC, SOC can approach a state of equilibrium over tens to hundreds of years (Lal et al. 2021).

Like CO_2, methane (CH_4) is a carbon-containing GHG that is naturally produced and consumed by soils and can play a significant role in global climate regulation (Canadell et al. 2021). Methane is produced in soils during the microbially mediated decomposition of organic matter under anaerobic conditions. While waterlogged soils, such as those found in wetlands and rice paddies, constitute the most prominent pedogenic sources, CH_4 may also be produced when non-flooded soils experience anaerobic conditions or in anaerobic pockets or during the process of anaerobic soil disinfestation (Kim et al. 2012; Prescott et al. 2023; Wan et al. 2023). Soils also remove CH_4 from the atmosphere due to the activity of methanotrophic microbes, which metabolize it as their source of carbon and energy; this activity accounts for up to 5 percent of the total CH_4 sink globally (Saunois et al. 2020; Canadell et al. 2021). Soil CH_4 flux dynamics are influenced not only by physical conditions, such as soil moisture and aeration, but by microbial activity. In addition, vegetation, which both enables oxygen transport to the rhizosphere and can serve as a conduit for CH_4 transport from soils to the atmosphere (Kim et al. 2012; Conrad 2020; Canadell et al. 2021). Thus, soil health and management have the potential to influence soil CH_4 dynamics via multiple pathways.

GHG emissions, from soil nutrient cycles or other sources, contribute to global warming when the global warming potential of gases emitted exceeds that of the processes that sequester or remove these gases from the atmosphere.[1] The detrimental effects of global warming on human health are numerous and predicted to increase (Hayden et al. 2023). Land management practices present opportunities to counteract GHG emissions. For example, land restoration or land use change to less disturbed management systems (e.g., from annual cropping to pasture or forest) typically results in increased SOC concentrations (Guo and Gifford 2002). The rate of CO_2 uptake by land (soil and vegetation) globally was estimated to be 3.3 GtC per year for the 2013–2022 period (Friedlingstein et al. 2023). Overall, the opportunity for carbon sequestration and GHG emission reduction through land use and land restoration-based strategies comprises one of the areas with the greatest projected climate change mitigation potential—on par with (though likely more costly and therefore more difficult to achieve than) wind and solar energy (IPCC 2022b).

Importantly, soil restoration and carbon sequestration—processes that are of critical importance for climate regulation—are also closely correlated with the building and maintenance of soil health. Concentrations of SOM and SOC are tightly linked, with carbon typically making up about half of SOM by mass (Pribyl 2010). Thus, increases in SOC concentration are associated with increases in SOM, and increased SOM is associated with greater microbial diversity and activity, enhanced soil physical structure, and various other indicators of soil health (see the section "Indicators of Soil Health" in Chapter 4). Intriguingly when soil is restored, soil biological networks have been found to become more tightly connected and enhance carbon uptake (Morriën et al. 2017), further highlighting the reciprocity between soil health and soils' climate-regulating function.

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[1] Global warming potential (GWP) measures the amount of energy that the emissions of 1 ton of a gas will trap over a set period of time as compared to the emissions of 1 ton of CO_2. Over 100 years, non-fossil CH_4 has a GWP of 27. Over the same time period, N_2O has a GWP of 273 (Forster et al. 2021).

Furthermore, while significant short-term opportunities exist to sequester SOC in soils where it has been depleted due to land use change, the role of SIC on climate regulation operates over a wider range of timescales. Enhanced mineral weathering in soil is a climate change mitigation strategy that applies crushed silicate rock amendments, such as basalt or olivine, to break down in soils and capture and store atmospheric CO_2 in solid form in soil (Andrews and Taylor 2019; Calabrese et al. 2022). The technology can potentially help in climate change mitigation and enhance soil fertility. Its feasibility for widespread use in U.S. cropping systems is under investigation with promising preliminary results, though further research is needed to assess scalability and environmental impacts (Calabrese et al. 2022; Beerling et al. 2024).

Soil Surface and Albedo

The character of the soil surface over large areas may also impact climate regulation by affecting albedo. In agricultural settings, some soil amendments, such as biochar and manure, darken the soil surface and can reduce albedo (meaning that more light energy is absorbed, which contributes to warming), whereas crop residue cover and reduced tillage contribute to higher albedo. Soil management practices such as tillage and manure application can also affect rates of snow melt, which can further influence albedo (i.e., faster snowmelt means lower average albedo) (Kunkel et al. 1999; Stock et al. 2019; Lal et al. 2021).

Water Regulation

Soil's piece of the water cycle is instrumental to the provision of clean water, clearly a regulating service as well as one of the objectives of One Health (Figure 3-4). Soils with enough large pores and high aggregate stability allow precipitation to infiltrate the ground, preventing erosion and runoff, which would otherwise carry nutrients, sediments, and other pollutants into surface water bodies. Soil also acts as a natural filter. As gravity pulls water down through the soil, contaminants it may carry can be trapped in soil pores, bound to clay minerals or organic matter, or degraded by soil organisms (Keesstra et al. 2012). Soil's ability to hold moisture is also obviously key to the productivity of plants and thus the provision of food.

Healthy soils promote hydrologic processes that benefit human health such as purification of water resources, regulation of leaching of nutrients or contaminants, and control of floods. Improving properties such as soil aggregation, structure, and SOC/SOM that enhance nutrient and water movement and storage are critical for efficiently managing scarce water supplies in agricultural systems (Acevedo et al. 2022). For example, water tends to infiltrate or enter the soil more quickly in sandy-textured soils or those with larger aggregates and pore spaces at the soil surface, which in turn reduces ponding or flooding. Yet, this rapid movement of water in coarse-textured soils can be detrimental if it accelerates leaching of excess nutrients or contaminants such as NO_3^- to groundwater (Donner et al. 2004; Kurunc et al. 2011). Low SOC and SOM, which is frequent in sandy-textured soils, further reduces the capacity to adsorb and remove contaminants from leaching water (Li et al. 2023) because increased SOM helps increase the retention of pollutants in the biologically active surface layer until they can be degraded by soil biota (Neumann et al. 2014).

SOM also improves soil water infiltration and storage (Bagnall et al. 2022; Kharel et al. 2023), which helps protect soils and crop yields against drought (Kane et al. 2021). Compared to sandy-textured soils, soils with higher clay contents and porosity have higher ion exchange

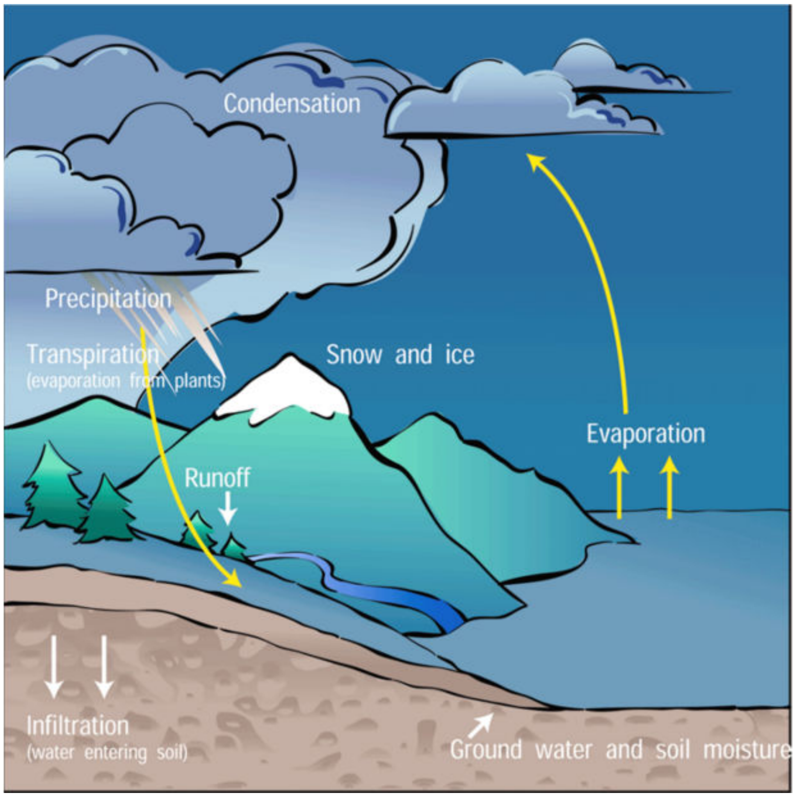

FIGURE 3-4 The water cycle.
SOURCE: © UCAR 2024.

capacity and thus can more tightly hold greater amounts of water and accrue more SOC and SOM (Schimel et al. 1994), which can both slow the movement of contaminants to groundwater and allow more time for chemical or biological removal of contaminants (Montoya et al. 2006). Even within high-clay soils, differing mineralogy and weathering can significantly affect adsorption and movement of excess nutrients or contaminants, where less-weathered clay minerals with higher surface areas are more effective at fixing or removing excess nutrients from the soil solution (Nortjé and Laker 2021). Soil texture and mineralogy are not typically responsive to management practices, but managing soils to improve aggregation, structure, and soil carbon can help improve soil water retention and availability for plants, reduce flooding or ponding, and reduce movement of excess nutrients and contaminants into groundwater systems.

Suppression of Plant Disease

The ability by some soils to suppress disease has been known for more than 60 years (Menzies 1959) and can be an important function of healthy soils (van Bruggen and Semenov 2000). Development of disease-suppressive soil is an example of a positive plant–soil feedback that can benefit future plant productivity through the lasting effects of plant–soil interactions (Mariotte et al. 2018). The focus on this NCP has been in agricultural systems, where worldwide crop losses can amount to more than 15 percent of the attainable yield (Oerke 2006); however, it is also highly relevant for plant health in nonagricultural soils. Disease suppression does not refer to the complete elimination of soil-borne pathogens, but the reduction in soil-borne diseases where host plants and pathogens are present and environmental conditions are conducive (Jayaraman et al. 2021). Suppression can be broadly classified into "general," "induced," and "specific," although it should be noted that these are not distinct categories; rather, soils exist in a continuum of suppressiveness (Raaijmakers et al. 2009). General suppressiveness is an innate nonspecific phenomenon of soil, where its resident microbiome controls various soil-borne pathogens via competitive or antagonistic activities; induced defense refers to biotic and abiotic agents that can trigger systemic resistance in plants against invading pathogens; and specific suppression involves particular microbial species or groups (Schlatter et al. 2017; Sagova-Mareckova et al. 2023). An example of the latter is members of the genus *Trichoderma* fungi that have been commercially marketed as biopesticides due to their ability to protect plants under a range of soil conditions (Woo et al. 2023). Disease suppression is not restricted to soil microbes, however: protists (unicellular eukaryotes) as well as nematodes can reduce bacterial pathogens by exuding bactericides or by selective feeding (Gao et al. 2019; Martins et al. 2022). Likewise, an emerging—but largely untapped—biocontrol potential involves viruses that predate bacterial and fungal pathogens (Martins et al. 2022; Enebe and Erasmus 2024).

Due to the complexity of soils and the many factors that influence plant-microbe-soil interactions, disease suppression is currently difficult to predict (Sagova-Mareckova et al. 2023), although recent attempts to use molecular tools to identify individual taxa as well as responses in microbial network structures associated with disease are promising (Batista et al. 2024). The presence, transport, and persistence of pathogens within soils that contribute to plant, animal, and human diseases are regulated by many of the same physical, chemical, and biological constraints as beneficial microorganisms, such as soil structure, pH, nutrients, and organic matter (Janvier et al. 2007; Ghorbani et al. 2008; Lekberg et al. 2021) and interaction with other soil biota (Jayaraman et al. 2021). In agricultural settings, many management practices that promote microbial abundance and diversity—such as crop rotations, cover crops, residue retention, minimum tillage, and compost or manure addition—have also been shown to promote disease suppression (Ghorbani et al., 2008; Jayaraman et al. 2021).

NONMATERIAL NATURE'S CONTRIBUTIONS TO PEOPLE

Nonmaterial contributions from soil to people are the often-intangible ways that soils influence humans and human systems, including soil and ecosystem effects on individual or societal experiences, behavior, values, and organization. The specific types of contributions include: cultural and social value; community engagement and participation; educational opportunities; aesthetic and inspirational value; biodiversity conservation; sense of ownership and stewardship; health and well-being; cultural practices and traditions; and recreation and outdoor activities (Chan et al. 2012; Milcu et al. 2013). Many of these aspects relate not only to individual or population-level health and wellness outcomes through interactions with soil and nature, but also to human well-being and security through stable economic systems that rely on healthy soils.

Disconnection of humans from soil is considered by many to have contributed to agricultural unsustainability and environmental degradation, with significant societal consequences (Hillel 1992). Soil traditionally played a role in many traditions and practices of farmers throughout the world (Hillel 1992; Fitter et al. 2010). Many philosophical systems and religions associate soils with spirituality, considering it a source of vitality and generative power (Minami 2009).

The emergence of the concept of "soil health" reflects a growing recognition of soil's vitality, capacity to be rejuvenated, and the need to improve how practitioners, policy makers, and citizens, among others, relate to soil (Krzywoszynska 2019; Puig de la Bellacasa 2019). Although soil health and the role of soil in NCPs are not emphasized in calls to improve human-nature connectedness as an intervention pathway for ongoing climate and environmental crises (Richardson et al. 2020; Riechers et al. 2021), healthy soil as the basis for natural, agricultural, and urban ecosystems is the foundation of human-nature connections.

Soil is an integral part of various art forms and cultural traditions (Feller et al. 2015; Toland et al. 2018). From pottery to landscape paintings, soil has served as both a medium and a subject in artwork. Soils are also repositories of human cultural heritage, preserving physical artifacts and historical sites (Adhikari and Hartemink 2016). Local knowledge of soils, known as ethnopedology, provides cultural context and experience that, in turn, guides sustainable land management practices appropriate for specific regions (Barrera-Bassols and Zinck 2003).

Natural spaces, and their soils, offer social, recreational, and therapeutic benefits to humans (Fitter et al. 2010). Connection to soil is increasingly recognized for its positive impact on mental and physical health, such as in movements like Nature Rx and the creation of healing gardens (Marcus and Sachs 2014; Kondo et al. 2020). Multiple reviews have explored how natural environments and greenspaces are beneficial to human health and how protecting these areas and the soils that support them is more critical than ever as greater proportions of people populate urban areas (Jackson et al. 2013; Hurly and Walker 2019). For example, improved connections to nature and access to greenspaces has been linked to individual health improvements, such as alleviating post-traumatic stress disorder in veterans (Varning Poulsen 2017) and better behavior in children (Roe and Aspinall 2011), and to community-level health improvements, such as better cardiovascular health (Chen et al. 2020) and lower rates of infant mortality (Schinasi et al. 2019). Researchers have also found positive effects of quiet natural spaces and soundscapes on human stress relief and recovery (Buxton et al. 2021) and on restoring attention spans and concentration (Ohly et al. 2016).

In other words, in addition to the multitude of material and regulating NCPs discussed earlier in this chapter, an underrated but critical way that nature, supported by healthy, unsealed soil, improves human health and well-being is simply through providing verdant, calming spaces that offer restorative peace and quiet. Furthermore, a recent study conducted in Youngstown, Ohio, demonstrated that communities that engage in greening vacant lots in cities can reduce violent crime in the surrounding streets by improving both the physical and social environment, even more than adding professional maintenance of the lots not implemented by the community (Gong et al. 2023). This finding builds on earlier research demonstrating that community engagement in maintaining and greening vacant lots can reduce violent crime in the area by nearly 40 percent and improve community members' safety and well-being (Heinze et al. 2018).

Given these benefits to both individual and community health, increasing focus has been placed on improving access and quality of greenspaces in urban environments. However, the relative health benefits of improved access to natural areas and urban greenspaces are heavily influenced by socioeconomic and cultural factors and inequalities (Hurly and Walker 2019). Simply adding more parks or recreational areas may not increase physical activity in communities with low social cohesion and inclusion or poor public transportation (Seaman et al. 2010; Price et al. 2023) and may in fact exacerbate social exclusion (Jelks et al. 2021). Further, a long-term study conducted in Philadelphia found that more accessible and higher-quality urban parks and open spaces helped reduce health and mortality inequities in marginalized neighborhoods, especially those with inequities based in racialized residential segregation and economic deprivation (Schinasi et al. 2023). However, the authors warned against the unintended long-term outcomes of gentrification and community exclusion when adding or modifying greenspaces as a tool to improve public health (Schinasi et al. 2023).

TRADE-OFFS AMONG NATURE'S CONTRIBUTIONS TO PEOPLE

Maximizing food production (by focusing solely on a material NCP) has often been achieved in ways that negatively affect regulating NCPs, which underpin the capacity of a soil to produce food. For example, the Green Revolution in agricultural production, which took hold in the mid-20th century, increased biomass yields of cereal crops substantially, but the concomitant intensive use of synthetic fertilizers and pesticides is also often associated with degraded soils, reduced air and water quality, and alterations in nutrient cycling (Tilman et al. 2002; Smith et al. 2015). Another example is the conversion of wildland to agriculture, which increases food production while at the same time typically reducing soil carbon sequestration, biodiversity, the regulation of water flow and quality, and potentially the cultural and esthetic value of the landscape (Smith et al. 2015). These outcomes highlight trade-offs among NCPs, in which the promotion of material NCPs come at the expense of regulating or nonmaterial NCPs (DeFries et al. 2005; Foley et al. 2005; Stavi et al. 2016).

Trade-offs among NCPs are also often on display across different crop production systems. For example, Wittwer et al. (2021) used a long-term farming system experiment in Switzerland to show the highest yields associated with conventional, high-input cropping systems whereas organic and conservation agricultural[2] systems harbored greater biodiversity, soil and water quality, and climate mitigation but exhibited relatively lower yields. Trade-offs can also occur *within* categories of NCPs, such as in the case of the Palouse River watershed of the U.S. Pacific Northwest where no-till management may reduce erosion and promote SOM but accelerate soil acidification (Davis et al. 2023).

Trade-offs may also be considered alongside co-benefits and in conjunction with socioeconomic factors. For instance, policies and incentives that promote soil carbon sequestration for climate-mitigation purposes have the co-benefit of enhancing numerous other regulating NCPs due to the positive impact of increased SOC on soil health. However, when soil carbon sequestration incentives take the form of marketable carbon offsets, they introduce a notable trade-off within a single NCP: between the sequestration of organic carbon on the one hand—aiding in climate regulation—and the potential for further emissions of fossil carbon on the other hand (Oldfield et al. 2021).

USDA has programs that prioritize regulating NCPs over food production or that encourage producers to adopt practices that support nonmaterial NCPs. The Conservation Reserve Program (CRP), for example, pays producers to take land that is highly erodible or environmentally sensitive out of production (Hellerstein 2017). In addition to protecting soil from erosion, CRP land creates habitat for wildlife. The program is also a vehicle for protecting wetlands. The Environmental Quality Incentives Program assists producers with the adoption of conservation practices on working lands (Stubbs 2022). However, adoption of such practices can be difficult if an economic loss occurs. Therefore, when it comes to food production, a pressing challenge is to identify, quantify, and minimize trade-offs between productivity and ecosystem

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[2] In the study cited, conservation agriculture followed these practices: minimum tillage, 6-year crop rotation, and permanent soil cover with crop residues and cover crops (Wittwer et al. 2021).

health. Given the expected increasing frequency and duration of extreme weather and climate events due to global warming (Leung et al. 2023), identifying factors and management practices that contribute to resilience will also become increasingly important.

Complex models have been developed to quantify and assess trade-offs (Sanou et al. 2023). However, most are too cumbersome to inform decisions that a producer needs to make each day or each season. Tools that rely on remote sensing and GIS applications hold promise for providing real-time information to producers to assess trade-offs between food production and other NCPs (Sanou et al. 2023).

CONCLUSIONS

Soil is fundamental to human health. While the importance of soil for food production is easily appreciated, other services have received less recognition. These include nutrient, water, and air quality regulation and providing habitat for soil biota that conduct many essential functions in soils and harbor resources for potential future medicines. There is also an increasing awareness of the importance of soil for climate regulation due to its ability to sequester and release large amounts of carbon and other GHGs and of the role of healthy soils in supporting educational, cultural, and spiritual health and well-being. Recommendations for enhancing human health via soil-mediated NCPs revolve primarily around raising awareness of the many essential regulating and nonmaterial roles of soil, characterizing and monitoring NCPs to avoid detrimental trade-offs, preserving soil habitat and biodiversity, and enhancing soil-mediated NCPs within and across landscapes.

Awareness

Broader societal awareness of the role of soil in providing essential NCPs—and in the importance of these NCPs to promoting and sustaining the health of both individuals and populations—is an overarching priority. While soil-mediated NCPs comprise largely indirect linkages between soil health and human health, they are of supreme importance. For example, both natural and working lands play a significant role in global CO_2, CH_4, and N_2O fluxes, and they are interlinked with global carbon and nitrogen cycles. The critical importance of soil processes in climate regulation establishes a profound link to human health. As climate change leads to rising temperatures, increased occurrences of extreme weather events, and myriad disruptions to natural cycles and ecosystems, these factors, in turn, have far-reaching consequences to the stability and security of food production systems, natural resource provisioning, and the exposure of populations to climate-related health risks such as heatwaves, wildfires, and water-, food-, and vector-borne diseases (IPCC 2022a).

Climate regulation is just one example of how healthy, functioning soils constitute one of the fundamental pillars regulating Earth systems on which humans depend for survival. Breakdown of these systems would threaten not only the sustainable provisioning of food but the livable environment more broadly. Therefore, it is imperative that entities concerned with the contributions of soil to the well-being of people make the value of these essential services widely known. Many federal agencies have a role to play in such a campaign. USDA is primarily concerned with the health of soil for food production, but habitat issues, such as for pollinators, also fall within its areas of interest. The habitat supported by soil is also important to agencies such as the Fish and Wildlife Service, the National Park Service, and the Bureau of Land

Management. Beyond the federal government, the Soil Science Society of America, and its sister societies the American Society of Agronomy and the Crop Science Society of America, have ongoing efforts to draw attention to the importance of soils, and other scientific societies, such as the American Society of Microbiology, the American Phytopathological Society, the Entomological Society of America, and the Ecological Society of America, have given increasing attention to the soil microbiome and soil habitat in recent years. Many of these agencies and societies have already started public messaging campaigns to communicate the importance of soil to the general public, as has the Food and Agriculture Organization, which successfully persuaded the United Nations General Assembly to recognize an annual World Soil Day, starting in 2014. Such public awareness efforts are warranted and should be continued to help ensure that the value of soil functions is recognized.

Recommendation 3-1: Federal agencies and scientific societies should continue their work to promote the public awareness of the importance of soil health and its societal value beyond its immediate material benefits.

Quantification

While the value of material NCPs are frequently realized internally to an enterprise, the risks associated with degradation of regulating and nonmaterial NCPs are more frequently external and borne by society at varying spatial scales. Raising awareness, understanding, and clear-eyed management of these trade-offs both within and among NCPs is therefore a challenge that belongs not only to researchers and land managers but to society more broadly. For example, it involves improving empirical understanding of how NCPs—for which some basis to measure contributing properties already exist, such as outcomes related to carbon and nitrogen cycling or soil structure and stability—affect human health and societal outcomes such as food security or agriculture-based livelihoods. It also requires new efforts to better determine and measure the individual processes or properties related to more general NCPs (such as disease suppression) and the nonmaterial NCPs related to human health and community well-being (such as the interconnected environmental, structural, and societal properties that regulate availability and use of high-quality greenspaces and natural areas). Improving the quantification of NCPs will improve the ability to value them against one another and to communicate their importance to the public.

Recommendation 3-2: USDA and other agencies should prioritize research to better characterize and monitor NCPs (e.g., nitrogen cycling or the nonmaterial NCPs related to human health), to understand the underlying mechanisms to improve predictions (e.g., disease suppression), and to assess their importance across different scales (e.g., plot to landscape and upward). This research should be translated into tools that can be used by land managers in agricultural and nonagricultural settings to inform decisions that involve trade-offs among NCPs.

Preservation

Better characterization and monitoring of NCPs will support efforts to preserve soil. It is likely that resources within the soil that have not yet been discovered are lost each day to erosion, urbanization, and deforestation. Preservation of soil biodiversity needs greater prioritization in general habitat management because it is critical for current services (such as building materials and food provision), potential future services (e.g., undiscovered antibiotics), and the capacity for resilience. Preservation of soil also prevents water and air pollution from dust and sediment, maintains habitat for other organisms, and protects nonmaterial NCPs.

> **Recommendation 3-3: Land managers and city planners should manage landscapes in a way that preserves and promotes soil habitat and biodiversity by minimizing disturbance and soil sealing and optimizing plant cover and diversity wherever possible.**

Enhancing Nature's Contributions to People for Targeted Benefits

NCPs hold the potential to deliver greater benefits, but the mechanisms underlying many of them are poorly understood. As discussed above, certain soils have the ability to suppress diseases, the knowledge of which could be highly beneficial in cropping systems, either through development of new management practices or via inoculation of selective taxa. However, deeper understanding of underlying mechanisms and their context dependency is needed before these benefits can be fully realized. Similarly, enhanced mineral weathering approaches could potentially capture and store atmospheric CO_2 in solid form in soil, but their feasibility needs further investigation. It is also possible that benefits from enhanced NCPs can cascade to adjacent landscapes. For example, preserving wetlands enhances water regulation in adjacent cropland. However, modeling to understand these interactions and how they might be enhanced is still in the early stages.

> **Recommendation 3-4: USDA, the U.S. Geological Survey, and other agencies involved in land management should support research that explores the mechanisms driving soil-derived regulating NCPs and approaches through which their benefits can be enhanced.**

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4

Impacts of Agricultural Management Practices on Soil Health

Understanding how common management practices influence physical, chemical, and biological attributes of soil health is key to fostering sustainable agricultural production systems that balance the need to produce food with the provision of other non-food related services. In this chapter, the committee reviews indicators used to measure soil health and major categories of agricultural management practices and their effects on soil health. However, it should be noted that a practice that is appropriate in one region and cropping system may not be appropriate in another. Also, it is unlikely that a practice is universally good or universally bad. A good example is reduced tillage, where residues are often retained on the surface that reduce erosion and promote microbial biomass and soil organic matter but may also stimulate plant pathogens that reside in those residues (Kibblewhite et al. 2008).

There is great diversity in the kinds of farms and the types of farming practices implemented in the United States. To some extent, the variety is determined by factors outside the farm manager's control, such as climate, landform, hydrology, soil type, population density of the area, distance to market, and length of growing period. Factors such as farm size and resource endowments also influence the farm enterprise undertaken. In addition, a range of management approaches differentiate U.S. farms. Common distinctions include management complexity and philosophy (e.g., conventional, organic, or regenerative; Box 4-1). Many studies have used these contrasts—particularly organic production versus conventional production—to assess effects on crop yield and soil health (e.g., de Ponti et al. 2012; Tahat et al. 2020; Wittwer et al. 2021). The problem with this approach for the committee's task, however, is that there is overlap among these approaches. For example, an organic farm can employ frequent tillage to combat weeds, whereas a conventional farm may use conservation tillage combined with synthetic herbicide applications. As such, evaluating the effects of these production systems on soil health is not necessarily straight-forward as tillage may reduce soil organic matter, a key variable associated with soil health. For this reason, the committee focused on effects of specific management practices, such as tillage and cover cropping, on key variables of soil health irrespective of management system.

INDICATORS OF SOIL HEALTH

The health of the soil can play a major role in how resilient or resistant an ecosystem will be when challenged with disturbances due to climate change, land use change, and other pressures. A healthy soil suppresses pathogens, sustains biological activities, decomposes organic matter, inactivates toxic materials, and recycles nutrients, water, and energy (Tahat et al. 2020). However, assessing a soil as "healthy" is complex, site-specific, and hotly debated (Letey et al. 2003; Ritz et al. 2009). There are numerous soil variables that can be measured (Figure 4-1), and it is not always clear which ones best correspond to the concept of soil health and how they should be compiled and compared (Karlen et al. 2019). Indicators need to be sensitive to variations in management, correlate with soil functions that allow assessments of specific ecological processes in different land uses or ecosystems, be accessible to many users, and allow for comparisons among soils. For example, frequently measured variables, such as microbial biomass and soil respiration, clearly relate to pool sizes and carbon cycling but may be less informative in context outside these gross measurements (Ritz et al. 2009, Bünemann et al. 2018). Additional considerations for indicators relate to sample collection and handling, as well as analytical cost and reproducibility. Lastly, recognizing that each specific soil has inherent characteristics determined by climate, topography, living organisms and parent material, setting universal target values for soil health indicators in absolute terms is likely unproductive (Lehman et al. 2015). Instead, values need to be compared to appropriate reference communities and preferably measured over time to assess responses to shifts in management.

BOX 4-1
Terminology Characterizing Farming Systems

Farming systems[a] are often broadly categorized based on the types of crops grown, the spatial and temporal patterns of cultivation, and the philosophy informing agricultural management practices. There is a high degree of overlap and variety of management practices between and within systems, and farmers often use a combination based on local conditions and specific needs. Below is a nonexhaustive list that briefly describes terms discussed in this report.

Spatial Patterns of Cultivation

Cropping systems vary based on the spatial distribution of crops. Common distributions include:

1. Monoculture: This strategy represents the simplest cropping system where a single crop is grown in a field within a cropping cycle. It is probably also the most used method in the United States as conditions can be optimized for a single species. However, because a single species is grown, this system is more susceptible to pests and diseases than other cultivation patterns.
2. Polyculture: Multiple crops are grown simultaneously, which promotes biodiversity and reduces risk of pest and disease outbreaks. Yield per acre may increase due to complementary interactions among crops, and weed pressure may be reduced due to less open space. However, management and harvest may be complicated due to crop-specific requirements. Intercropping, strip cropping, agroforestry, and integrated crop-livestock systems are all examples of polycultures.

Temporal Patterns of Cultivation

The timing or sequence of planting decisions is also variable. Common patterns include:

1. Double cropping: This cultivation practice refers to the harvesting of multiple crops from one piece of land in the same year, typically via sequential monocropping, such as winter wheat followed by soybeans (Borchers et al. 2014). Relay cropping is a type of double cropping where a second crop is planted directly into an established crop prior to harvest to allow the second crop more time to establish instead of waiting until the first crop is harvested.
2. Crop rotation: This system involves rotating crop species across seasons. If crops are not closely related, rotation can help break pest and disease cycles, reduce soil erosion, and maintain and build soil fertility by varying nutrient demands among crops and by including nitrogen-fixing legumes.

continued

BOX 4-1 *continued*

3. Cover cropping/green manure: Crops are planted to cover the soil between periods where main crops are grown. The aim is to keep the soil covered by a living plant to prevent erosion, build soil structure, and provide resources to soil biota. Also, if the cover crop is a nitrogen-fixing legume, soil fertility will increase, especially if residues are incorporated into the soil. If the cover crop forms mycorrhiza, it can also maintain viability and build the abundance of mutualistic fungi that may benefit the next crop. In more arid systems, however, cover crops may use water that could adversely affect yield of the subsequent main crop (or “cash crop”).

Principles and Philosophy of Management Systems

Cropping systems may also be distinguished by the principles and philosophy of management and inputs applied. These terms are often difficult to quantitatively define, and their meanings and use are highly context dependent. For example, what is considered a “sustainable” alternative system in one region may be the conventional norm in another, and sustainable practices may become the conventional norm with time and increased adoption by farmers. This categorization of farming systems typically relies on comparing the relative intensity of inputs and the degree to which management decisions, intent, and priorities are focused on agricultural outputs or on other factors such as environmental conservation or restoration. Common categories include:

1. Conventional farming: This term describes farming practices such as the application of synthetic fertilizers and pesticides and the intensive use of tillage. In many cases, this term is used to denote “business-as-usual” farming practices in contrast to sustainable or regenerative alternatives (such as conventional tillage practices broadly encompassing those that frequently or heavily disturb the soil compared to conservation tillage practices that significantly reduce or remove tillage entirely). It can produce high yields and is the most common production system in the United States. However, it may be associated with environmental degradation and low sustainability. It also frequently involves monoculture cropping where single crops are grown in a year, although usually with a rotation of other single crops in subsequent years. This type of farming can reduce biodiversity and increase susceptibility to pests and disease, which would necessitate the use of pesticides.
2. Sustainable farming: This term describes systems that implement agricultural management practices intended to mitigate environmental degradation and depletion of natural resources, with a focus on sustaining agricultural productivity. “Sustainable” and “conservation” systems or practices are often used interchangeably. These terms are frequently and broadly used to contrast with conventional farming practices, such as the addition of cover crops meant to protect soil from erosion and prevent nutrient losses between cash crop seasons in contrast to the conventional absence of cover between cash crops.
3. Organic farming: This way of farming avoids synthetic fertilizers and pesticides and aims to build and maintain soil health by practicing crop rotation, cover cropping, and composting. It also aims to minimize environmental degradation, promote biodiversity, and produce food in a sustainable way. While yield is often lower than in conventional farming systems, the price for produce tends to be higher, resulting in similar profit. In the United States, organic farmers can opt to complete legal requirements governed by the U.S. Department of Agriculture (USDA) to have their farms certified as organic. Certified farms are allowed to use the USDA organic seal to market their crops. The certification system prohibits the use of genetically modified

continued

BOX 4-1 *continued*

organisms and the application of synthetic fertilizer and pesticides and sewage sludge. Some organic farmers choose to follow the USDA rules for organic production but forego certification and the use of the organic label because of the minimum 3-year time commitment to convert to USDA-certified organic production.

4. Regenerative farming: This is a term coined in the 1980s to describe a holistic approach that seeks to promote agroecosystem health and resilience by focusing on practices that restore soil health, such as no-till or reduced-till, cover cropping, and rotational grazing. This farming system aims to increase carbon sequestration to build soil health, mitigate climate change, and improve the sustainability of farming by promoting nutrient cycling and water retention. While sustainable farming describes management efforts to maintain or improve agricultural productivity while conserving natural resources, regenerative farming revises this concept to draw more heavily on principles of soil health management and more explicitly prioritize restoring and enhancing natural resources and ecosystem functioning while sustaining or improving agricultural productivity (Schreefel et al. 2020). Regenerative farming currently does not have a formal USDA definition or certification system, but several third-party certification systems with differing criteria exist.[b]

[a] The farming systems described here mainly apply to crop agriculture.

[b] See, for example, https://www.regenerativefarmersofamerica.com/regenerative-agriculture-certifications (accessed January 31, 2024).

Of all indicators used, the most common is soil organic matter (Karlen et al. 2019). This fact is not surprising because small increases in soil organic matter can have cascading effects and promote aggregate stability, increase water and nutrient holding capacity, and boost soil fertility and microbial biomass (Lehman et al. 2015). It is clear, however, that no single measurement could evaluate all aspects of soil health, and assessments frequently include multiple variables, such as microbial biomass, mineralizable nitrogen, aggregate stability, electrical conductivity, pH, water-holding capacity, bulk density, infiltration rate, and inorganic nitrogen, phosphorus, and potassium (Figure 4-1). Bagnall et al. (2023) argued recently for a minimum suite of indicators for use in North American agricultural systems—soil organic C concentration, aggregate stability, and 24 h C mineralization potential—based on the breadth of information they provide about the effect of soil health management practices as well as their scalability and affordability. Efforts such as this to pare down the suite of indicators used in large-scale or producer-focused soil health assessments are valuable to reduce the cost and increase the scope of monitoring, although researchers continue to select indicators for studies based on the measurements that are most appropriate to address specific research questions.

Soil monitoring in the United States is not yet required by law, but soil surveys are conducted by U.S. Department of Agriculture (USDA) agencies, specifically the Natural Resources Conservation Service and the Forest Service (Kimsey et al. 2020). However, indicators used often differ depending on agency and land use type. Outside these monitoring programs, there are two major soil health assessment approaches: (1) the Soil Management Assessment Framework (SMAF), which selects biological, physical, and chemical indicators based on ecosystem services and management objectives (Andrews et al. 2004), and (2) the Comprehensive Assessment of Soil Health (CASH), formerly known as the Cornell Soil Health Test, which is more standardized (Bünemann et al. 2018). Elements of both the SMAF and

CASH frameworks were recently revised and expanded to create the Soil Health Assessment Protocol and Evaluation (SHAPE) tool that better accounts for soil and climate contexts and produces more regionally applicable soil health assessments (Nunes et al. 2021). Additional methods that consolidate variables to compare soil health in organic and conventional production systems or in response to anthropogenic pressures have also been proposed (Klimkowicz-Pawlas et al. 2019; Wittwer et al. 2021). Finally, not all tests are based on laboratory-based techniques, and visual soil evaluation methods are also available for scientists, extension specialists, and farmers (Emmet-Booth et al. 2016).

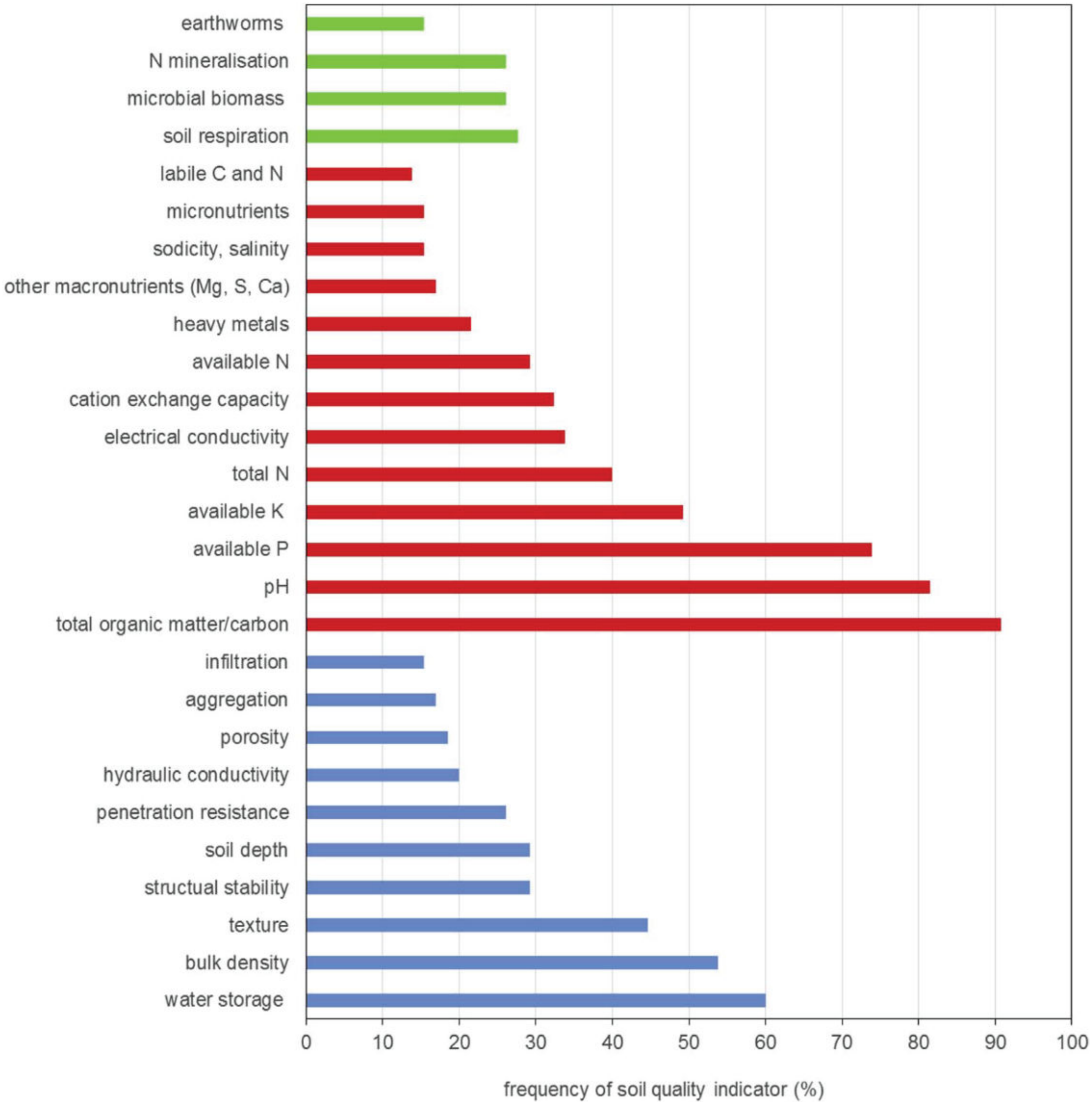

FIGURE 4-1 Frequency of soil health indicators from a review of 62 publications where biological indicators are in green, chemical indicators are in red, and physical indicators are in blue.
NOTE: N=nitrogen; C=carbon; Mg=magnesium; S=sulfur; Ca=calcium; K=potassium; P=phosphorus.
SOURCE: Used with permission of Elsevier Science & Technology Journals, from "Soil Quality—A Critical Review", Bünemann et al., *Soil Biology & Biochemistry* 120, 2018; permission conveyed through Copyright Clearance Center, Inc.

Interpretable, affordable, and accessible data are needed to establish soil health baselines and evaluate changes to soil health in response to different management practices and climate conditions. The lack of harmonized approaches within and among U.S. agencies, researchers, farmers, and analytical laboratories complicates comparisons. An inspiring approach used in the European Union is the recently developed Soil Health Dashboard,[1] which allows for broad assessments of the extent of unhealthy soils and the degradation processes behind them. It consolidates measures from 15 indicators, including aspects of erosion, compaction, salinization, sealing, pollution, nutrients, as well as loss of soil organic matter and biodiversity.

The focus on physical, chemical, and biological indicators have changed over time (Karlen et al. 2019; Yang et al. 2020). In the 1930s, soil structure was primarily measured in the United States, most likely prompted by the erosion associated with the Dust Bowl. Post−World War II, a greater emphasis was placed on physical and chemical indicators due to the increased usage and availability of tillage and synthetic fertilizers in agriculture (Lehman et al. 2015). Soil biological properties were largely omitted during most of the 20th century (Lehmann et al. 2020; Liu et al. 2023), likely to the detriment of soil health and long-term sustainability. Most of the processes essential for the functioning of healthy soils—nutrient cycling, organic matter decomposition, disease suppression, soil structure—are governed by the extraordinary biological diversity of bacteria, fungi, archaea, viruses, protozoa, and fauna found in soil (Delgado-Baquerizo et al. 2019). These organisms thereby play an essential role in the productivity and sustainability of agroecosystems. Recent studies, for example, have shown that increasing soil microbial diversity can promote crop yields and the ability of soils to provide multiple ecosystem functions and services (Wagg et al. 2014; Lankau et al. 2022). Therefore, microbial indicators related to biomass, activity, and diversity are increasingly used due to their ecological relevance, sensitivity, and quick response to changes in environmental conditions (Bünemann et al. 2018). Some drawbacks of biological assessments include technical constraints, requirement of specific knowledge and skills, and lack of standardized information and reference values that hinders the interpretation (Bünemann et al. 2018; Yang et al. 2020). A recent effort in California to address current practices and future directions for integrating soil biodiversity into soil health analysis for agricultural producers, policy makers, governing agencies, and stakeholders recommended soil biodiversity as a principal measure in soil health evaluation and proposed a selection framework for how to choose biodiversity indicators relevant to different contexts (CDFA 2023). Wageningen University in the Netherlands has similarly developed the web platform Biological Soil Information System (BIOSIS) to map the relationships between soil organisms and nutrient cycling, climate regulation, water regulation, and disease and pest management.[2]

The development of advanced molecular methods has opened what was once a black box further and has facilitated the study of nonculturable soil microbes. Using compositional or functional aspects of soil microbes as health indicators have potential (Sahu et al. 2019) as these methods can perform faster, cheaper, and possibly more informative measurements of soil biota and soil processes than many other methods. Further, network analyses, structural equation modeling, and machine learning may at some point elucidate clear links between indicators and function, although this is not yet possible (Fierer 2017). There may be three main reasons for this: (1) there is great functional overlap among taxa, (2) an unknown proportion of DNA could come from dormant microorganisms (Fierer 2017), and (3) a large proportion of soil microbes

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[1] European Commission Joint Research Centre. “EUSO Dashboard.” Accessed April 29, 2024. https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/.

[2] BIOSIS. “BIOSIS Platform.” Accessed April 29, 2024. https://biosisplatform.eu/.

still needs to be characterized taxonomically and functionally. For example, less than 20 percent of molecular taxa found in a survey from 230 locations matched known bacterial species (Nannipieri 2020), indicating that the majority of microbial diversity is still unknown. The diversity and functionality of viruses is even more opaque; the roles phages may play in soil ecosystems is just beginning to be understood (Martins et al. 2022). As such, molecular methods that more directly target functions and link to ecosystem processes irrespective of taxon ID may be more informative than those that describe composition. Such methods, including stable isotope probing transcriptomics, metabolomics, and metaproteomics, continue to advance and could be assessed against other measures of function. They are further discussed in Chapter 7.

Technology is also changing the ease and affordability of collecting data on soil health indicators. As reviewed in the National Academies' report *Science Breakthroughs to Advance Food and Agricultural Research by 2030*, a network of sensors to measure biological, chemical, and physical reactions in soil over time is not science fiction (NASEM 2019). Unfortunately, there are still challenges to solve when it comes to deploying sensors that transmitted reliably and indefinitely under field conditions (NASEM 2019).

AGRICULTURAL MANAGEMENT PRACTICES

Lehman et al. (2015, 998) argued that "soil and crop management practices must: (1) maintain soil carbon, (2) control erosion, (3) maintain soil structure, (4) maintain soil fertility, (5) increase nutrient cycling efficiency, (6) reduce export of nutrients and thus the need for increased inputs, and (7) reduce pesticide input requirements and potential export of either their materials or their residuals." These requirements broadly align with four approaches often highlighted to promote soil health, which includes maximizing continuous living roots, biodiversity, and soil cover while minimizing disturbance (Figure 4-2).

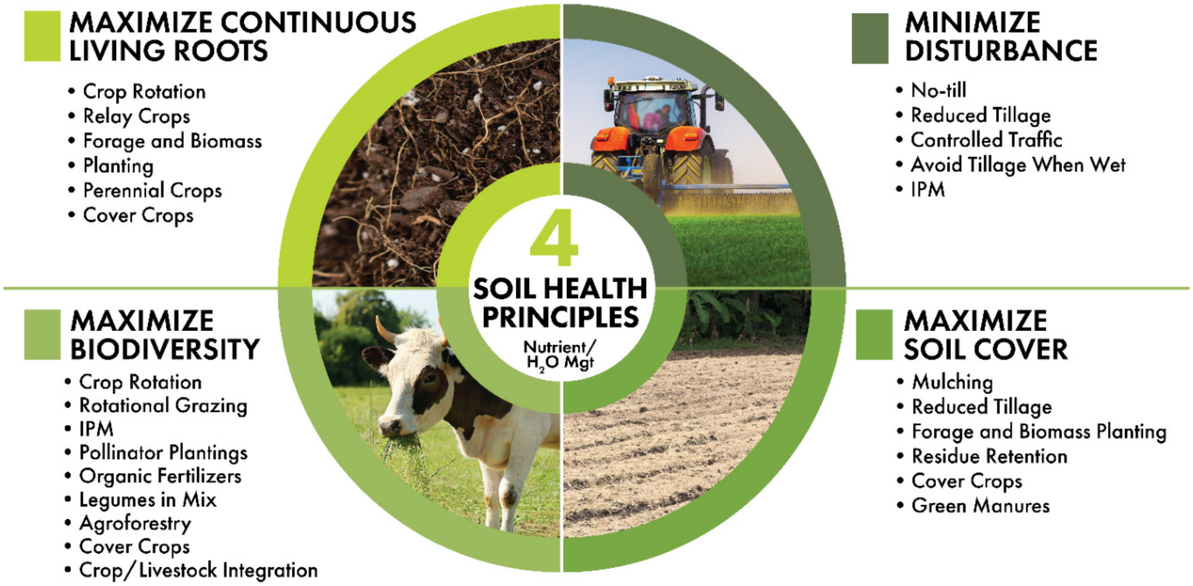

FIGURE 4-2 Four broad approaches that are often highlighted to promote soil health as well as common management practices that can align with those goals.
SOURCE: USDA–NRCS (2019).

Recognizing that effects of management practices and their applicability is region and crop specific, the committee reviewed how common practices may affect key variables associated with soil health. Most research has been conducted on row crops, but the committee cites examples from other cropping systems when possible (Box 4-2).

BOX 4-2
Urban Agriculture

While not explicitly in its statement of task, the committee felt it was important to draw attention to urban agriculture as a small but growing food production setting in the United States. Urban food production has long been important during times of distress. For example, more than 23 million U.S. families participated in subsistence garden programs during the Great Depression, and during World War II, many households grew produce for home consumption, recreation, and morale as part of the victory garden campaign (Lawson 2005). Gardening in urban and suburban areas blossomed during the Covid-19 pandemic, with noted benefits for food security and well-being (Falkowski et al. 2022).

In recent decades, there has been a resurgence in urban gardening and farming due to an increased appreciation of local food production, community-building, and a desire to increase food security (Yuan et al. 2022). In addition to produce, urban gardening has shown clear benefits to human health and well-being by providing access to nature, enjoyable physical activity, reduced air and noise pollution, and stress relief (Schram-Bijerk et al. 2018). Personal gardens also offer habitat for many plant, animal, and microbial species and have the potential to be islands of biodiversity (Goddard et al. 2010). Urban food production may also provide many regulating services, including carbon sequestration, nutrient cycling, water storage for flood control, and a reduction of heat islands (Artmann and Sartison 2018; Schram-Bijerk et al. 2018). Recognizing these many potential benefits, the 2018 Farm Bill authorized a new Office of Urban Agriculture and Innovative Production to promote urban, indoor, and other emerging agricultural practices; new pilot projects in U.S. counties with a high number of urban and suburban farms; and a competitive grants program for research and extension activities related to urban, indoor, and other emerging agricultural practices (CRS 2019).

In general, the same principles used for building soil health in rural agricultural soils (see Figure 4-2) apply in urban soils. However, food grown in urban settings may need specific strategies guided by soil tests to assess the level of potential heavy metal contamination, nutrient availability, soil organic matter, and pH, and interventions or trainings can be helpful in raising awareness of possible contamination issues to those working the soil (Hunter et al. 2019). Heavily contaminated soils would need to be either replaced—an often-cost prohibited strategy—or capped by landscape fabric or clay that prevents mixing with noncontaminated media added on top. Soils with low levels of contamination may be amended with compost so long as compost additions do not reduce soil pH as this could exacerbate the bioavailablity of heavy metals (Murray et al. 2011; Attanayake et al. 2014). To enhance soil functions, biodiversity, and nature's contribution to people, gardeners should promote plant diversity, lower management intensity, apply mulch, and avoid soil tilling as much as possible (Tresch et al. 2019). Increased collaboration between urban planners, soil biologists, and farmers is also crucial to ensure soil health is part of the urban planning policies (Guilland et al. 2018).

Tillage

The practice of physically cultivating, or tilling, the soil serves many purposes. It is used to control weeds, incorporate crop residue or fertilizer into the soil, and prepare the soil for seeding. Tillage practices range widely in equipment used (from hand-hoeing to tractor-mounted equipment), frequency (never, annually, or multiple times per year), and depth (from shallow scratching for seedbed preparation or soil crust disturbance to deep plowing greater than 20 inches). These practices vary widely by location as topography, weather, soil type, and precipitation affect the timing and type of tillage used.

Conventional tillage and conservation tillage are two broad groups of practices, with a great deal of variation within each category (Claassen et al. 2018). “Conventional tillage” typically refers to practices that invert the surface layers of the soil, such as through use of a moldboard plow, that may be followed by secondary tillage to smooth or shape the soil surface. “Conservation tillage” applies to various strategies that either remove tillage entirely (i.e., “no-till”) or reduce the frequency and intensity of soil tillage (e.g., “reduced tillage,” “minimum tillage,” or “strip tillage[3]”) compared to conventional practices for a given cropping system (Blevins and Frye 1993).

Research on conservation tillage practices began in the United States in the 1940s (Allmaras and Dowdy 1985), and such practices are used widely in the production of wheat, corn, soybean, and, to a lesser extent, cotton today (Figure 4-3). Nevertheless, survey data from USDA found that almost half of U.S. land in these crops is conventionally tilled each year (Figure 4-4). Geography and soil conditions matter, but the frequent use of conventional tillage is also partly because choices about tillage practices are closely tied with the crop that is planted and with the longer-term plan for crop rotations and land-cover management on the farm (Claassen et al. 2018).

Tillage can positively affect soil health when used judiciously in certain management systems, soil types, and climates to incorporate plant or animal residues into the soil, reduce weed or pest pressure, or temporarily alleviate compacted surface or subsoil layers and increase aeration (Çelik et al. 2019; Li et al. 2019; Peixoto et al. 2020). However, the body of literature to date has shown that conventional tillage, often in combination with monoculture cropping systems, results in lower soil health through physical disturbance of soil aggregates that influences soil nutrient and carbon flow and the physical soil habitat for microorganisms and other soil fauna compared to reduced tillage or no-till systems (Nunes et al. 2020a,b; Liu et al. 2021). Lower soil organic carbon (SOC) and microbial biomass are generally observed in conventionally tilled systems compared to conservation tillage or no-till systems or undisturbed perennial systems (Nunes et al. 2020b). Long-term studies have reported lower size and stability of soil aggregates under conventional tillage compared to reduced tillage or no-till systems (Beare et al. 1994). Destroying large, stable soil aggregates through tillage has also been shown to release previously protected carbon and nitrogen into the easily available fraction, which may temporarily improve short-term plant and microbial growth but significantly depletes soil carbon and nitrogen stocks with time (Cambardella and Elliott 1993; Mikha and Rice 2004). Lower SOC combined with degraded soil structure are both linked to lower soil water-holding capacity (Bagnall et al. 2022), although a few long-term field studies have found mixed or neutral effects of tillage on soil water holding capacity (Blanco-Canqui et al. 2017).

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[3] Strip till is a type of conservation tillage practice that minimizes soil disturbance by tilling only in narrow strips of soil in which the seeds will be planted. See Claassen et al. (2018).

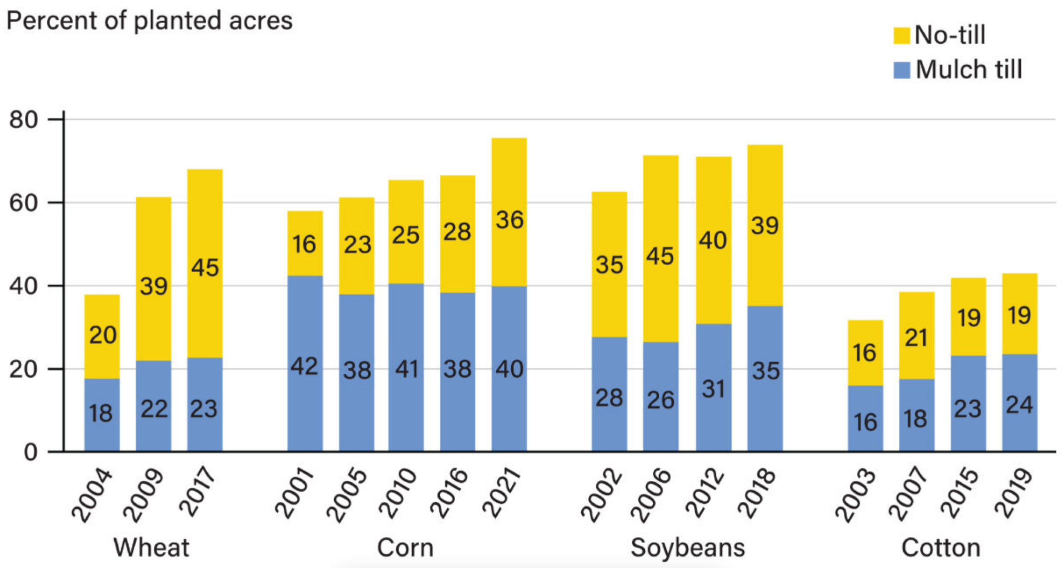

FIGURE 4-3 Percent of mulch till and no-till planted acreage for four crops.
NOTES: In no-till production, farmers plant directly into remaining crop residue without tilling. Mulch tilling involves using instruments such as a chisel or a disk with low soil disturbance. Conservation tillage is the sum of no-till and mulch till acreage. Data reflects the year in which each crop was included in the survey.
SOURCE: U.S. Department of Agriculture–Economic Research Service. "Adoption of Conservation Tillage Has Increased Over the Past Two Decades on Acreage Planted to Major U.S. Cash Crops." Accessed April 27, 2024. https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=105042.

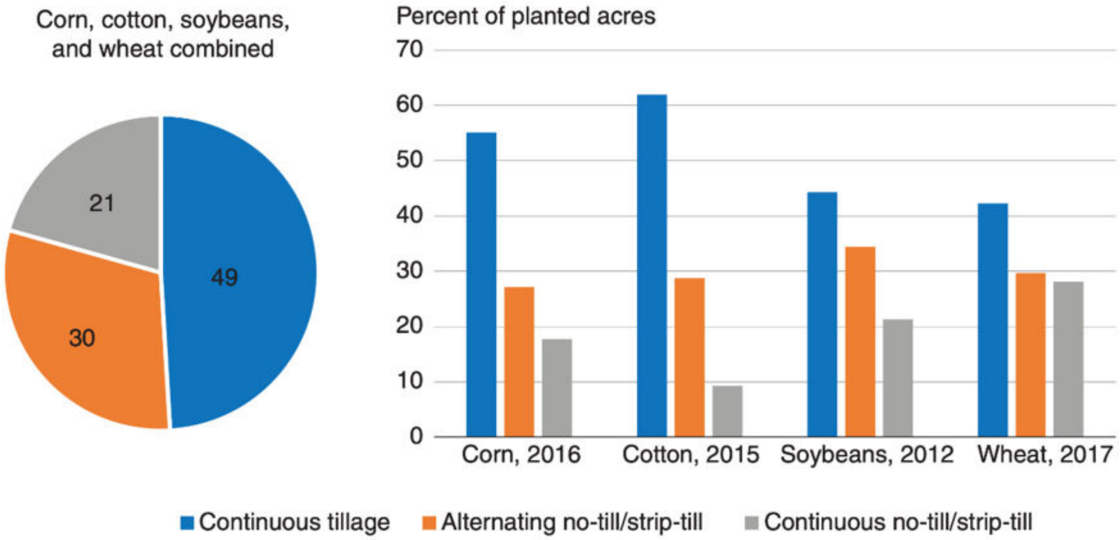

FIGURE 4-4 Percentage of acreage, by survey crop and for all crops combined, using a tillage practice for four consecutive years.
NOTES: Continuous tillage is continuous full-width tillage for 4 years. Survey fields grew wheat in 2017, soybeans in 2012, cotton in 2015, or corn in 2016 but could have been planted in other crops during any of the 3 years preceding the survey year.
SOURCE: Claassen et al. (2018).

Elucidating the effect of tillage on soil biota is sometimes complicated by confounding effects of other treatments. For example, no-till experiments are often combined with cover cropping where beneficial effects on soil microbiome diversity (Kim et al. 2020) may result primarily from the presence of multiple plant species and not necessarily from a lack of disturbance. Likewise, the higher bacterial diversity in no-till systems found in a recent meta-analysis (Y. Li et al. 2020) was mainly attributed to the remaining stubble, not the absence of tillage. Some decreases in bacterial diversity have been observed in response to no-till despite higher microbial biomass and activities (Tyler 2019). Nonetheless, there may be some general patterns related to soil biota effects of tillage. First, larger organisms, such as earthworms and beetles, are often more negatively affected than smaller organisms, although microbial biomass and activities are typically significantly lower under tillage as well. This decrease in microbial biomass may be driven more by fungi than bacteria because tillage disrupts fungal hyphae, especially at shallow depths (Frey et al. 1999). Not all fungi respond the same, however, and tillage may favor saprotrophic fungi that decompose residues that are incorporated, while suppressing symbiotic mycorrhizal fungi (Kabir 2005; Helgason et al. 2010; Sharma-Poudyal et al. 2017; Schmidt et al. 2019). For mycorrhizal fungi, tillage is especially damaging if done in the fall and combined with fallow, as hyphal fragments may not survive the winter to colonize emerging plant roots in the spring. This loss, in turn, may negatively influence both soil and plant health because these fungi promote aggregate stability (and thus infiltration and water holding capacity) in soils and aid in plant nutrient uptake, drought tolerance, and pathogen protection (Kabir 2005; Delavaux et al. 2017).

Furthermore, mixing the upper soil horizons[4] through tillage can reduce the stratification of carbon, microbial activities, and certain nutrients near the surface that naturally develops in undisturbed ecosystems (Prescott et al. 1995; Van Lear et al. 1995; Schnabel et al. 2000; Franzluebbers 2002) and no-till agricultural soils (Dick 1983; Melero et al. 2009; Blanco-Canqui and Ruis 2018; Blanco-Canqui and Wortmann 2020). Stratification of soil layers in previously tilled agricultural soils with poor structure that have been converted to no-till may also lead to surface or subsoil compaction in some systems (Blanco-Canqui and Ruis 2018), but this can be alleviated either in the short term with occasional tillage or in the long term by allowing soil structure and porosity to recover and develop naturally with time in no-till systems (Voorhees and Lindstrom 1984; Sidhu and Duiker 2006). Soil compaction more frequently results from heavy machinery traffic and tilling when the soil is wet in conventional tillage systems (Kirby and Kirchhof 1990).

Reduced soil structural stability from tillage can also make soils more vulnerable to wind and water erosion (Baumhardt et al. 2015). Given that the physical loss of soil by erosion is a significant ongoing threat to the soil's ability to sustain productivity alongside negative human health outcomes of sediment inhalation from dust storms caused by erosion (see Chapter 3), slowing the rate of erosion through adoption of conservation tillage or no-till practices combined with cover cropping is a critical step in ensuring sustainable and resilient long-term agricultural production.

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[4] Soil forms in layers called horizons. The surface horizon is labeled A (to a depth of ~10 inches), the subsoil is B (10−30 inches deep), and the substratum is C (30−48 inches deep). Some soils may have an O or organic horizon on the surface, which may be 1−2 inches in depth. Every soil has unique combinations of horizons due to the influence of soil-forming factors and processes and may not contain all of the primary horizons described above. For more information about soil horizons, see Soil Science Division Staff (2017).

However, implementation of no-till practices has also been accompanied by sustainability trade-offs such as greater reliance on synthetic pesticides to combat weed and pest pressure in the absence of tillage. Increased adoption of conservation tillage and no-till has been noted as a contributing factor to the rising use of the herbicide glyphosate in agricultural systems (Benbrook 2016). Tillage is an effective strategy for controlling weeds and incorporating crop residues, whereas herbicides such as glyphosate play a key role in weed management in no-till systems. The effects of tillage and of no-till systems on animal pests (e.g., insects, birds, and nematodes) vary according to the influence of tillage on the pest species and on its natural enemies (Murrell 2020). Lower insecticide runoff in no-till systems was observed in one study (Mamo et al. 2006), presumably because the larger pore sizes in no-tilled soil allow the insecticide to enter the soil and be bound to soil minerals or organic matter or degraded by soil microbes (Shipitalo et al. 2000). This soil infiltration does not occur in no-till vegetable systems that use plastic mulch, so pesticide runoff can be extremely high in such systems (Arnold et al. 2004; Rice et al. 2007). Increased loads of herbicides and insecticides have been detected in runoff from no-till fields compared to conventionally plowed fields according to a global meta-analysis (Elias et al. 2018).

While no-till and diverse cover cropping are effective strategies for increasing soil health and stability of agroecosystems, it will be challenging to develop no-till systems that are free from the use of herbicides (Colbach and Cordeau 2022; Ferrante et al. 2023). However, increased research in conservation tillage and no-till systems with novel management strategies hold potential for addressing these issues, such as implementing diverse cover crop mixes that include species with allelopathic effects on weeds (Sharma et al. 2021). Collaborative research is also underway in California to reduce tillage in organic cropping systems (Filmer 2020).

Water Management

Irrigating to provide sufficient water for crop production influences soil health. Irrigation practices range widely based on the mechanism (equipment types and gravity vs. pressure driven), location (above or belowground, localized vs. distributed irrigation), and the frequency, amount, and timing of water delivered to crops. The use of irrigation, its efficiency, and the type of crops irrigated has also varied over time in the United States (Hrozencik and Aillery 2021).

More than 54 million acres of U.S. cropland was irrigated in 2017, and irrigated harvested cropland was about 17 percent of all harvested cropland that year (Hrozencik and Aillery 2021; Figure 4-5). The impetus to irrigate depends on location and the crop being grown. For example, irrigation in the western United States is used to supplement insufficient precipitation to support crop production whereas, in the Mississippi Delta, flood irrigation supports rice production (Hrozencik and Aillery 2021). Over the past 25 years, irrigation has been moving from the West to the East as water resources for agriculture become more constrained in the West due to declining surface and groundwater resources for irrigation, reduced precipitation, and competition from nonagricultural uses while the pull to mitigate against drought in traditionally rain-fed systems has grown in the East (Figure 4-6).

As of 2017, the crop with the most acres irrigated was corn. The 14 million acres of irrigated corn accounted for 25 percent of all irrigated acres, although that acreage was less than 15 percent of the total numbers of acres of harvested corn (Hrozencik and Aillery 2021; Figure 4-7). By contrast, 70 percent or more of the acres planted to vegetables, rice, and orchard crops are irrigated.

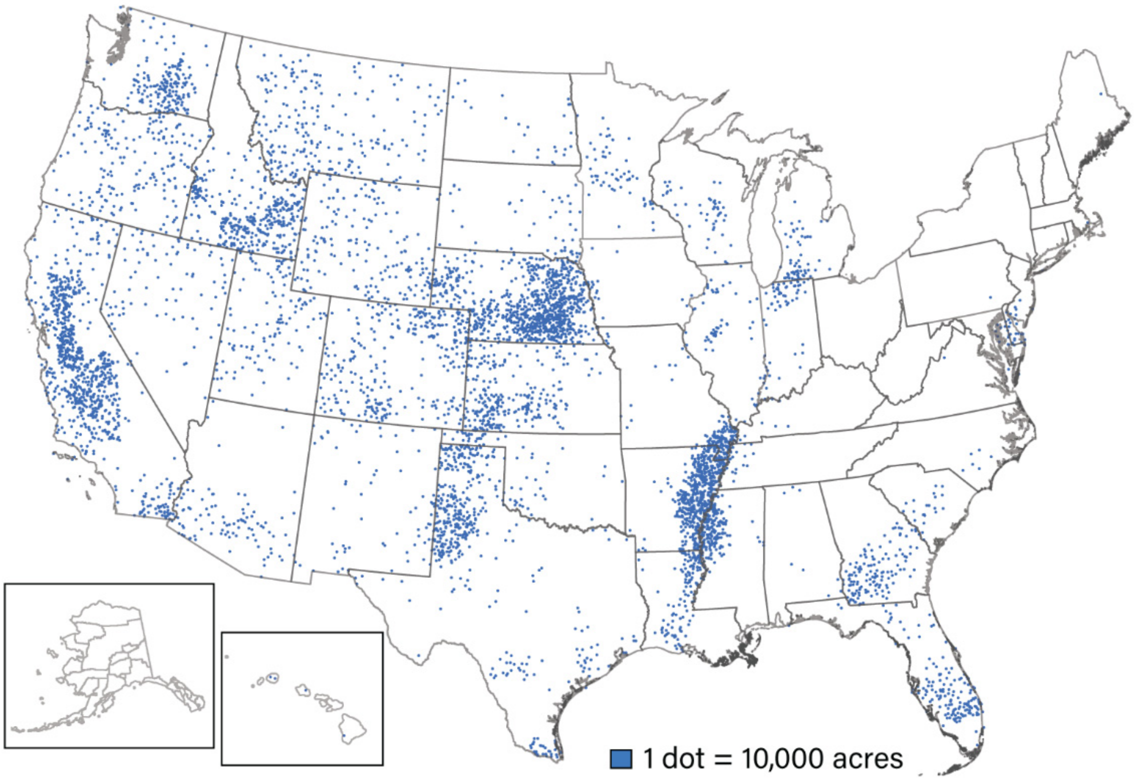

FIGURE 4-5 The spatial distribution of U.S. irrigated farmland in acres, 2017.
NOTE: Fifty-four million acres of cropland and 4 million acres of pastureland were irrigated in 2017.
SOURCE: Hrozencik and Aillery (2021).

Researchers and land managers are continuing to develop and implement different irrigation strategies in an effort to increase crop water use efficiency, conserve diminishing water supplies, and leverage recycled water sources to sustain or increase agricultural productivity under future climate conditions. Strategies such as subsurface drip irrigation, which applies water below the soil surface using perforated flexible tubing installed along the rows, or deficit irrigation, where water is judiciously applied only during the plant growth stages where they would be most damaged by drought (e.g., during early vegetative growth or fruit ripening) can significantly increase crop yields with less water loss compared to surface irrigation or flooding (Ayars et al. 1999; Geerts and Raes 2009).

Increased plant productivity and water conservation under subsurface drip or deficit irrigation could benefit soil health and microbial communities, especially in dry climates where these resources are highly limited, but little research has focused on soil health outcomes of different irrigation methods. Studies comparing subsurface drip irrigation (which is more common in reduced tillage or no-till systems than in frequently tilled systems due to risk of damaging the drip tape during cultivation activities, unless it is buried well beneath the tillage depth) to furrow irrigation in organic tomato systems in California have revealed that subsurface drip can increase plant productivity and water savings, but at the same time may lower microbial biomass and carbon sequestration potential due to microbial responses to altered wet-dry cycles and lower macroaggregate formation (Griffin 2018; Schmidt et al. 2018; M. Li et al. 2020). While irrigated cropping systems in dry environments can potentially contribute to increased greenhouse gas (GHG) emissions (Sainju et al. 2008), studies have also shown significantly decreased emissions of CO_2, CH_4, and N_2O under subsurface drip irrigation (Wei et al. 2018; Guardia et al. 2023). These decreases are highly beneficial in terms of reducing the GHG footprint of irrigation and crop production, but if paired with lower microbial biomass and carbon-cycling in some cases as referenced above, it may also be indicative of trade-offs in microbial activities and soil health compared to more heavily irrigated agricultural systems. Some studies have shown that different inputs such as biochar or other organic amendments may be able to improve or sustain soil microbial abundance and activities under drip irrigation in arid systems (Liao et al. 2016), which shows the potential for combining certain agricultural management practices with efficient irrigation strategies to alleviate potential trade-offs. Developing strategies that balance both water savings and productivity with improved soil health and carbon sequestration potential compared to systems with inefficient or higher irrigation inputs is therefore critical to achieving complimentary goals of increasing soil health and long-term agroecosystem productivity.

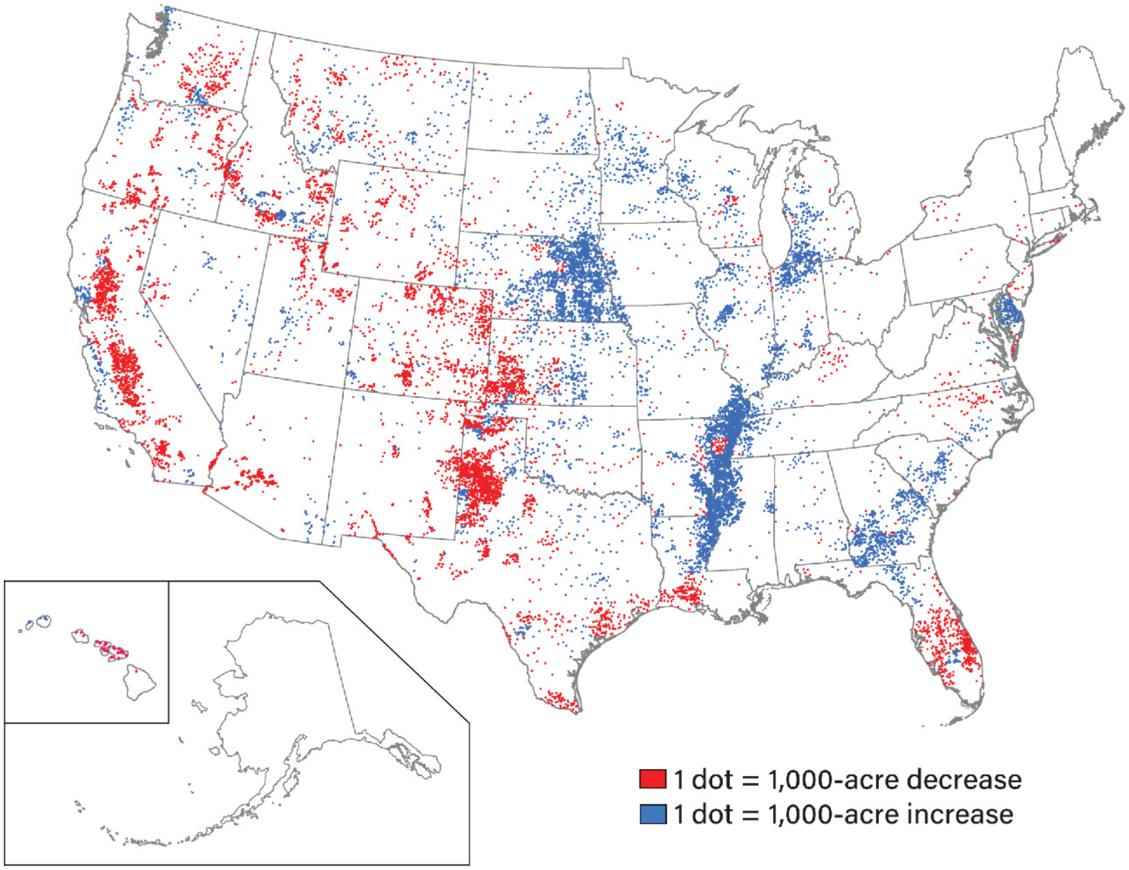

FIGURE 4-6 The change in spatial distribution of U.S. irrigated farmland in acres, 1997 to 2017.
NOTES: Net increase in of 1,724,735 acres between 1997 and 2017. Dots represent county-level changes in irrigated acreage.
SOURCE: U.S. Department of Agriculture–Economic Research Service. “Irrigated Agricultural Acreage Has Grown, Shifted Eastward, While Western Irrigated Acreage Has Declined.” Accessed April 27, 2024. https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=107509.

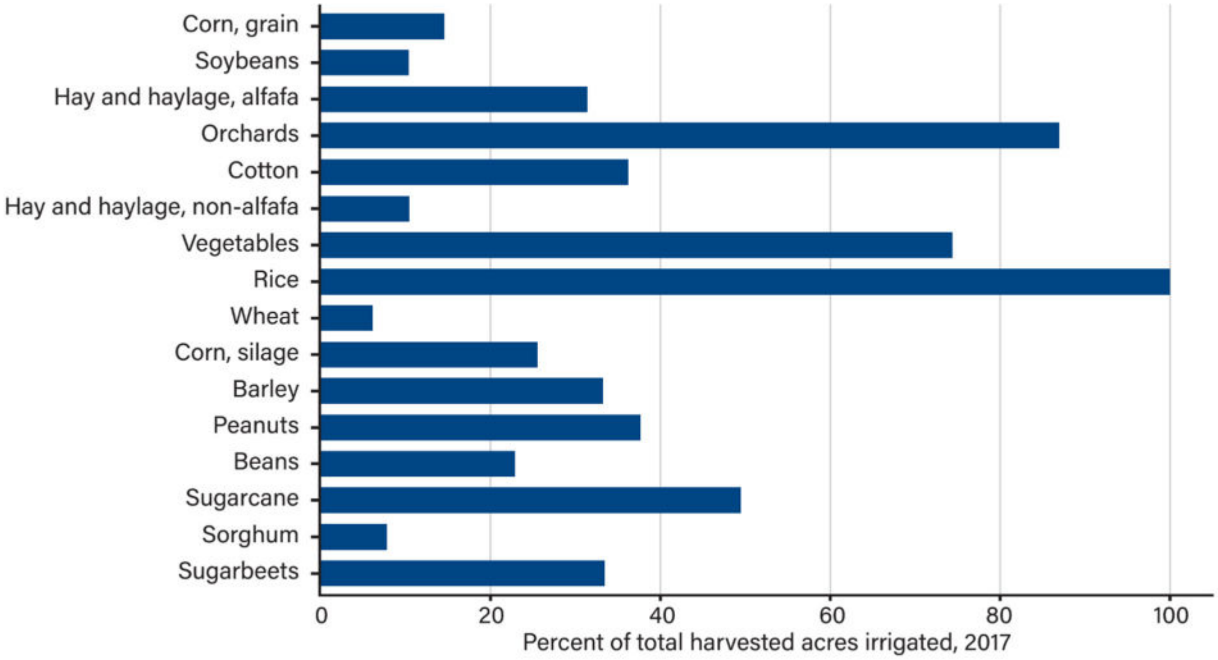

FIGURE 4-7 Irrigated acres as a share of total acres harvested by crop in 2017.
SOURCE: Hrozencik and Aillery (2021).

Irrigation-induced change in the natural water input patterns and seasonality of plant and microbial activities when natural drylands are converted to agriculture or urban systems disrupts ecosystem processes that had been adapted to, or even dependent on, water-limited conditions (Hoover et al. 2020). Biological activity and nutrient cycling in drylands typically operate in a system of pulse dynamics, where plant and microbial activities may be reduced or dormant during long dry periods, then a flush of activity occurs during rainfall events (Collins et al. 2014). In arid and semi-arid agricultural systems, irrigation to alleviate water deficits can theoretically improve soil health by sustaining plant growth and soil microbial activities through otherwise dry periods because plant growth and soil biological activities rely on adequate soil moisture (Manzoni et al. 2012). Although added water in otherwise dry ecosystems can potentially increase both plant growth and microbial incorporation of residues into soil organic matter (Gillabel et al. 2007; Apesteguía et al. 2015), the outcome is not always increased SOC, especially when considering deeper soil depths (Denef et al. 2008). In addition, land use change from unirrigated natural drylands to irrigated agricultural systems are typically accompanied by tillage-induced disturbance and removal of plant residues through harvest that can lead to reduced microbial activities and carbon sequestration compared to undisturbed drylands such as native rangeland or grasslands enrolled in USDA's Conservation Reserve Program (Acosta-Martinez et al. 2003).

The source and quality of water used for irrigation can significantly influence the relative benefits of added moisture for soil health. Accumulation of salts and water-soluble nutrients such as NO_3-N in soils and groundwater resources from irrigation is of significant concern in semi-arid agricultural regions (Scanlon et al. 2010), and increased salinity or sodicity from irrigation can inhibit soil microbial activities (Rietz and Haynes 2003; Yuan et al. 2007). In an effort to conserve increasingly scarce potable water for human consumption, researchers and land managers are exploring ways to use reclaimed water (from industrial, municipal, and off-farm and on-farm animal operations) and recycled water (captured effluent from soil drainage systems) for irrigation. Recycled water was used on approximately 1 million acres, while water from reclaimed sources was used to irrigate 520,000 acres in the United States in 2018. Combined, this acreage accounted for less than 2 percent of total U.S. irrigated acreage (Hrozencik and Aillery 2021). While reusing water holds potential for improved water-use efficiency, there are also concerns with these sources. Reclaimed industrial or municipal water leveraged as a novel irrigation source frequently contains high salinity and contaminants that potentially harm certain plants or beneficial soil microorganisms. It remains to be seen how these resources can be used sustainably or what their impacts on human health or soil health will be (Becerra-Castro et al. 2015; Miller et al. 2020).

Excessive levels of salts in even treated irrigation water are also of particular concern, especially in arid or semi-arid environments that have high soil pH and experience less frequent flushing of water through the soil profile and are thus more susceptible to salt accumulation in soils (Corwin 2021; Díaz et al. 2021). Excess salts and nutrient loads from recycled water are also a concern for sustainable water reclamation in soils that have been managed with tile drainage to prevent flooding and anaerobic conditions, as effluent tends to include high levels of salts, phosphorus, and NO_3-N (Skaggs et al. 1994). However, little research has focused on the soil health outcomes of reusing tile drainage water in irrigated systems, and a recent study found no negative long-term effects of drainage water recycling on soil health (Kaur et al. 2023).

In some areas, a primary challenge to soil management is too much water rather than too little. Historically, draining soils in areas that received too much rainfall or in low-lying areas with rich soil but high water tables allowed agricultural production to flourish, including in many states across the midwestern United States. In addition to direct management of surface or subsurface drainage, other agricultural practices to improve drainage and alleviate waterlogging stress on plants include strategic deep tillage to loosen compacted subsoil layers, planting companion crops with high water demand and tolerance to waterlogged conditions, and planting earlier for some crops (such as small grains) so that they are less susceptible to early-growth damage (Manik et al. 2019). Alleviating waterlogged or poorly drained agricultural soils remains critical in many regions of the United States to improve soil aeration and nutrient cycling and to increase plant root growth and leaf photosynthetic activity to improve crop yields (Manik et al. 2019). However, drainage and conversion of wetlands to agricultural land incurs significant costs to water quality, wildlife communities, and soil health (Fausey et al. 1987). Tile draining soils for agricultural use, even in soils that are not formally classified as wetlands, can cause issues due to increased salt and nutrient loads in drainage effluent, although this also helps to prevent salt and nutrient accumulation in the soil that is being drained (Skaggs et al. 1994). Overall, extensive agricultural drainage systems that alter the natural hydrology and connections between watersheds has significantly increased nutrient loads and pollutant runoff to aquatic systems and disrupted water and nutrient cycles, which causes further issues not only for the supply and quality of water for human use but also for the health and functioning of human and natural ecosystems (Blann et al. 2009; see also the section "Nutrient Cycling and Climate Regulation" in Chapter 3).

One of the well-documented impacts of wetland drainage for agricultural production is the potential for acid-sulphate soils to form when previously reduced forms of iron and sulfur are exposed to air during drainage. After drainage, the soil pH is severely reduced, which damages both agricultural production and groundwater resources for human and agricultural use (Dent and

Pons 1995). Water runoff from areas that have been subjected to wetland drainage tend to have higher salinity and nutrient loads than runoff from areas where wetlands remain intact or are restored (Fisher and Acreman 2004; Westbrook et al. 2011). Exposing wetland soils that had previously served as a sink for carbon and organic residues to air also significantly increases GHG emissions (Tan et al. 2020). In arid and semi-arid regions where groundwater is a primary source of irrigation, drainage or inhibiting wetland functionality (e.g., of "prairie potholes" in the northern U.S. Great Plains, or "playas" in the southern U.S. Great Plains) can inhibit long-term groundwater recharge and reduce water quality and quantity for human and agricultural use (Luo et al. 1997; Luo et al. 1999; Westbrook et al. 2011; Bowen and Johnson 2017).

Crop Choice and Rotation

The amount and form of organic material entering agricultural soils is strongly influenced by the choice and management of crops and cropping systems. Decay and incorporation of above-ground plant biomass, root growth and secretion of exudates, and root turnover are all mechanisms through which plant-derived organic material enters the soil, feeds microbial communities, and contributes to soil structure. The diversity of plant species present—across both space and time—and the extent to which land remains covered by plants and populated with live roots exert a strong influence on soil health. Depending on plant diversity and species identity, plant–soil feedbacks will also generate microbial communities that can promote or suppress yield, depending on the buildup of mutualists or crop-specific pests or pathogens. A mechanistic understanding of how plant–soil feedbacks shape long-term changes in soil health and crop productivity is key to developing new management strategies that leverage interactions between crop plants and soil biota to improve agricultural sustainability and response to climate change (Mariotte et al. 2018).

Land Cover, Biomass Input, and Living Roots

After crops are harvested, leaving crop residues (e.g., stover) on a field (with or without incorporation into the soil) can provide a valuable input of organic matter, whereas residue removal (e.g., for straw or biofuels) can accelerate depletion of soil organic matter (Wilhelm et al. 2007; Xu et al. 2019). The proportion of crop residue removed logically influences the carbon sequestered in the soil, as confirmed by a meta-analysis of corn stover removal studies (Xu et al. 2019). Across the studies analyzed, the removal of less than half the corn stover in a field resulted in SOC levels that were 1.4 percent lower than corresponding fields in which all the stover had been retained in the field, while removal of more than 75 percent of stover had SOC levels that were 8.7 percent lower. The authors indicated that "limiting stover removal to a low level (e.g., 30–40 percent) could minimize the adverse impacts of stover removal on SOC, as is currently the recommended practice" (Xu et al. 2019, 1227).

Cover crops[5] can serve as an additional source of biomass input while also taking up and retaining nutrients in the agroecosystem, protecting and anchoring soil during periods between cash crops when the soil might otherwise be exposed to wind and water erosion, and supporting

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[5] The U.S. Department of Agriculture defines cover crops as "crops, including grasses, legumes, and forbs, for seasonal cover and other conservation purposes. Cover crops are primarily used for erosion control, soil health improvement, weed and other pest control, habitat for beneficial organisms, improved water efficiency, nutrient cycling, and water quality improvement" (USDA–NRCS 2019).

soil microbial communities (Dabney et al. 2001). For example, cover cropping to shorten duration of fallow has been found to promote the abundance of mycorrhizal fungi across a range of studies, which in turn increased the root colonization, phosphorus uptake, and yield of subsequent crops (Lekberg and Koide 2005). Leguminous cover crops such as clover and vetch have the added ability to fix nitrogen via symbiosis with soil bacteria, providing a nitrogen-enriched source of organic material that can promote soil health by reducing the need for fertilizer inputs and delivering a slow release of nutrients as the biomass is decomposed by soil macro- and microorganisms (Boddey et al. 1997; Bohlool et al. 1992; Soumare et al. 2020; Wittwer and van der Heijden 2020). If added or maintained on the soil surface, they can also reduce erosion, prevent soil sealing, and suppress weeds (Blanco-Canqui and Lal 2009). For example, Brassica plants that produce glucosinolates have been shown to suppress weeds, fungal pathogens, and disease-causing nematodes, which could reduce the need for pesticides if used correctly (Haramoto and Gallandt 2004; Larkin and Griffin 2007).

Despite these potential benefits, cover crop adoption in the United States is relatively low. Only 5 percent of U.S. cropland used a cover crop in 2017 (Wallander et al. 2021). The lack of widespread adoption may be related, in part, to the modest yield reductions associated with recent adoption of cover cropping (Deines et al. 2023). The use of cover crops also varies across the country because of differences in the types of crops planted, the properties of the soil, the extension and financial assistance available in an area, and the expenses associated with cover crop seed acquisition, planting, and termination (Wallander et al. 2021). Studies of the use of cover crops in low-precipitation, dryland cropping systems have found that cover crops may deplete soil water available to cash crops and reduce yields (Adil et al. 2022; Garba et al. 2022 Kasper et al. 2022). However, despite trade-offs in water use from cover crops in dryland systems, the long-term benefits of cover crops that protect vulnerable soils from erosion and add reside and root inputs for greater soil stability and organic matter sources are a worthwhile investment for sustained productivity and soil restoration. A long-term study in New Mexico demonstrated that even when water use by cover crops decreases cash crop yield, after accounting for additional benefits of cover crops such as preventing soil erosion and contributing nitrogen from legumes, use of cover crops is more economically feasible than fallow periods between cash crops (Acharya et al. 2019). Recent work from long-term semi-arid cotton cropping systems have further shown that, although cover crops may indeed deplete soil water during the period of peak growth and around termination, cover crop presence in no-till soils consistently and significantly increases the soil's ability to store what little water is received from precipitation or irrigation throughout the cotton growing season and reduces overall soil water resource depletion by the cotton crop compared to conventionally tilled monoculture cotton systems (Burke et al. 2021, 2022). Trade-offs between water use and soil health benefits of cover crops in drylands can potentially be addressed and managed within different environmental contexts by regulating the timing of cover crop planting and termination and selection of cover crop species with enhanced root morphology and water use efficiency (Engedal et al. 2023; Zhang et al. 2023).

Crop lifespan and rooting depth also influence soil health. Plant roots form the foundation of the rhizosphere (see the section "Soil and Plant Microbiomes" in Chapter 2), participating in myriad dynamic interactions with soil microbiota (Venturi and Keel 2016) that influence both soil health and agroecosystem performance. As plant roots grow, they exude a variety of chemical compounds, slough off dead cells, and eventually decompose, delivering nutrient- and carbon-rich organic material directly into the soil (Nguyen 2009; Dijkstra et al. 2021). Shorter-lived crops such as annuals often have smaller, shallower root systems compared to perennial crops, and thus tend not to contribute as much organic materials to soils via rhizodeposition and root turnover (Zan et al. 2001; Monti and Zatta 2009; DuPont et al. 2014; Panchal et al. 2022). Inclusion of deep-rooted and perennial crops (such as forages) in crop rotations and fully perennial systems (such as agroforestry) can enhance soil carbon sequestration and soil health via their deeper and more well-developed root systems.

Crop Diversity

Crop diversity is declining in the United States, with consolidation to fewer species across large swaths of agricultural land (Crossley et al. 2021). This homogeneity is of concern for soil health and overall agroecosystem resilience because spatiotemporal diversity can be an important driver of soil health and ecosystem services (Tamburini et al. 2020; Yang et al. 2020). Greater diversity among crop species—and the functional niches they occupy—can enhance the diversity of soil chemical nutrients and physical structure and promote soil microbial diversity through the creation of diverse microclimates and ecological niches (Vukicevich et al. 2016; Finney and Kaye 2017; D'Acunto et al. 2018; Kim et al. 2020; Saleem et al. 2020; Yang et al. 2020). Diversity can be increased by growing multiple crops in close proximity to one another (i.e., polyculture, see Box 4-1). Various polyculture systems have been widely used throughout the history of agriculture and are still used in many smallholder cropping systems (Gliessman 1985). However, spatial diversification is currently underutilized in U.S. agriculture. By avoiding monocultures, pest, pathogen, and weed problems may be reduced as the host plants are harder to find and more of the soil is covered. Also, by occupying a greater soil depth, nitrogen losses may be reduced, and the increased productivity and functional diversity may also promote carbon and nitrogen sequestration (Bybee-Finley and Ryan 2018). While ecosystem services are likely to increase with the number of crop species, so does management complexity. Thus, there may be an optimum number of crops where services are maximized and management complexity minimized (Bybee-Finley and Ryan 2018), and this number will likely differ depending on specific crop species, their functional complementarity, and the specific environmental conditions.

Crop diversity can also be increased temporally through crop rotation. Crop rotation has been shown to increase microbial biomass and bacterial diversity relative to continuous monoculture (Liu et al. 2023). Crop rotations can also promote soil structure (Ball et al. 2005), most likely resulting from an increased carbon input and greater microbial biomass. Overall, promoting crop diversity wherever possible should be encouraged, although it may present some logistical challenges related to management and harvest. Furthermore, successfully increasing the diversity of crops planted each season and over a number of seasons—and incorporating more perennial and cover crops—will require a commitment to plant breeding (Box 4-3).

Fallow

Unlike cover cropping, fallow is an agricultural practice that leaves the field uncropped for some time. Depending on other management practices, climate, and the type and duration of fallow, it can have profound and divergent effects on soil health. For example, in natural fallows where surrounding vegetation is allowed to colonize or where specific plants are planted as an improved fallow, soil fertility, microbial biomass, and soil structure are promoted as those plants grow, die, and decompose. Indeed, this was—and still is in many subsistence farming systems—the main management practice to rebuild soil fertility by farmers prior to synthetic fertilizers

BOX 4-3
Breeding for Soil Health

Beyond the choice and management of crop species in agroecosystems, soil health can be influenced by the genetics of crop plants. Breeding for resistance to pests and diseases and for competition with weeds, for instance, is not only directly beneficial in terms of plant health and productivity but can benefit soils through reduced pesticide usage, which decreases the pesticide burden on soil microbial communities.

Both traditional breeding methods and transgenic and gene editing techniques can also improve the suitability of plants for use in soil health-promoting cropping systems. Until recently, for instance, cover crops received relatively little attention from plant breeders. Increasing efforts, however, are now being directed toward the improvement of cover crops to maximize plant biomass and integrate into no-till systems (Brummer et al. 2011; Silva and Delate 2017; Griffiths et al. 2022; Moore et al. 2023). Similarly, efforts to optimize food crops for no-till and diversified cropping systems and to develop perennial grain plants and expand biological nitrogen fixation capabilities hold potential to enhance soil health through facilitating the adoption of soil health-promoting production systems (de Bruijn 2015; Soto-Gómez and Pérez-Rodríguez 2022; Moore et al. 2023).

Of particular note when it comes to soil health is the fact that crop improvement for modern agricultural systems has traditionally focused on aboveground traits such as yield, quality, and plant shoot architecture with less emphasis placed on belowground traits. Indeed, the domestication and breeding of modern crops has for some species resulted in unintentional shifts in root architecture and/or interactions with the rhizosphere microbiome, including possible reductions in associations with mycorrhizal fungi (Lehmann et al. 2012) and the quality of microbially mediated nitrogen fixation by some legumes (Gioia et al. 2015; Schmidt et al. 2016; Brisson et al. 2019; Martín-Robles et al. 2019; Liu et al. 2020). In most cases, these unintentional changes have resulted from indirect selection on root traits within intensive and nutrient-rich production systems.

Placing an emphasis on traits such as root system development and rhizosphere interactions within breeding programs therefore holds potential to positively influence soil health (Kell 2011; Brummer et al. 2011). Root architecture, anatomy, and physiology influence the ways in which plants explore soil profiles and capture water and nutrients as well as the ways in which they influence soil nutrients, carbon, and microbial populations (Galindo-Castañeda et al. 2022; Lynch et al. 2022). Diversity in root-related traits which may have been lost due to the genetic bottlenecks of domestication and continued breeding can be introgressed from wild relatives and landraces, and gene editing techniques can be used to accelerate trait improvement (Griffiths et al. 2022). Analyses of the microbial communities associated with diverse crop genotypes are confirming that plant genetic variation can also influence rhizosphere microbial assembly (Leff et al. 2017; Yue et al. 2023). Efforts are underway, for instance, to develop cultivars with optimized root exudation that would facilitate beneficial soil microbial populations to enhance crop growth and quality (Trivedi et al. 2017; French et al. 2021).

(Vågen et al. 2005). In 1986, recognizing the degree of soil degradation in many agricultural soils, USDA created the Conservation Reserve Program where farmers were paid to stop growing crops on highly erodible or environmentally sensitive land and to establish improved fallows (Hellerstein 2017). In 2023, 24.8 million acres of agricultural land was enrolled in this program (Clayton 2023). Even weedy fallows may promote soil health relative to bare soil by reducing nitrogen leaching, promoting above and belowground biodiversity, and—if mycorrhizal—promoting the abundance of mycorrhizal fungi, although legacies of weed seeds may generate another suite of problems (Wortman 2016; Trinchera and Warren Raffa 2023).

The term fallow often refers to bare soil, however. This type of fallow may be used in low-rainfall regions where crops are grown every other year to conserve soil moisture. It may also be practiced for weed control. The soil is kept bare during those periods by tillage, grazing animals, or herbicides, which leaves the soil vulnerable to wind and water erosion. For example, wind erosion associated with summer fallow fields in Washington's dryland wheat region can amount to almost 20 kg C ha^{-1} (Sharratt et al. 2018), with negative effects on soil physical, chemical, and biological properties. For soil biota, bare soil also means no host for symbionts, no plant exudates for the rhizosphere community, and no residues for decomposers (Lehman et al. 2015). Indeed, a review of semi-arid wheat fields found that fallow consistently reduced microbial biomass and activity, particularly of fungi, relative to cover cropping (Rodgers et al. 2021). However, for similar reasons, depriving microbes of host plants can also promote soil health by disrupting pest and pathogen cycles.

Synthetic Fertilizer

Farmers typically apply products to the soil to improve the growing conditions for their crops. Some products may replace nutrients that have been depleted from the soil. Nitrogen is often the limiting nutrient in crop production because the nitrogen in the air is not available to plants in a form they can take up without the help of microorganisms (see the section "Nitrogen Cycling" in Chapter 3). Synthetic fertilizer, which is produced by using high-energy industrial processes to convert N_2 into forms of nitrogen that are available to plants, is used heavily in U.S. crop production today (Figure 4-8). Along with nitrogen, synthetic fertilizer typically contains phosphorus and potassium, two other necessary macronutrients for plants. Recent USDA survey data found that synthetic nitrogen fertilizer was applied to more than 90 percent of corn acres, nearly 70 percent of cotton acres, nearly 75 percent of wheat acres, and more than 25 percent of soybean acres.[6]

Although intensive use of synthetic fertilizer has enabled enormous increases in crop production over recent decades, the relationship between such fertilizer additions and soil health is highly dependent on context and application rates (Singh 2018). On the one hand, when applied at or below levels where maximum yield is achieved, synthetic fertilizers can increase microbial biomass and soil organic matter by promoting plant growth and rhizodeposition, including the input of litter and root biomass into the soil (Geisseler and Scow 2014). Indeed, soil organic matter increased at the agronomic optimum nitrogen addition rate in continuous corn at four Iowa locations over a 14–16 years period (Poffenbarger et al. 2017). Where no nitrogen was added, or where excessive additions occurred, soil organic matter decreased. The suppressive effects of excessive applications may be due to altered abundances and activities of soil microbes. For example, nutrient limitations of decomposers may be alleviated, resulting in increased mineralization of soil organic matter and increased decomposition rates. Also, large amounts of nitrogen and phosphorus may suppress groups of root-associated microbes that aid plants in nutrient acquisition, such as mycorrhizal fungi and rhizobia (Zahran 1999; Treseder 2004). Effects may also be abiotic as synthetic fertilizers applied in excess can pollute soil, air, and water, cause salinization, and alter soil pH (Singh 2018; Pahalvi et al. 2021).

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[6] Survey data for planted acres of corn and cotton were from 2018; for wheat and soybean, data were collected in 2017. Data available at https://www.ers.usda.gov/data-products/fertilizer-use-and-price/documentation-and-data-sources/.

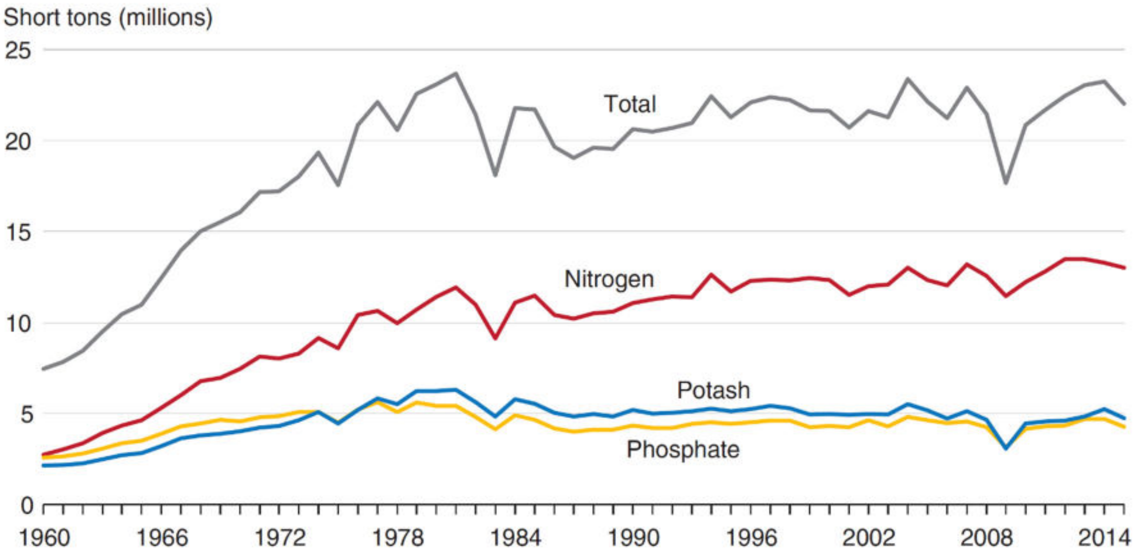

FIGURE 4-8 U.S. consumption of plant nutrients, 1960–2015.
NOTE: Potash is the oxide form (K_2O) of potassium; phosphate (P_2O_5) is the oxide form of phosphorus.
SOURCE: Hellerstein et al. (2019).

Organic Soil Amendments

Farmers may also apply organic products that build up depleted nutrients or enhance the physical characteristics of the soil, such as improving water retention or drainage, promoting microbial growth, improving nutrient cycling, or changing the soil's pH. Such amendments originate from various sources (agriculture, urban, and industry), are subject to different treatments, and are added either as liquid or solid. As such, they can have very different effects on soil health (Goss et al. 2013; Urra et al. 2019). However, unlike synthetic fertilizers, they all add carbon directly to the soil that is likely incorporated into soil organic matter, resulting in improved soil structure and enhanced water- and nutrient-holding capacity. Also, all these organic sources provide microbes with carbon and energy and thus promote microbial biomass compared to soils without amendments or additions of synthetic fertilizers (Zhao et al. 2015; Dincă et al. 2022). The duration of the effects varies among amendments and type of benefits (chemical, physical, and biological) but generally ranges from less than a year to up to 10 years (Abbott et al. 2018). Biochar (pyrolized biomass), however, can remain in soil for centuries to millennia (Zhou et al. 2021).

The use of compost (or digestate if originating from anaerobic digestion) reduces fertilizer requirements and returns nutrient resources to agricultural lands, adds carbon to the soil, and lowers the cost of urban waste disposal in cases where sources are external to the farm. In 2012, Platt et al. (2014) estimated that more than 19 million tons of organic urban material, including food scraps and yard trimmings, was diverted to composting facilities in the United States, and this has likely increased since then. The source of material being composted influences the chemical properties of the product, however, and this should be considered when assessing the potential effect on soil health (Abbott et al. 2018).

Manure is a combination of feces, urine, and animal bedding with the nutritional value and pH depending on the source (Goss et al. 2013; Abbott et al. 2018). It can supply essential macro- and micronutrients, but if applied in excess, it can be an environmental pollutant similar to the use of excess synthetic fertilizers (Abbott et al. 2018). Depending on the source of manure, it can also introduce heavy metals and various other contaminants, and microbes in manure can carry antibiotic resistance genes into soils if animals are routinely treated with antibiotics (Goss et al. 2013). In U.S. agriculture, manure is largely sourced from cows, pigs, and poultry and can either be removed from feeding operations and applied in another location or be deposited naturally by livestock within a grazed field system (Box 4-4). Compared to synthetic fertilizer, manure is applied to a much lesser extent. In 2020, less than 17 percent of corn acres, 4 percent of cotton acres, 2 percent of wheat acres, and 2.3 percent of soybean acres were treated with manure (Lim et al. 2023).

BOX 4-4
Livestock and Soil Health

The presence of livestock and poultry in agricultural systems can influence soil health both directly and indirectly. Well-managed grazing can stimulate plant growth and root development, facilitate nutrient cycling via the deposition of feces and urine, and foster ecosystem diversity in pasture and rangelands—all of which can benefit soil health. Such systems are often known as “rotational grazing” and are characterized by short periods of intense herbivory followed by longer periods of regrowth (Byrnes et al. 2018; Derner et al. 2018; Teague and Kreuter 2020). Continuous or poorly managed grazing systems, however, can lead to notable declines in soil quality due to soil compaction (from animals treading on the same area repeatedly or when the soil is wet and particularly susceptible to compaction), erosion (due to overgrazing and subsequent exposure of the soil to the forces of wind and water), loss of forage diversity (from overgrazing of favored plant species), and imbalances in nutrient cycling (e.g., due to concentrated deposition of manure in animal congregation areas) (Borrelli et al. 2017; Byrnes et al. 2018; Xu et al. 2018).

Outside of grazing systems, confinement-based animal agriculture also exerts an influence on soil health via the rations fed to livestock and poultry. While ruminant livestock such as cattle and dairy cows may consume diets that include roughage from deep-rooted perennial forages, the vast majority of U.S. livestock and poultry rations—particularly among monogastrics such as pigs and poultry—is derived (either directly or as byproducts) from annual crops such as corn and soybean often grown in high-input, low-diversity annual cropping systems (Schnepf 2011; Picasso et al. 2022).

The spatial decoupling of animal and plant agriculture in the United States has led to local and regional nutrient imbalances, with some areas beset by nutrient pollution while carbon and nutrients are depleted in areas with intensive crop production (Flynn et al. 2023). Strategic management of “manuresheds” and the development of technologies for recovering nutrients and carbon from manure can help address water pollution problems while enhancing soil health. The use of manure from animal agriculture has traditionally maintained nutrient and soil organic matter levels and continues to play an important role in soil health in contemporary dairy systems. Greater reintegration of crop and livestock production system promises to contribute to reduced pollution from livestock excreta and the improved sustainability of agricultural soils (Spiegal et al. 2020).

Municipal biosolids are a nutrient-rich byproduct of sewage treatment processes. Biosolids, also known as sewage sludge, have the potential to promote soil health as they contain macro- and micronutrients in variable quantities (Goss et al. 2013). According to the U.S.

Environmental Protection Agency (EPA), approximately 25 percent of the biosolids produced in the United States (1.15 million dry metric tons) were applied to agricultural land in 2021 (EPA 2023). However, similar to manure and compost, biosolids can contain pathogens, heavy metals, and other contaminants such as antibiotic residues, PFAS, and microplastics (Goss et al. 2013; Urra et al. 2019; see also the "Contaminant Case Studies" section in Chapter 6). The presence of these contaminants requires efficient strategies to mitigate risks associated with some organic amendments to soil while reaping the benefits they could provide (Urra et al. 2019). Current EPA requirements for land application set pathogen and heavy metal limits, but there are no thresholds for antibiotic residues, antibiotic resistance genes, PFAS, or microplastics. Thermochemical transformation of biosolids to biochar offers one pathway for reducing regulated and unregulated hazards associated with land application of biosolids (Paz-Ferreiro et al. 2018).

Biochar is of broad interest for building and maintaining soil organic carbon because it is stable over long periods of time in soils. This stability is important both for soil health and for carbon sequestration. Biochar is a carbon-rich soil amendment that is similar to charcoal and produced by pyrolysis (thermochemical transformation under low-oxygen conditions) of organic matter, which allows carbon to persist for hundreds or thousands of years. Biochar can be produced from a wide variety of organic materials, such as wood, crop residues, weeds, and biosolids. Biochar has a high surface area that enables it to take up water and nutrients, giving soil a greater ability to hold water and provide the slow release of nutrients to plants (Weber and Quicker 2018). The specific properties of the biochar depend on the feedstock and the details of the pyrolysis process (e.g., temperature and speed), which affect the surface area and chemistry and thus its effects on soils. Biochar can make nutrients more available to plants (Gao et al. 2019) and can have a range of other positive effects on soil health, with the caveat that performance varies by soil and source of biochar (Joseph et al. 2021).

Biostimulants

Similar to the potential of probiotics and prebiotics to enhance human health (Kerry et al. 2018), there is an increasing interest in various microbial soil amendments to promote soil and crop health and productivity (Rouphael and Colla 2020). Types of amendments include (but are not limited to) N_2-fixing bacteria, mycorrhizal fungi, disease-suppressing microorganisms, and less-specialized rhizosphere bacteria as well as amino acids, chitosan, seaweed extracts, compost teas, and humic substances. In the United States, the biostimulant market has grown exponentially in the last decade, and globally it is estimated to reach $4.14 billion by 2025 (Madende and Hayes 2020). A plant biostimulant is described as "a substance or microorganism that, when applied to seeds, plants, or the rhizosphere, stimulates natural processes to enhance or benefit nutrient uptake, nutrient efficiency, tolerance to abiotic stress, or crop quality and yield" (USDA 2019). It is also assumed that biostimulants are added in small quantities and that crop benefits are unrelated to the biostimulant's nutrient content (Rouphael and Colla 2020).

As discussed in Chapters 2 and 3, microorganisms cycle and sequester carbon and nutrients, suppress disease, and alleviate abiotic stresses in plants, produce phytohormones, degrade pollutants, and promote soil aggregation and water infiltration. While healthy soils may host at least one billion bacterial cells and 100 meters of mycelia per gram of soil that provide many important functions (Figure 4-9), detrimental management practices may have resulted in loss of many taxa and reduced overall abundance (Hart et al. 2017; Wittwer et al. 2021). Due to this loss, and because microorganisms are increasingly viewed as supplements to synthetic fertilizer and pesticides (e.g., Ahmad et al. 2018), the interest in microbial inoculations of single strains or diverse consortia have increased dramatically (O'Callaghan et al. 2022). Large investments by venture-backed companies in anything from naturally occurring to genetically engineered and custom-made microbes have followed this interest (Waltz 2017).

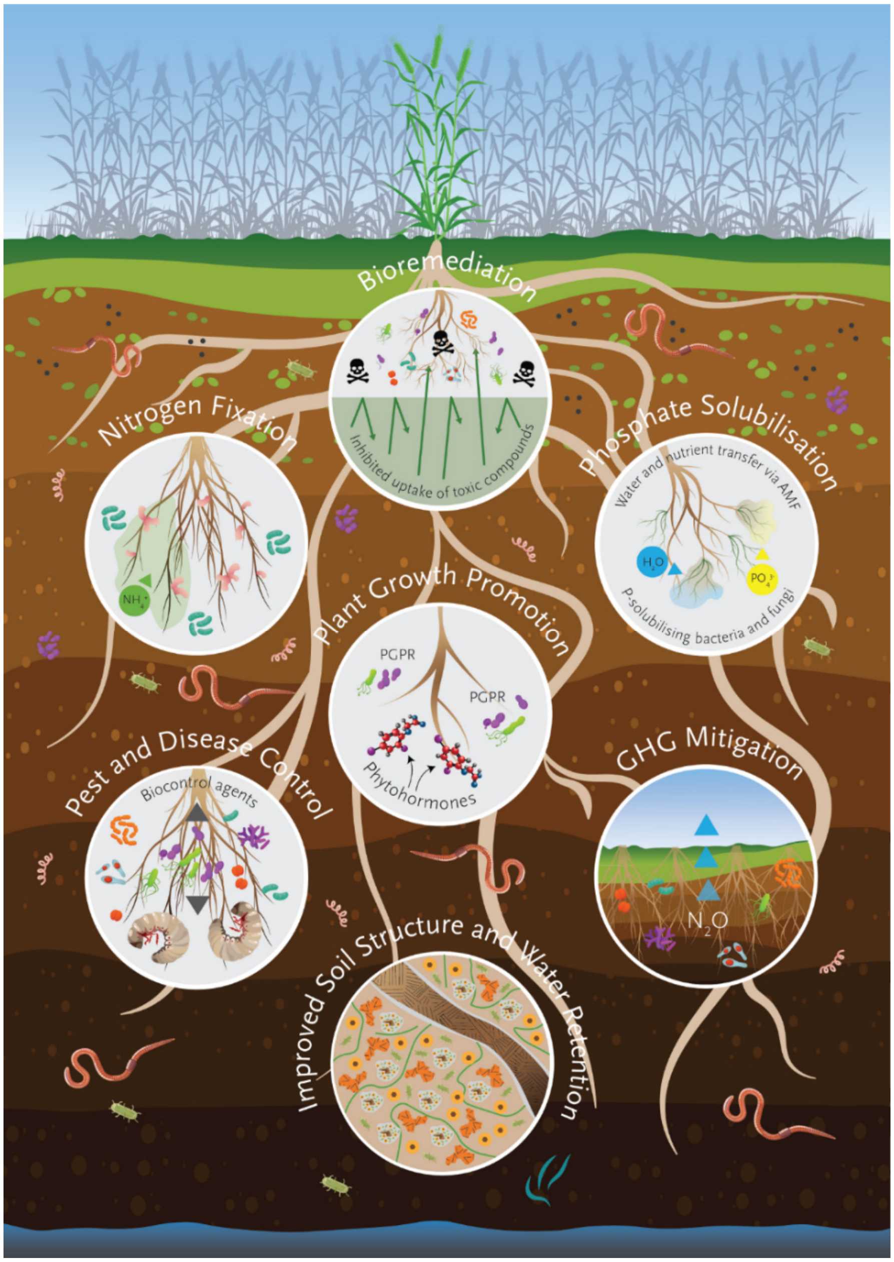

FIGURE 4-9 Potential functions microbial inoculants could enhance or provide in soils if the soil function is currently lacking or is limited by low abundance or activity of the inoculated organisms. SOURCE: Used with permission of John Wiley & Sons, from "Soil Microbial Inoculants for Sustainable Agriculture: Limitations and Opportunities", O'Callaghan et al., *Soil Use and Management* 38 (3), 2022; permission conveyed through Copyright Clearance Center, Inc.

Perhaps the best-known commercial inocula with a long and successful history are the symbiotic N_2-fixing bacteria added in furrows or on seeds to enhance the performance of legumes (Lehman et al. 2015). The bacterial genera *Bacillus*, *Pseudomonas* and *Serratia* have also repeatedly shown an ability to control phytoparasitic nematodes in the greenhouse as well as in field experiments in a range of crops (Migunova and Sasanelli 2021). Other plant growth promoting bacteria isolated from bulk and rhizosphere soil can also benefit plant growth and soil health through various mechanisms (Khatoon et al. 2020), as could mycorrhizal fungi (Delavaux et al. 2017) and other fungi, including various *Trichoderma* spp. (Zin and Badaluddin 2020). However, the potential of these microbes has largely been assessed under controlled greenhouse conditions, and there are several reasons why establishment and performance may vary in the field (Kaminsky et al. 2019). First, environmental preferences and tolerances of bacterial and fungal taxa differ, and conditions may not be suitable for their establishment (Poppeliers et al. 2023). Thus, similar to the "personalized medicine" approach, microbial inocula might have to be targeted for specific conditions as it is unlikely that one taxon or consortia will work universally. A recent example is the—12-percent to +40-percent range in growth response in corn with field inoculations with one species of mycorrhizal fungi across 54 fields (Lutz et al. 2023). Interestingly, benefits were greatest where the abundance of pathogenic fungi was highest—not where phosphorus concentration was lowest—which is indicative of pathogen protection rather than increased resource acquisition by mycorrhizal fungi in these soils. Establishment may also be affected by competition with native soil biota (Verbruggen et al. 2013; Poppeliers et al. 2023). Even if establishment is successful, the intended function may not be realized as performance will depend on environmental conditions, selection pressures, and rapid evolution (Kaminsky et al. 2019). There is also a growing concern of possible legacies of inoculants on the indigenous soil microbiome and invasions with unexpected consequences for soil health. Based on this, there has been an increasing interest in using local sources for microbial inocula, although more so in restoration ecology than in agriculture (e.g., Emam 2016; Duell et al. 2023). Added to these concerns of commercial inocula are their significant cost, variation in quality (Salomon et al. 2022a), and largely unregulated market (Malusà and Vassilev 2014; Madende and Hayes 2020; Salomon et al. 2022b). Thus, while microbial biostimulants could play a role in rebuilding soil health, there are still many unknowns. First and foremost, it is often unknown whether ecosystem processes are limited by the abundance of specific microbial groups under field conditions. If abundances are low, it is usually unclear whether inoculations alone will alleviate this or if shifts in management are required. Below is a decision tree highlighting relevant questions to ask when determining if inoculations are likely to be beneficial (Figure 4-10). If and where they are, an additional question is whether inoculations with single taxon or diverse consortia that range in environmental tolerances and functions make a difference (Lutz et al. 2023).

Of the nonmicrobial biostimulants, the specific mode of action is often unknown but may range from morphological, biochemical, and physiological changes in plants and compositional and functional shifts in plant-associated microbial communities (Rouphael and Colla 2020; Meddich 2023). Understanding when and how nonmicrobial biostimulants benefit crop yield and quality and when they can help restore degraded soils are important next steps to optimize their use and return of investment.

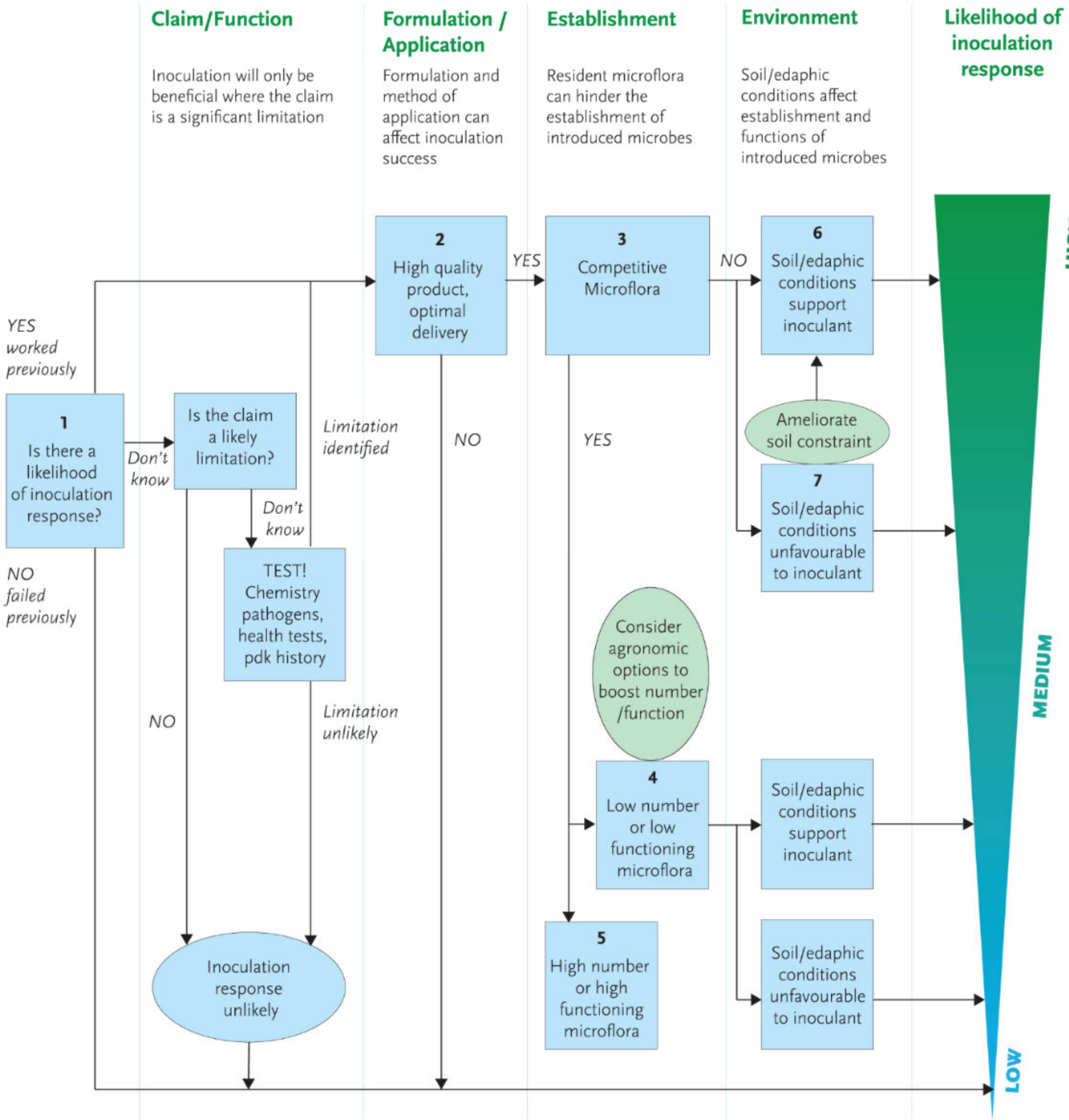

FIGURE 4-10 Decision tree to assess whether microbial inoculations are likely to solicit crop response. SOURCE: Used with permission of John Wiley & Sons, from "Soil Microbial Inoculants for Sustainable Agriculture: Limitations and Opportunities", O'Callaghan et al., *Soil Use and Management* 38 (3), 2022; permission conveyed through Copyright Clearance Center, Inc.

Pesticides

As discussed above, crop rotation and diversity, cover crops, tillage, and the timing of planting are a few strategies to mitigate pest pressures on crops; another is the use of pesticides. Pesticides are substances intended for preventing, destroying, repelling, or mitigating undesirable plants, insects, animals, nematodes, fungus, or microorganisms in the environment.[7] They encompass herbicides, insecticides, nematicides, fungicides, and rodenticides as well as products such as soil fumigants, defoliants, and desiccants (Fernandez-Cornejo et al. 2014). Pesticides are not exclusively synthetic—for example, baking soda, vinegar, and some bacteria are used as pesticides—but most of pesticidal products used in U.S. agriculture have been developed in laboratories and created through industrial chemical processes. More than 600 million pounds of active ingredient—the chemicals within the pesticides that control the pests—were applied to just five U.S. crops in 2014 (Hellerstein et al. 2019).[8]

The objective of pesticide use is to mitigate impediments to crop productivity. They may be applied to leaves (or neighboring weeds), to the soil, or as seed coatings, depending on the target pest. Only a small fraction of pesticides reaches the intended target (Pimentel and Burgess 2012), with the rest taken up by nontarget organisms, mineralized, sorbed onto the soil matrix, or leached.

Simple assertions about the impacts of pesticides on soil health are difficult to make because environments, soils, and pesticides are diverse, as are the biota that inhabit soils, other agricultural management practices in use, and the pesticide-associated compounds that are included in product formulations (Bünemann et al. 2006; Raj and Syriac 2017; Ankit et al. 2020; Ruuskanen et al. 2023). The myriad of methods and conditions used to assess effects of pesticides on soil biota, especially microbial communities, complicates comparisons across studies (Thiour-Mauprivez et al. 2019; Ke et al. 2022).

Nonetheless, some generalizations can be made. Physical and chemical properties of pesticides (e.g., dissociation constant, molecular weight, and water solubility) may influence their ecological impact and persistence in soils (Gevao et al. 2000; Tudi et al. 2021; Ke et al. 2022). Fungicides, insecticides, and herbicides can all affect the abundance, composition, and function of meso- and macrofauna such as earthworms and nematodes (Bünemann et al. 2006; Wołejko et al. 2020).

The effect of pesticides on the soil microbiome can vary depending on the pesticide types. Riah et al. (2014) reviewed studies using enzymes as indicators of soil microbial communities, finding that fungicides generally tended to reduce soil enzyme activity, while the effects of insecticides and herbicides varied from positive to negative. Some pesticides can negatively affect soil microbial contributions to agroecosystem functioning (Walder et al. 2022).

Some fungicides, including azoxystrobin and propiconazole, lower the rate of soil respiration and the metabolic activity of microbial organisms, which may also have an impact on soil organic carbon storage and turnover (Wang et al. 2020; Zhang et al. 2020). Triazole fungicides inhibit fungal growth and the production of ergosterol, a key component of fungal membranes. Fungicides can suppress the abundance and alter the composition of beneficial mycorrhizal fungi in soils (Wilson and Williamson 2008), with potentially negative consequences for plants (Helgason et al. 2007). High doses of these compounds strongly affect soil microbial communities, reducing soil microbial biomass and activity and decreasing the activity of soil enzymes (Roman et al. 2021).

Herbicides constitute more than half of the pesticides applied to U.S. crops (Hellerstein et al. 2019). They can broadly be divided into groups that target cell metabolism, light processes,

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[7] United States Code, 2013. Title 7–Agriculture. Chapter 6, Insecticides and Environmental Pesticide Control, Subchapter II - Environmental Pesticide Control, Sec. 136 – Definitions.

[8] These crops were corn, cotton, fall potatoes, soybeans, and wheat. They accounted for two-thirds of the amount of pesticide applied (Hellerstein et al. 2019).

and growth and cell division (Thiour-Mauprivez et al. 2019). Herbicides can be employed to promote soil health by facilitating the use of cover crops and no-till agriculture, which can reduce the mineralization of soil organic, decrease erosion, and conserve water (Lee et al. 2014). On the other hand, some herbicides remain in the soil for long periods of time as environmental pollutants and can delay germination, slow root growth, and lower yields of subsequent crops and negatively influence soil biota. For example, the degradation of glyphosate—the most used herbicide globally with more than 130,000 tons applied in the United States annually (Maggi et al. 2020)—is much slower than originally anticipated and remains in the soil for up to 1,000 days (van Bruggen et al. 2021). This slow degradation is problematic because glyphosate targets the pathway that produces essential amino acids, which is also present in fungi, bacteria, archaea, and protozoa (van Bruggen et al. 2021).

Sensitivity to herbicides appears to differ within the soil biota, which can result in altered microbial community compositions as well as soil function (Rose et al. 2016; Ruuskanen et al. 2023). Herbicides have been shown to affect meso- and macrofauna and can disrupt earthworm activity and nematode assemblages, suggesting changes in soil food webs (Zhao et al. 2013; Rose et al. 2016). Nonetheless, while herbicides such as paraquat, diquat, and 2,4-D are highly toxic to animals (de Castro Marcato et al. 2017), many reviews and meta-analyses indicate direct effects of herbicides on soil biota and soil function are temporary and relatively minor when applied at recommended doses (Rose et al. 2016; Raj and Syriac 2017; Duke 2020). Indirect effects of herbicides on root- and rhizosphere-associated biota and soil organic matter, mediated by altered host abundance, root exudation, and residue input, may be more severe and longer lasting than direct effects (Lekberg et al. 2017; Raj and Syriac 2017).

CONCLUSIONS

As discussed in Chapter 1, the increases in crop yield since the mid-20th century have often come at the expense of soil degradation. Rebuilding soil health will require better monitoring, data collection, research on soil health indicators, changes to common practices today to maximize resources and minimize trade-offs, and investment in solutions to technological, biological, and logistical constraints. It will also necessitate an increase in the complexity of farm management.

Quantifying Soil Health

Several hundred indicators exist to measure chemical, physical, and biological aspects of soils, but their relationship to soil health is not always clear. In particular, reaching consensus on which biological indicators are useful to measure in a given context has continued to be a struggle, even as tools to measure soil organisms and their processes have advanced. Furthermore, the spatiotemporal heterogeneity of soil means that single point measurements do not necessarily provide meaningful data for informing management actions to improve soil health. Collecting sufficient data across space and time to measure soil health and act on the information requires that (1) data collection is affordable, (2) data are stored in a way that is accessible and useable by others, and (3) data are analyzed in ways that are consistent and can be reproduced.

Databases already exist on which new databases focused on soil health–human health connections can be built or used as models. Large-scale research and monitoring networks such as the National Ecological Observatory Network and Long-Term Ecological Research network of the National Science Foundation (NSF) or USDA's Long-Term Agroecosystem Research network provide excellent examples of large-scale research studies that build long-term, accessible databases with time based on consistent measurements, but the data collection is limited to sites and studies from within the network. The USDA's Ag Data Commons is another example of a data repository for any research conducted or funded by the agency and captures a wide suite of sites and studies. The Soil Survey Geographic Database (SSURGO) of USDA's Natural Resources and Conservation Service (NRCS) contains over a century of soil profile characteristic data collected by soil survey and mapping professionals. A great example of database use for public access and education is the NRCS's online Web Soil Survey platform, which uses SSURGO data to illustrate and deliver soils information to the public.

However, no similar standardized databases have been created or similarly made accessible in an easily usable way to the public specifically on soil health. Non-profit organizations such as the Soil Health Institute have initiated large-scale soil health monitoring efforts and database development, yet having similar or coordinated efforts through public entities and federal organizations would help safeguard longevity and public access of databases produced from these efforts. Validating useful indicators over time and in their agricultural contexts would greatly advance the utility of soil health indicators to producers. Existing frameworks for selecting and measuring biological indicators, such as BIOSIS or that in the California Department of Food and Agriculture's soil biodiversity report, provide starting points for this effort. Examples from other countries such as New Zealand's National Soils Database further provide a model to harmonize large datasets from multiple sources and make these publicly accessible. The recent "Signals in the Soil" program co-funded by NSF and USDA is an example of efforts to improve data collection and use, with completed and ongoing projects within the program focused on developing and improving sensor technology and use to better measure and understand interrelated soil processes and properties. The majority of projects funded by this program thus far have focused on *detecting* or *manipulating* signals in the soil through novel methods or improved technologies, which should be aptly expanded on through future research that focuses more on modeling efforts to leverage existing and developing datasets to *interpret*, *respond to*, and *predict* changes in those signals. This development would allow more effective use of and learning from a national soils database.

Another area in need of more research is underlying mechanisms that influence soil health. Oftentimes research projects combine management practices (e.g., no-till and cover crops) or contrasts cropping systems (organic vs. conventional), which makes it difficult to elucidate contributions by individual practices. Likewise, funding cycles are frequently too short to allow for assessments of slow processes, such as soil organic matter accrual. Finally, while experimental control is important, it sometimes comes at the expense of realism, which may best be achieved when farmers, industry, and scientists collaborate.

Recommendation 4-1: USDA should develop a coordinated national approach to monitor soil health over time and space. This approach would allow for broad comparisons across locations and an ability to identify areas of concern. Over time, it would also enable comparisons among management practices as well as their context dependency. To achieve this would require:

- **Learning from monitoring efforts outside the United States (e.g., the European Union and New Zealand).**

- **Developing harmonized methods with known relationships to soil health.**
- **Research to answer questions about the best biological indicators of soil health to measure in a given context.**
- **Continuing the development and improvement of interpretation and predictive power of soil data from soil sensors and other tools for more rapid and in-situ measurement of abiotic and biotic soil properties and their usefulness to assess soil health.**
- **Support to develop a user-friendly soil data management system to store soil health information in a way that is publicly accessible and comparable over time.**

Recommendation 4-2: USDA should fund research projects that:

- **Are designed to identify the underlying mechanisms of soil health and the plant–soil feedbacks that drive changes in soil health and how they affect long-term ecosystem outcomes. Such projects may require factorial experiments where management practices are tested in isolation.**
- **Involve longer-term studies where slow processes can be studied under realistic settings as well as account for climate variability and exposure to environmental stressors such as drought.**
- **Support collaborative on-farm research with scientists, farmers, and industry to identify the underlying mechanisms of soil health. Such research should take into consideration historical and current land management practices.**

Maximizing Resources with Minimal Trade-offs

Some agricultural management practices benefit soil health but may be associated with another practice or risk that decreases the overall favorable impact on soil health. For example, no-till or reduced tillage practices improve soil structure and, especially when combined with practices that minimize bare soil, reduce soil erosion. However, reduced tillage has been accompanied by increased use of herbicides to control weeds or terminate cover crops. Along similar lines, use of recovered resources, such as reclaimed water and biosolids, can minimize pressure on fresh water sources or lessen demand for synthetic fertilizer. However, the introduction of soil contaminants is often associated with the use of recovered resources. Biostimulants are gaining popularity as an amendment, but evidence of cost-effective results in variable field conditions is lacking. Another unknown is whether subsurface drip or deficit irrigation decreases GHG emissions compared with less water-efficient irrigated systems but also reduces microbial activity and carbon cycling in soil, especially in dry climates.

There are also resources that are underutilized because of logistical or technological constraints; this is especially the case for organic soil amendments. Animal manure and municipal biosolids, yard trimmings, and compost are available organic material that could reduce the need for applying synthetic fertilizer and build organic matter in soils. Variability in nutrient content, contaminant concerns (see Chapter 6), and transport costs currently suppress demand for these resources. Biochar's nutrient content is also variable depending on the source material, and at present, the costs of producing biochar are not competitive with synthetic fertilizer.

Some options exist to address these constraints. Source separation of excreta and container-based sanitation would reduce water use and contamination of excreta, enabling more efficient reuse of nutrients and organic matter. Thermochemical transformation of solid excreta (human and animal) can reduce the mass and volume of the material, enabling more efficient transport. Yet, even though research over the past century has evaluated the environmental outcomes of applying municipal biosolids and animal excreta to soil, advances in technologies to remove potentially harmful compounds, balance the fertilizer value, and increase the economic competitiveness of such products has not kept up with the pressing need to create circular nutrient economies. Novel practices and combinations of management strategies, as well as underutilized resource streams, provide currently unrealized potential to solve context-specific agricultural management and productivity challenges when deployed in ways that optimize resource use without negative trade-offs to soil health or human health.

Recommendation 4-3: USDA and other agencies should support research that:

- **Develops novel strategies or management combinations to overcome potential trade-offs from common agricultural management practices. For example, soil health would benefit from non-pesticide dependent ways to address weed, insect, and pathogen pressure or terminate cover crops in no-till systems. Similarly, new plant varieties or strategies that minimize water use from cover crops while maximizing soil protection and soil carbon inputs in arid and semi-arid regions should be studied. These efforts should include research in controlled environments and under field conditions to understand when and how biostimulants can help restore degraded soil and how their use compares biologically and economically with other methods to improve soil health.**
- **Investigates the short-term and long-term impacts of diverse pesticides, including mixtures, on soil biota and their functions, which have implications for soil health.**
- **Increases the safe and effective use of underutilized resource streams (such as biosolids, manure, and compost) as sources of nutrients and organic matter for crop production. These efforts would include developing technologies and waste management practices to improve the feasibility and affordability of assessing nutrient content, screen for and remove contaminants or compounds of concern to human health, and formulate and distribute these recycled resources to producers in ways that are competitive with commercial fertilizers.**

Improving Soil Health Through Increased Complexity

Management practices that prioritize soil health are not always in line with management practices that maximize yield. The adoption of agricultural management practices that improve soil health will require financial recognition of soil health's contributions to people, discussed in Chapter 3. It will also require the reduction of barriers to prioritizing soil health and an increase in the tools and resources available to maximize soil health.

Making cropping systems more complex would go a long way in addressing soil health concerns. More crop rotation, increased use of cover crops, and incorporation of more perennial crops would increase soil organic matter and microbial diversity and mitigate insect, weed, and pathogen pressure. Making such options possible requires a greater investment in and diversification of plant breeding efforts, which have traditionally focused on food crops and aboveground traits and paid little attention to the traits and crops that support system complexity and soil health. These changes would, in turn, reduce the need for synthetic fertilizer and pesticide use and increase the water holding capacity of soil, perhaps mitigating the need for irrigation in some locations.

However, increasing the complexity of cropping systems requires a reversal of the trend in U.S. agriculture over the past century. The financial burdens and risks entailed in diversification cannot be placed solely on the shoulders of producers. It will require movement in a number of areas.

Recommendation 4-4: USDA's Agricultural Research Service should pursue and USDA's National Institute of Food and Agriculture should support plant breeding research that improves:

- **The suitability of cover crops in all farming systems, including those in low precipitation locations.**
- **Belowground crop traits, such as root system development and rhizosphere interactions with soil biota.**
- **Perennial crops and polycultural systems.**

Recommendation 4-5: USDA farm-support programs should consider the benefits of soil health as a context-specific metric of success in restoring degraded soils and as a tool to monitor vital soil functions rather than solely focusing on yield outcomes from management practices and should provide assistance for land managers to support transition to more complex systems. Such assistance could include:

- **Incentives and insurance for adopting practices that could improve soil health and are designed to contend with certain risks in some areas (e.g., cover cropping in arid or semi-arid regions).**
- **Incentives to increase spatial and temporal diversification.**

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5

Linkages Between Agricultural Management Practices and Food Composition and Safety

As discussed in Chapter 1, there has been an interest in establishing a link between the health of soils and the healthfulness of the food produced on those soils. The 1993 National Academies report on soil and water quality raised this possibility, observing that some researchers had "suggested that soil quality has important effects on the nutritional quality of the food produced in those soils but noted that these linkages are not well understood and that research is needed to clarify the relationship between soil quality and the nutritional quality of food" (Parr et al. 1992 in NRC 1993, 40−41). Thirty years later, this question is still being asked. Therefore, one of the tasks set forth for the committee was an investigation of the evidence for linkages between agricultural management practices and the nutrient density of foods for human consumption, as well as other effects on food that were unspecified. This chapter looks at the evidence for connection between these practices and the nutrient density of the food produced. It then reviews the impact of food processing on the nutritional value of food. The chapter also covers the connections between agricultural management practices and food safety. Finally, it summarizes the effect of consumer choices on food production decisions, which can impact both soil health and human health.

LINKING AGRICULTURAL MANAGEMENT PRACTICES TO NUTRIENT DENSITY

There is a common perception that healthy, well-managed soils produce healthier foods; however, the connection is not always clear. Nutrient availability in the soil, environmental conditions, management practices, and plant genetics all play a part in determining nutrient density in the food supply. What ultimately determines the nutritional quality of food crops or forages (Box 5-1) is the amount of nutrients that are transported to or synthesized within the edible portion of the plant. Essential nutrients of interest are minerals that are absorbed by fine roots and translocated to leaves, storage roots/tubers, and/or seeds, as well as biosynthesized macromolecules such as amino acids/proteins, carbohydrates, lipids, and vitamins (Grusak and DellaPenna 1999). Absorbed minerals play a key role as primary nutrients in foods but also are important co-factors in numerous enzymatic and photosynthetic processes, which enable the synthesis of various essential macromolecules and potential health-promoting phytochemicals (White and Broadley 2009; White et al. 2012), the latter being potentially beneficial but not essential for human health.

Variation in nutritional quality is highly dependent on plant genetics. Numerous studies of crop genetic diversity have shown broad ranges in nutrient density or concentration, including for protein (Katuuramu et al. 2018), lipids (Attia et al. 2021), vitamins (Jiménez-Aguilar and Grusak 2017), and minerals (Farnham et al. 2011; McClean et al. 2017; Qin et al. 2017; Vandemark et al. 2018). While this variation does exist, it can only be demonstrated to its fullest when the raw materials (e.g., minerals, water) are available in sufficient quantities to meet the genetic potential of each crop cultivar. If the raw materials are limiting in soil, only those genotypes with higher absorption potential can accumulate them to adequate or higher levels. Thus, the ability of soils to provide these materials (especially minerals) has a significant impact on the nutritional quality of food.

BOX 5-1
Effects of Management Practices on Forage Quality

This report has focused primarily on the effects of agricultural management practices and soil health on the composition of food crops consumed directly by humans. However, soils also support forage crops (in addition to some grain crops) that are consumed by livestock and that affect the quality and composition of animal food products. Because forage crops require essential minerals similar to food crops, the management practices noted in this chapter that affect the physical, chemical, or biological properties of soils will also affect the yield of forage crops and their nutritional quality (Duru et al. 2013; Barker and Culman 2020). Factors relevant to soil health will, furthermore, affect (positively or negatively) the secondary metabolite composition of forages, which subsequently has effects on the concentration of potential health-beneficial phytochemicals in animal food products (van Vliet et al. 2021).

Forages for livestock are usually grasses (Poaceae) or herbaceous legumes (Fabaceae) but also include tree legumes, perennial legumes, Brassica species, and fodder beet (Capstaff and Miller 2018). In certain parts of the world, rangeland forages are unmanaged, but more commonly rangelands are managed using practices that include fertilization, grazing, controlled burning, or a combination of these strategies. As with the food crops, these management practices can have positive effects on yield, but mixed effects on forage quality. It should be noted that forage quality for livestock (especially ruminants) not only includes nutritional composition (e.g., minerals, protein, vitamins) but also dry matter content and digestibility to support energy for animal growth and metabolic maintenance (Hatfield and Kalscheur 2020; Mertens and Grant 2020).

Some examples of management outcomes on forage quality are given here. The application of nitrogen fertilizer in a legume/corn intercropping system had a positive effect on total yield, crude protein yield, and crude fat concentration, along with decreases in the concentration of neutral detergent fiber and acid detergent fiber (Zhang et al. 2022). Decreases in neutral detergent fiber and acid detergent fiber are associated with improved forage quality. In a rangeland ecosystem containing 16 species with diverse growth forms (rosette, grass tussock, stemmed-herbs), fertilization with nitrogen and phosphorus in combination with intensive grazing (relative to non-fertilization and moderate grazing) resulted in mixed results depending on the growth form of the resident forage species (Bumb et al. 2016). Dry matter content, dry matter digestibility, nitrogen concentration, and neutral detergent fiber were all influenced by management regime, with rosettes having higher dry matter digestibility and nitrogen concentration but lower neutral detergent fiber and dry matter content than tussocks in response to fertilization and intensive grazing. Controlled burning of grasslands has also been studied as a management tool because it is known that livestock tend to prefer pastures where natural fires have burned, relative to unburned areas (Eby et al. 2014). In some ecosystems, controlled fires can provide better forage quality, but the impact is transient, lasting over only one or two seasons (Augustine et al. 2010; Gates et al. 2017).

Nutritional quality is also dependent on crop yield. Values of nutrient quality (or density) are generally expressed as a concentration; thus, they are calculated on a weight basis (e.g., dry weight basis for grains; fresh weight basis for fruits and vegetables). The overall yield of a crop has relevance because, when changes in genetics, environment, or management practices lead to increased yields, those increases can negatively affect the concentration of certain nutrients through a dilution effect (Miner et al. 2020). A dilution effect can occur because all nutrients do not necessarily accumulate within edible plant tissues at the same rate. When macromolecules such as starch or protein are increased in a harvested tissue (e.g., adding weight per seed) and the accumulation of micronutrients such as minerals or vitamins do not increase similarly, the concentration or density values of the micronutrients will be reduced.

Agricultural management strategies that lead to crop yield increases are of course welcomed and important for their role in enhanced food security (Horton et al. 2021). Although there may be reductions in the density of certain nutrients (or health-beneficial phytochemicals), higher yields do provide more food per area of land and thus a higher overall supply of nutrients. Greater productivity has benefits to consumers through both increased availability and increased economic accessibility, as prices are likely to be lower when production is higher. In food insecure regions of the world, an availability of and ability to consume more food will help individuals meet their daily caloric and nutrient requirements, even if some nutrient densities are reduced in that food (Ritchie et al. 2018).

In a general sense, agricultural management practices can influence crop nutritional quality (or health-beneficial phytochemicals; Box 5-2), positively or negatively, through their effect on soil physical, chemical, or biological properties, which subsequently can affect mineral or water availability as well as crop yield. Comparative studies of different management regimes have been undertaken in an effort to assess the interplay of these effects on crop quality, but variations in experimental design, soil types, crop species, and environmental conditions have yielded divergent results. Unfortunately, as with most complex systems where biotic and abiotic factors are at play, the influence of a given management practice on crop yield or quality is not always predictable or consistent.

Tillage

The effects of tillage practices on soil properties and crop yield have been extensively studied (Schneider et al. 2017), but the impact of tillage on crop nutritional quality (i.e., nutrient density) has gained only limited attention. Tillage, including the incorporation of manure or crop residues, can influence soil mineral and water availability in positive or negative ways (Aćin et al. 2023), which can subsequently affect the mineral uptake and quality of crops (Gebrehiwot 2022). Different tillage practices (from no-till to deep tillage) have shown mixed effects on crop yield, with no-till often resulting in reduced yields compared to conventional tillage in cereal crops (Pittelkow et al. 2015), but duration of no-till and its site-specificity could also lead to higher yields in certain cases (Daigh et al. 2018). Similarly, a meta-analysis of deep tillage showed that site specificity could lead to higher or lower yields (Schneider et al. 2017). Unfortunately, these studies did not assess the impact of altered yield on crop nutritional quality, although a dilution effect for some minerals at elevated yields could be expected (Gebrehiwot 2022). Conversely, when tillage practices result in increased levels of organic matter (e.g., with no-till or tillage with incorporation of crop residue), this can help retain soil minerals and lead to increased mineral concentrations in grain crops (Wood et al. 2018; Shiwakoti et al. 2019). In addition, reduced tillage (i.e., less soil disturbance) has also been linked to an increase in arbuscular mycorrhizal fungi colonization and higher concentrations of phosphorus in shoot tissues (Lekberg and Koide 2005).

BOX 5-2
Agricultural Management Practices and Plant Bioactives

Beyond the primary nutrients, plant health will affect the production of various health-beneficial phytochemicals (also referred to as bioactive secondary metabolites)—including phenolics, alkaloids, or isoprenoids (terpenoids), among others—that are commonly associated with reduced risk of chronic diseases in humans. Some studies have demonstrated that management practices that improve soil organic carbon and microbial biomass may lead to increased levels of bioactive compounds such as phenolics and ascorbic acid in fruits and vegetables (on a dry matter basis), although such differences largely disappear when edible plant tissue yield is considered (Reganold et al. 2010). Such studies are commonly confounded by management practices not exclusively related to soil health, making it difficult to distinguish causation from correlation. For example, the link between organic farming practices and bioactive compounds accumulation in food plants has not been clearly established despite numerous studies. Some authors have reported higher levels of bioactive antioxidant accumulation in organically produced crops relative to conventional production (Barański et al. 2014), while others have reported no difference (Langenkämper et al. 2006; Mulero et al. 2010) or the opposite effect (Mishra et al. 2017). The inconsistencies could be related to the fact that the diversity of the bioactive molecules in plants is complex, and many of these compounds function as signaling or defensive molecules that can be differentially produced in response to various environmental stresses, including pests, pathogens (Adhikary and Dasgupta 2023), and ultraviolet radiation (Pfeiffer and Rooney 2015). By this token, a reduction in plant stress may lead to lower concentrations of these bioactive compounds in plant foods, due to reduced inducible biosynthesis of the compounds. However, recent evidence linking soil microbiome composition and function to plant tolerance to pathogens and diseases (Wei et al. 2019) also suggests the production of secondary metabolites as plant defense molecules may actually be enhanced in some cases in plants under healthy soil conditions. Given the important role of plant-derived bioactive compounds to human health, robust studies that credibly demonstrate the impact of soil health, as well as agricultural management practices, on phytochemical accumulation in edible plant tissue are critically needed.

Crop Choice and Rotation

The incorporation of crop rotations, including fallow or seasonal cover crops, can benefit soil parameters that influence soil mineral availability and/or root penetration into the soil profile (Iheshiulo et al. 2023), but how crop rotations might affect crop nutritional quality is poorly understood. The inclusion of perennial forages in a long-term wheat cropping system demonstrated mixed results on soil mineral levels and grain protein and mineral concentrations (Clemensen et al. 2021, 2022). Protein levels increased with some legume-wheat rotational combinations, but negative correlations were also found between yield and wheat grain protein and grain mineral concentrations (Clemensen et al. 2021). A cropping system study with alfalfa and spring wheat showed increased wheat grain concentrations of nitrogen, sulfur, copper, magnesium, and zinc, presumably due to increased soil availability of these minerals following the alfalfa phase of the rotation (Smith et al. 2018); however, reductions in grain nutrient concentrations were found when the cropping system combination resulted in higher yields. An analysis of 32 long-term cropping system experiments (10–63 years) across Europe and North America demonstrated that crop rotational diversity enhanced small-grain cereal yields (Smith et al. 2023). This study suggests a benefit of crop rotations on overall food production, which would contribute to human health, but data were not gathered on these rotations' impact on crop nutritional quality.

Nutrient Application

Evidence indicates that proper timing of soil nitrogen supplementation can improve both crop yield and grain protein content in grain crops, like wheat (Hu et al. 2021). The application of nitrogen, phosphorus, or both was used in a long-term field experiment to assess effects on yield and grain quality in spring wheat (Smith et al. 2018). Fertilizer phosphorus increased grain phosphorus, potassium, magnesium, and manganese concentrations relative to controls but decreased grain zinc and calcium concentrations. Lowered grain zinc in response to soil phosphorus application has also been reported in other studies (Clapperton et al. 1997; Zhang et al. 2012; Ova et al. 2015). Reasons for this could be a suppression of mycorrhizal fungi by phosphorus fertilization (Clapperton et al. 1997) or due to reduced soil available zinc caused by precipitation with applied phosphorus (Kirchmann et al. 2009). Nitrogen fertilization in the spring wheat study (Smith et al. 2018) increased crop yields, but reduced grain concentrations of several minerals (phosphorus, potassium, calcium, magnesium, manganese, and zinc), apparently due to a dilution effect.

Other studies, however, have shown a positive effect of nitrogen fertilization and whole-plant nitrogen status on zinc concentration in wheat grains (Waters et al. 2009; Cakmak et al. 2010; Kutman et al. 2011; Shiwakoti et al. 2019). Some of the differences in these observations could be due to the level of nitrogen fertilization and nitrogen levels achieved in soils. A global meta-analysis of nitrogen fertilization effects on grain zinc and iron in major cereal crops (wheat, maize, and rice) confirmed that higher nitrogen rates generally resulted in increases in zinc and iron concentrations in these cereals, except for grain zinc in maize (Zhao et al. 2022); however, grain zinc was unchanged or reduced at lower nitrogen rates. Green manure addition and other organic soil amendment practices have been shown to enhance plant uptake of zinc, resulting in increased mineral concentrations in edible plant tissue (Aghili et al. 2014; Kumawat et al. 2023).

Fertilization effects on other nutrients have also been studied. A meta-analysis of nitrogen fertilization and water stress effects on corn grain quality (Correndo et al. 2021) showed consistent increases in grain protein levels in response to nitrogen fertilization, little impact on grain oil, and a slight reduction in grain starch, while the responses to water stress were quite variable, possibly due to large variations among the reported treatments. Nitrogen fertilization also has been shown to increase protein levels in other grain crops (Maheswari et al. 2017; Miner et al. 2018) but can lead to a dilution effect on grain oil concentrations in oilseed crops. The effect of nitrogen fertilization on vegetable crops can lead to higher protein levels in edible tissues, but elevated tissue nitrate levels can also be a human health concern (Maheswari et al. 2017). The addition of organic matter can also indirectly improve food nutritional/health quality by reducing plant uptake of harmful heavy metals, for example, cadmium in wheat (Liu et al. 2009; see also Chapter 6).

Biostimulants

As discussed in the previous chapter, nonmicrobial and microbial soil inoculants may influence crops; in some cases, the influence in crops can in turn affect human health. These effects are a bit more nuanced rather than direct, but those connections are explored here. It may be possible to bolster micronutrient deficiencies in crops through biostimulant addition to soils (Santos et al. 2019; O'Callaghan et al. 2022). In experiments with sterilized soil in pots (corn, Kothari et al. 1990) and in the field (wheat, Rana et al. 2012), plant–microbe interactions have been shown to improve the nutritional standing of soil by enriching mineral availability and subsequently uptake by plants.

Application of beneficial microbes, such as plant growth-promoting rhizobacteria and mycorrhizal fungi, has been shown to increase crop yields in laboratory and field studies (Zhang et al. 2019; Chen et al. 2023). Plant growth-promoting rhizobacteria can increase plant nutrient levels by altering the composition of root exudates and increasing interactions with other soil microbes (Fasusi et al. 2021). Several bacterial genera may be considered plant growth-promoting and are being studied for their roles in enhancing soil productivity, plant health, and plant stress tolerance; these include *Aeromonas*, *Arthrobacter*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Clostridium*, *Enterobacter*, *Gluconacetobacter*, *Klebsiella*, *Pseudomonas*, *Rhizobium*, and *Serratia* (Mannino et al. 2020; Pathania et al. 2020).

Mycorrhizal fungi can mine nutrients from the soil, enhancing plant nutrition by exploring a larger volume of soil than a plant's root system and passing these nutrients on to the plant. The role of mycorrhizal fungi in modulating zinc and phosphorus in plants has been well studied (Cavagnaro 2008; Wang et al. 2023). Zinc deficiency is a global challenge, and many individuals experience inadequate dietary zinc intake resulting in human health issues (Brown and Wuehler 2000). Nutrients in plants increase as a result of mycorrhizal colonization of the roots, which can cause morphological and physiological changes in the roots. Mycorrhizal fungi can also increase uptake of other nutrients, and improvements in plant nutrients can occur in soils of low nutrient status or where soil nutrients are heterogeneous or depleted (Cavagnaro 2008). Soils inoculated with mycorrhizal fungi and plant growth-promoting rhizobacteria improved nutrient uptake and plant water retention under drought conditions (Zheng et al. 2018; Bhantana et al. 2021) and may be of particular benefit because of changing climates and climate anomalies such as droughts and flooding events that can adversely affect crop production.

There is potential for biostimulants to affect overall food security by increasing crop yield and plant growth under stress and to use plant growth-promoting rhizobacteria and mycorrhizal fungi inoculants to enhance specific nutrients in plants to influence human health. For instance, the application of organic soil amendments, retention of crop residue, and use of bacteria and fungi were shown to increase rice yield, protein content percentage, and micronutrient concentration in the grain (Kumawat et al. 2023). However, as discussed in Chapter 4, the composition of biostimulants (diverse consortia versus a single taxon), the climate and soils of the fields to which they are added, and the interactions with indigenous soil microbes are all confounding factors when it comes to understanding the degree to which biostimulants could positively affect crop nutrient density. To ensure the most practical and efficient use of plant growth-promoting rhizobacteria and mycorrhizal applications, it would be helpful to better understand the symbiotic relationships and metabolic pathways linking mycorrhizal fungi and plant growth-promoting rhizobacteria with host plants (Desai et al. 2016). Use of gene-editing tools and -omics data can shed light on how the manipulation of these systems could promote growth and nutritional enhancement of crops in the future. Within these studies, it is equally important to understand the role of environmental factors in the persistence of microbial inocula under field conditions and on microbe colonization in the plant. Ultimately, the effectiveness of inoculations, both in terms of impacts on nutrient composition and economically, needs to be further tested and vetted under field conditions.

Linking Soil Micronutrient Status, Plant Micronutrient Status, and Human Nutrition

In sum, plants vary considerably in their tolerance to soil nutrient deficiencies (Impa and Johnson-Beebout 2012). Nutrient-deficient soils can have a major impact on plant growth and productivity. For example, the two micronutrients most commonly deficient in human diets globally, iron and zinc, are also associated with poor plant performance and significant yield reduction (up to 90 percent) when deficient in soil for plant growth (Alloway 2008). Furthermore, approximately 30–50 percent of heavily farmed soils around the world are deficient (content and/or bioavailability) in the key micronutrients, with the problem being more prominent in developing regions (Singh et al. 2005; Cakmak and Kutman 2018). Application of macronutrients to deficient soils (through synthetic fertilizer or other means), as widely practiced in the United States, generally improves crop yield without necessarily increasing micronutrient content of the edible part of the plant (Alloway 2009) and may sometimes have a dilution effect on food micronutrient concentrations (Cakmak and Kutman 2018). Furthermore, plant genetic traits that confer enhanced micronutrient uptake from soils do not always translate into enhanced nutrient accumulation in the edible plant tissue (Grusak 1994; Impa and Johnson-Beebout 2012).

This fact has led to a persistent challenge in identifying practical strategies to reduce micronutrient deficiency in humans through enhanced nutrient density in staple food crops, especially for at-risk populations in developing regions of the world (Pfeiffer and McClafferty 2007). Ongoing strategies, like agronomic biofortification (e.g., foliar zinc application in non-deficient soils), show promise but have produced mixed results in terms of impact on edible plant micronutrient density (Alloway 2009; Cakmak and Kutman 2018). In the context of the United States, the translocation efficiency of micronutrients from soil to edible plant tissue per se has relatively limited impact on human nutritional status and health, largely because of widespread and low-cost micronutrient supplementation in staple products (e.g., baked goods, cereals, dairy, and beverages) as well as overall diversity of the diet. Therefore, in the United States (and other developed regions), soil micronutrient status is largely relevant primarily in its impact on food availability and affordability (via impact on crop productivity). In developing regions where nutrient supplementation is not practical among large parts of the population, the added dimension of reducing malnutrition through soil micronutrient status and plant trait development is highly significant. In a highly globalized world, this need cannot be ignored.

EFFECTS OF FOOD PROCESSING ON NUTRIENT DENSITY

Discussion of nutrient density and bioactive compounds composition in edible plant material in reference to human health and well-being is incomplete without acknowledging the processes the harvested crops must undergo before consumption. Nearly all commercially harvested plant foods are processed in some way to make them safe to consume and improve their palatability and other important attributes such as shelf life. Such processes can alter the nutritional and health attributes of the harvested material in major ways. For example, milling cereal grains to produce a more palatable and shelf-stable ingredient often involves the removal of bran and germ tissues that contain most of the bioactive secondary metabolites, dietary fiber, minerals, and vitamins. Other processes such as thermal treatment or fermentation can enhance bioaccessibility or bioavailability of some nutrients and bioactive compounds but may also lead to the degradation and loss of others. Thus, it is always important to consider the final form of edible plant tissue that is consumed when evaluating soil–plant–human health interaction.

Food processing encompasses a broad array of techniques used to transform raw agricultural commodities and other nonagricultural material into edible products or ingredients that meet end-user (consumer) needs. Food processing occurs not only at the industrial or commercial level but also at home. Familiar appliances, including home stoves, microwave ovens, refrigerators, freezers, blenders, and mixers, are used to process food at the home level. Depending on the starting raw material and intended product, the technique used in food processing can be as simple as washing and coating (e.g., fresh fruits) and thermal treatment (pasteurization, freezing) or involve a complex array of thermo-mechanical, physical, or electro-chemical processes and other techniques.

Regardless of the method, one of the primary goals of food processing, besides improving palatability, is to make products safe to consume by eliminating pathogens, toxins, or contaminants that may accompany harvested commodities (Box 5-3). In addition, products must provide adequate nutrition for basic human function, consistently meet consumer sensory expectations, have an adequate shelf life, offer convenience to fit busy consumer lifestyles, and remain affordable. For these reasons, food processing has been an integral part of human lifestyle for millennia. For example, techniques such as salting, dehydration, and fermentation to preserve and produce new foods have been in use for at least 1.7 million years (Knorr and Watzke 2019). The mastery of fermentation technology (Bryant et al. 2023) and fire for cooking approximately 1.5 million to 700,000 years ago (van Boekel et al. 2010; Herculano-Houzel 2016) enabled humans to improve food nutritional and sensory quality in unprecedented ways. Both fermentation and cooking are credited with significantly affecting human intellectual and economic development (Eisenbrand 2007; Herculano-Houzel 2016; Bryant et al. 2023).

One of the most impactful consequences of food processing is altering its nutritional profile; most processes enhance not only the palatability of the food but also the ability of humans to derive calories and nutrients from the food. In fact, invention of food-processing techniques enabling more efficient calorie assimilation from foods is credited with enabling the human brain to develop much faster than that of other primates (Herculano-Houzel 2016; Bryant et al. 2023). The fundamental impact of food processing on nutritional and caloric profile of foods implies that food processing is a critical and integral component to consider when examining possible linkages between agricultural management practices and the nutrient density of foods for human consumption and other effects on food.

Common Food-Processing Methods with Consequences for Nutritional Profiles of Foods

Because food processing includes a diverse array of techniques, this review contains select examples of common food-processing techniques that have a substantial effect on the nutritional and health attributes of plant-derived food commodities.

Milling

Milling, the primary method used to convert cereal grain commodities into edible or functional food ingredients, is perhaps one of the most consequential food-processing methods. Cereal grains are the most widely consumed staples around the world, directly contributing more than half of global caloric intake (Awika 2011), and milling often dramatically alters the nutritional profile of the grain, especially in terms of micronutrient and bioactive compounds profile. Regardless of the grain type or intended product, the milling process often involves separation of anatomical components of the grain, that is, the outer protective pericarp (bran), the germ, and the endosperm. The primary goal is to obtain a clean endosperm, the most abundant and economically valuable part of the grain. Grain milling leads to products like polished rice, refined wheat flour, or corn grits that can be readily used industrially or at home to make various products. Meanwhile, the milling waste stream (which mostly comprises nutrient-rich germ and bran) is, to a limited extent, used as a source of specialty ingredients for functional food applications in products such as high-fiber breakfast cereals and baked goods and rice bran oil.

BOX 5-3
Impact of Food Processing on Nonpathogenic Microorganisms That May Be Transferred to the Human Microbiome

Food-processing technologies are directed to control microbial growth and inactivate microorganisms, including those that can make people sick. It is important to note that most food-processing methods do not sterilize the food or remove all microorganisms; thus, certain nontarget, nonpathogenic microorganisms may remain in foods after processing, while others may be intentionally introduced (e.g., through fermentation). Inactivation and control of microbes in foods is a complex issue and is affected by the nature and chemistry of the food product, as well as by the target microorganism(s). Food-processing methods are validated for a specific microorganism of interest in a specific food product, allowing survival for some microbes that may increase in number toward the end of the produce shelf life. Naturally occurring microbes are often taken advantage of in the development of fermented vegetables, while inoculants or cultures are often added in the creation of fermented dairy products. The potential also exists for post-process contamination of food products in the food-processing facility (Teixeira et al. 2021) or elsewhere along the farm to fork continuum.

Consumers' preference for foods that have fresh-like flavor and texture for some products has increased the use of technologies that better preserve the original attributes of a product, especially fruits and vegetables, e.g., nonthermal processing. Such nonthermally processed foods must be convenient but also have sufficient shelf-life to make distribution feasible. Examples of such processes include fresh-cut fruits and vegetables that may be combined with active packaging, high pressure processing, ultrasound, pulsed-electric fields, UV-light, and atmospheric cold plasma. These technologies, often referred as mild processing technologies, are targeted at inactivation of microbial pathogens and are recognized alternatives to traditional thermal processing and pasteurization.[a]

Mild technologies may be advantageous in comparison to conventional technologies for preservation of nutritional and organoleptic properties of foods, while also ensuring safety throughout the product shelf life (Barba et al. 2017). Given the potential for more frequent use of these techniques, it is likely that some microbes may survive processing and be present in a variety of food commodities. Some bacteria produce spores, which lie dormant until provided the proper environmental conditions. Spores of *Bacillus* and *Clostridium* species require the most attention, due to their inherent resistance to inactivation via processing and the innate ability of their vegetative cells to conduct metabolic activities at refrigeration temperatures. Nonthermal processing methods reduce non-spore-forming bacterial populations, but they do not inactivate bacterial spores (Markland et al. 2013).

The fate of commensal microbes in food processing is not well studied. Microbial spoilage of food is of concern given the grand challenges of wasted food, sustainability of food production, and emission of greenhouse gases from spoiled food (Xu et al. 2023). Microbial population dynamics in processing environments occur, including psychotropic and psychrophilic bacteria like *Pseudomonas*, *Enterobacteriaceae*, and lactic acid bacteria genera that grow on fresh meats, seafood, and produce. These microbes along with other genera from plant origin (*Bacillus*, *Burkholderia*, *Rahnella*,

continued

BOX 5-3 *continued*

Pseudomonas, and *Klebsiella*) may be present in biofilms in production environments. Persistent and diverse microbial communities in food-processing facilities can become part of the human microbiome. A recent meta-analysis by Xu et al. (2023) showed that several nonpathogenic microbial genera are present in processing facilities, with the composition of the complex bacterial communities dependent on nutrient levels in biofilms. When tracing the connection of soil microbes through foods to human nutrition, the food-processing environment may be one worthy of future study.

[a] The U.S. Department of Agriculture's National Advisory Committee on Microbiological Criteria for Foods revised the definition of pasteurization to include both advanced thermal (ohmic, microwave heating) as well as nonthermal lethal (high pressure, UV radiation, pulsed electric field) agents as a part of processes leading to pasteurization (NACMCF 2006). Pasteurization is redefined as "any process, treatment, or combination thereof, that is applied to food to reduce the most resistant microorganism(s) of public health significance to a level that is not likely to present a public health risk under normal conditions of distribution and storage" (Balasubramaniam et al. 2016).

Milling is integral to grain processing not only because it converts grains into more functional food ingredients but also because it considerably improves palatability of the grains; consumers have a much stronger preference for refined-grain (as opposed to whole-grain) products. The improved palatability is primarily due to the removal of the protective fibrous bran tissue that is rich in nondigestible structural carbohydrates, waxes, and secondary plant metabolites (such as phenolic compounds) that help protect the seed from pests, pathogens, and environmental assaults. The structural carbohydrates and secondary plant metabolites often negatively affect food product texture, color, flavor, and other desirable sensory attributes. However, it is important to note that these same components that negatively affect food sensory appeal are also associated with significant beneficial effects on human gut microbiome composition and metabolite production, improved gut health (Awika et al. 2018), and systemic immune response (Spencer et al. 2021), among other benefits to human health. This trade-off highlights the ever-present challenge of delivering food products with broad consumer appeal and health-promoting properties. Another important benefit of milling is improved shelf life of products by removing the germ that is rich in lipids and lipolytic enzymes that can promote lipid oxidation resulting in product rancidity.

An unfortunate consequence of modern grain milling technologies invented in the 1800s is the considerable loss of essential micronutrients (minerals and vitamins), dietary fiber, and bioactive secondary metabolites, including phenolic compounds. The vast majority of essential micronutrients derived from grains, including minerals such as zinc and iron or B-vitamins, are concentrated in the bran and germ tissues that are removed during the milling process. Key micronutrients of concern, such as thiamin (vitamin B1), riboflavin (vitamin B2), niacin (vitamin B3), iron, and zinc, are reduced by 60–80 percent in refined (milled) grain products (Awika 2011), whereas bioactive secondary metabolites and dietary fiber are reduced by approximately 90 percent in the milling process (Awika et al. 2005; Awika 2011). Ironically, the discovery of several of the B-vitamins in the early 20th century is directly attributable to the industrialization of the modern refined milling process that led to the outbreak of vitamin deficiency-linked diseases like pellagra (vitamin B3) and beriberi (vitamin B1) (Carpenter 2000). The ubiquitous and highly successful enrichment program (incorporating predetermined levels of vitamins B1, B2, B3, B9, and iron to refined grain products) currently widely practiced by millers was encouraged by the U.S. government beginning in the 1930s to combat the negative nutritional consequences of modern grain milling processes.

In the above context, improvement of grain nutritional profile targeting micronutrients or bioactive compounds via genetic improvement or agricultural management practices to improve soil health can be a major challenge if the nutrients end up getting largely lost during the milling process. This circumstance indicates that, beyond the gross nutrient content/concentration of the resulting grain, the partitioning of the nutrients in specific tissues of the seed must be considered. In fact, the location of nutrients in different parts of the seed remains one of the major challenges in attempts to improve micronutrient profile of grains through biofortification (Díaz-Gómez et al. 2017). Furthermore, although nutritional and health benefits of whole grain components are well documented (Cho et al. 2013; Hu et al. 2020; Hullings et al. 2020), capturing these benefits to broadly affect human health remains challenging primarily due to low consumer acceptance of such products. Therefore, deriving full benefits of nutritionally beneficial plant commodities requires innovations in methods to minimize losses of such nutrients and bioactive compounds during processing while maintaining consumer acceptance. Novel methods that enhance beneficial effects of the desirable compounds in foods at lower levels of intake (to minimize undesirable sensorial properties)—for example, by exploiting synergistic biological activities of complementary molecules or altering the food matrix for targeted release of the compounds along the gastrointestinal tract (Awika et al. 2018)—are worth pursuing. Additionally, technologies that enhance the functionality of the grain milling waste streams in mainstream food applications to improve consumer acceptance while capturing their nutritional and health benefits are critically needed.

Thermal and Mechanical Processing

As mentioned previously, the invention of thermal processing has been one of the most consequential events in the human intellectual evolution (Herculano-Houzel 2016). Furthermore, innovations in modern thermal processes such as commercial sterilization (ca. 1800) and pasteurization (ca. 1865) have dramatically affected human health and well-being by improving food product safety and quality and revolutionizing the efficiency of the food value chain. Due to its predictable impact on food safety, shelf stability, and desirable sensory effects, thermal treatment is the single most common process food commodities undergo prior to consumption, both in industrial and home settings. Beyond safety and sensory quality, thermal processing can also have a major impact on nutritional profile of plant material. Furthermore, the thermal process is often accompanied by varying levels of mechanical processes, including agitation, crushing, homogenization, and pressure (e.g., in extrusion process), that may further affect the nutritional and quality profiles of the food product.

In general, an important, consequential effect of thermal processing is significant improvement in the bioavailability of both macronutrients and micronutrients. The macronutrients are made more bioavailable via thermal denaturation (e.g., starch gelatinization, protein unfolding) that makes them more accessible to digesting enzymes or via deactivation of antinutritional factors present in some commodities, such as lectins and trypsin inhibitors in legumes. The micronutrients can also become more bioavailable via improved release from cellular matrices that are physically disrupted during thermomechanical process. Processes that lead to more disruption of the plant cell wall matrix often lead to increased bioacessibility of micronutrients, including phenolic compounds and other secondary plant metabolites. Furthermore, thermal treatment can structurally degrade some antinutritional compounds (e.g., tannins and phytate), leading to enhanced micronutrient (especially iron) bioavailability (Raes et al. 2014).

However, it has to be noted that some micronutrients (e.g., ascorbic acid and some tocopherols) are not heat stable and can significantly reduce under thermal processing, especially when heat conditions are severe (exceed 110°C for several minutes), as can be encountered during canning, roasting, and extrusion. Nevertheless, it is generally recognized that common food thermal processes do not lead to catastrophic loss of the vast majority of macronutrients and that benefits of thermal processing on micronutrient bioaccessibility are more positive than negative (Dewanto et al. 2002; Ravisankar et al. 2020; van Boekel et al. 2010).

Fermentation and Germination

Crop fermentation and seed germination (often referred to as sprouting) are common processing techniques used to improve sensory and nutritional profile of plant-based crops (e.g., grain pulses and other legumes, cereal grains, and leafy vegetables) and, in the case of fermentation, shelf stability of various products (e.g., sauerkraut, kimchi, and olives). Both processes rely on partial enzymatic transformation of food components to produce secondary compounds with desirable properties, for example, acidity or volatile flavor profile. While germination relies largely on endogenous plant seed enzymes, fermentation is typically dependent on exogenous microbial enzymes. The overall nutritional consequences of exogenous or endogenous enzymes are similar. The enzyme action leads to partial hydrolysis of macronutrients (carbohydrates and proteins), making them more easily digestible by humans. At the same time, chelating antinutrients like phytates and tannins are also partially hydrolyzed (via action of phytase and tannase), which can considerably enhance bioaccessibility of micronutrients like iron (Raes et al. 2014). Partial degradation of cell wall polysaccharides by the enzymes also leads to enhanced release of micronutrients and bioactive phenolic compounds; for example, phenolic antioxidants extractability has been shown to increase more than two-fold during fermentation of cereal grains (Ravisankar et al. 2021). Furthermore, during fermentation, the resulting low pH and organic acids produced can enhance solubility of iron and zinc, further improving their bioacessibility (Raes et al. 2014). Consumption of fermented foods has also been found to increase microbiota diversity in the human gut and reduce inflammatory markers (Wastyk et al. 2021). The diverse array of nutritional benefits derived from food fermentation is hypothesized to be one of the key early triggers of human brain development in the evolutionary process (Bryant et al. 2023). Thus, fermentation and germination are processes that can be used to help overcome some of the undesirable consequences of other processes that result in reduced micronutrient density in some food commodities. For example, a combination of sprouting with the conventional fermentation process can improve whole wheat flour functionality and whole wheat bread sensory quality (Johnston et al. 2019; Cardone et al. 2020). These technologies could be innovatively exploited to enhance the sensory appeal of whole plant-based food components (e.g., whole grains), which would in turn reduce food waste and pressure on land needed to produce more food (Box 5-4).

Challenges of Measuring Human Health Impacts in Response to Foods

There is no pragmatic option to definitively examine the relationship between consumption of foods and the resulting health impacts. Dietary guidance is based on aggregated evidence from observational and mechanistic studies plausibly linking intake of foods to health outcomes by demonstrating both (1) linkages between components of human diets and health outcomes and (2) plausible physiological mechanisms demonstrating how the relationship between consumption of foods and their constituents can be causally related to health outcomes. Additionally, studies have measured the presence of food constituents in human blood after consumption of foods or extracted components of these foods. However, controlled experiments in humans examining disease outcomes in response to diet are limited to (1) studies of dietary supplements (e.g., fish oil concentrates) and (2) interventions that alter the entire dietary intake of participants (e.g., a vegetarian dietary pattern). More typically studies must rely on so-called intermediate markers of human health such as blood biomarkers, body composition, and functional status. These measurable characteristics provide evidence of the challenges in defining healthy soils as well as healthy humans, due to the lack of standards, detectable biomarkers, and comparable metrics in some cases. Further challenges include:

1. The absence of a universal measure of disease or health
2. The magnitude of effects and time scale by which food influences health
3. Human physiological variability (e.g., genetic variation)
4. Human environmental context
5. Interactions between foods and their components with other dietary aspects and lifestyle behaviors of individuals.

Therefore, directly measuring human health impacts of foods grown in different soils would be extremely challenging with existing research modalities.

BOX 5-4
Food-Processing Waste as a Tool to Improve Soil Health

Approximately 25 percent of food produced around the world is wasted every year (O'Connor et al. 2021), and this underutilized resource is expected to reach 2.2 billion metric tonnes globally by 2025 (Hoornweg and Bhada-Tata 2012). Plant-derived commodities account for more than 90 percent of food waste. In the United States, food processing and manufacturing account for almost 40 percent of the food waste (EPA 2023). Therefore, strategies that improve food manufacturing and handling practices can considerably reduce food waste, and in turn benefit food security as well as soil health.

Food waste leads to inefficiency in the production food value chain, which increases demand on land use to produce more food and, in turn, can accelerate soil nutrient depletion. Because food waste is primarily organic matter rich in nutrients, it can be a valuable source of nitrogen and other products for improving soil health and for soil remediation. For example, aerobic solid composting or anaerobic digestion of food wastes (Waqas et al. 2018; Cheong et al. 2020) can produce soil amendment products that improve beneficial soil microbial populations, increase soil water retention, and improve soil structure (Kasongo et al. 2011; Tampio et al. 2015; Sogn et al. 2018). Common food-processing byproducts, like cereal bran and coffee grounds, can also be recycled to directly produce other foods, for example, as substrates for mushroom production (Chai et al. 2021), further producing ecological benefits while reducing pressure on land use.

LINKING AGRICULTURAL MANAGEMENT PRACTICES TO FOOD SAFETY

Soil ecosystems are complex and can support the persistence of zoonotic and phytopathogens. Some pathogens found in the soil can cause human disease through ingestion of contaminated food; others enter the body by different routes (Box 5-5). Mycotoxins are diverse small molecules produced by fungi that reside in soil and colonize crops in the field or in storage. They have deleterious health effects when consumed, but they cannot be detected by taste or smell (Winter and Pereg 2019). Agricultural management practices can influence the presence and abundance of these types of food contaminants.

BOX 5-5
Soil-Borne Human Pathogens

In addition to foodborne illness, soils harbor pathogens that can cause human disease from cutaneous wound inoculation, direct ingestion of soil (geophagy), or inhalation of dust particles. The threat to human health from some soil-borne pathogens has been mitigated in the United States with the development of vaccines. For example, the bacterium *Clostridium tetani*, which lives in soil and manure and causes tetanus, typically enters the body through a wound. Cases of tetanus in the United States dropped from 500–600 per year in the first half of the 20th century to no more than 100 per year since the 1970s, due to the development and uptake of a vaccine starting in the late 1940s (Tiwari et al. 2021).

Soil-borne pathogens are often widely distributed but more likely to be a health concern for only some populations. For example, the fungus *Histoplasma* does not make most people who inhale it sick. However, people with weakened immune systems, infants, and adults aged 55 and older are at higher risk for severe infections of histoplasmosis.[a] Antifungal drugs became available for the treatment of severe histoplasmosis in the 1950s (Kauffman 2007).

Histoplasma is also an example of a pathogen that is more common in some areas than others because of the soil properties of a region. In the United States, most histoplasmosis outbreaks (more than two cases with a common environmental source) between 1938 and 2013 occurred in the Ohio and Mississippi River Valleys (Benedict and Mody 2016), although modeling indicates that soil environments more hospitable to *Histoplasma* have shifted to the upper Missouri River basin (Maiga et al. 2018).

Coccidioidomycosis, also known as Valley fever, is an example of a regionally specific soil-borne disease of growing concern in the United States. Severe disease causes lung problems; in rare cases, infection can spread to the brain, skin, and joints (Thompson 2011). The disease is caused by the fungus *Coccidioides*, commonly found in some of the dry, arid soils of the Southwest. People are exposed through inhalation of *Coccidioides* spores, and most cases reported are found in Arizona and California. There is evidence that increases in cases coincide with climate patterns (Smith et al. 1946; Park et al. 2005). There is also evidence that global warming is increasing the geographic habitat in the United States hospitable to airborne dispersal of *Coccidioides* spores (Gorris et al. 2019). The cause of increased *Coccidioides* spore dispersal and ways to mitigate exposure when dispersal is high continue to be studied.

These are organisms of concern, but this is in no way an exhaustive list of those with potential to cause disease associated with soil. Jeffery and van der Putten (2011, 8) identified 38 human diseases that result from a “pathogen or parasite, transmission of which can occur from the soil, even in the absence of other infectious individuals.” Although risk of disease from some organisms has been mitigated in the United States, as in the example of tetanus, the case of coccidioidomycosis (annual cases of which grew from an average of less than 7,000 a year for 2000–2009 to almost 15,000 a year for 2010–2019[b]) shows that soil-borne human pathogens are still a cause for concern.

[a] Centers for Disease Control and Prevention. “Histoplasmosis: Risk & Prevention.” Accessed April 27, 2024. https://www.cdc.gov/fungal/diseases/histoplasmosis/risk-prevention.html.
[b] Centers for Disease Control and Prevention. ‘Coccidioidomycosis: Statistics.” Accessed April 27, 2024. https://www.cdc.gov/fungal/diseases/coccidioidomycosis/statistics.html.

Foodborne Pathogens

Pre-harvest soil content and survival and growth of zoonotic pathogens can influence the safety of crops, in particular fruits and vegetables that may be consumed raw. Of particular concern are pathogen-contaminated crops that are consumed by individuals at increased health risk, including people 65 and older, young children (especially those 5 years of age or younger), and those who are immunocompromised, including pregnant women. It is worth noting these higher-risk individuals as this population is growing nationally. In the United States over the past two decades, several high-profile foodborne pathogen outbreaks—for example, of enterohemorrhagic *Escherichia coli*, *Salmonella* spp., and *Listeria monocytogenes*—have been linked to contamination influenced by amended soils of leafy greens, peppers, cantaloupes, and cucumbers (Sharma and Reynnells 2016).

Tillage and Cover Crops

As seen in Figure 4-3, U.S. farmers are increasingly using conservation or reduced tillage practices. These practices, along with crop residues left on the soil surface rather than being incorporated into the soil, may favor pathogen (plant and zoonotic) survival by lowering soil temperature, leaving the soil undisturbed, increasing soil moisture, and providing protection from degradation, lowering soil temperature, increasing soil moisture, and leaving the soil undisturbed (Bockus and Shroyer 1998). Tillage may be used to disc under plants that may be suspected of harboring zoonotic pathogens because zoonotic pathogens like *E. coli* and *Salmonella* may not survive well when buried below the soil surface (Koike 2022). Some fungal plant pathogens, however, survive in soils using the durable structures that allow them to adhere to the crop; another fungal pathogen strategy is to move through soil, water, or contaminated equipment in the dead tissue of diseased plants (Koike 2022).

As discussed in Chapter 4, cover crops are used for a variety of soil health objectives. Cover crops have variable effects on enteric pathogens, whereby some may increase pathogen survival (Bultman et al. 2013), while others likely have less effect (Schenck et al. 2019).

Organic Soil Amendments

Soils are often enriched with biological soil amendments of animal origin (BSAAO) to increase nutrient values, enhance water-holding capacity, and support crop growth and yield.[1] BSAAO can be delivered to soils in the form of raw animal manure, treated or composted manures, and compost teas. As discussed in Chapter 4, they promote soil structure and function, but they have been identified as a critical route of on-farm contamination of fresh fruits and vegetables (Sharma and Reynnells 2016; Teichmann et al. 2020). BSAAOs can contribute to food safety risks as they may: (1) be contaminated with zoonotic pathogens and (2) enhance the growth of zoonotic pathogens in and around the growth of raw agricultural commodities. Understudied liquid fertilizers and organic emulsions may influence the growth of pathogens in the soil depending on how they are processed (Ingram and Millner 2007; Mahovic et al. 2013;

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[1] "*Biological soil amendment of animal origin* means a biological soil amendment which consists, in whole or in part, of materials of animal origin, such as manure or non-fecal animal byproducts including animal mortalities, or table waste, alone or in combination. The term 'biological soil amendment of animal origin' does not include any form of human waste" (21 CFR 112).

Jung et al. 2014). These are considered raw or untreated fertilizers if nutrients (e.g., molasses, yeast extract, algal powder) are added to a manure-based agricultural tea to increase the microbial biomass, according to the Food Safety Modernization Act-Produce Safety Rule implemented by the U.S. Food and Drug Administration (FDA) (FDA 2015).

In raw animal manure, the manure type, the method of application or incorporation into soils, the type of soil, storage of manure before application on to soils, and the microbial diversity present and nutrient ratios in manure-amended soils can affect the persistence of bacterial and viral pathogens (Avery et al. 2004; Hutchison et al. 2005; Franz et al. 2008). It is important that growers use soil amendments appropriately for crop health and to minimize the risk of excess soil amendments leaving the field through runoff and entering produce fields.

Management of soil amendments can reduce food safety risks. Risk reduction approaches include assessing risks from the soil amendment being used, selecting low-risk crops for application (e.g., agronomic crops such as corn, soybeans, and wheat), and reviewing the application method (incorporated, injected, or surface applied) and timing (days to harvest; season of application). Raw manures, for example, are more often applied to agronomic crops rather than to crops that may be consumed raw (e.g., vegetables).

In the United States, the practice of applying animal-origin raw or treated manure in the crop field as a part of nutrient management plan may include application of manure from cattle, poultry, or other mixed manures (Pires et al. 2018). The FDA's Produce Safety Rule focuses on minimizing microbiological safety risks associated with application of treated or raw manure in the growing season for fresh consumed crops (FDA 2015). The rule states that there should be no contact between applied manure and the edible portion of the crop at any point of production, from planting to harvest. FDA has not yet published wait time intervals between manure application and crop harvest and is continuing to assess the data collected (FDA 2015); however, producers can follow guidance published from the National Organic Program of the United States Department of Agriculture (USDA), which states a time period of 120 days from application of manure to harvest of crops (USDA 2011). Nonpathogenic strains of *E. coli* are predominantly studied in laboratory and field trials and are used to indicate fecal contamination as well as for their potential to indicate pathogen survival in soils. Research has corroborated the 120-day time period as means to reduce food safety risks (Sharma et al. 2019; Litt et al. 2021).

BSAAO are often used in tandem with other agricultural management practices that suppress weeds. Data regarding the survival and persistence of bacterial zoonotic pathogens in soils and the ways in which these are affected by nutrient management continue to be produced, but less is known about the interaction with agricultural management practices for weed suppression. Use of plastic mulch during crop production along with poultry litter affected levels of *E. coli* in soil, whereby significantly ($p<0.05$) lower levels of *E. coli* were recovered from soil samples amended with poultry litter without plastic and from unamended plots compared to plots amended with poultry litter (Litt et al. 2021). *E. coli* populations declined faster in bare soil compared to soil with mulch and lettuce phyllosphere (Xu et al. 2016). This change was attributed to UV-radiation exposure in bare soil and lower levels of soil moisture. Higher soil moisture levels increase availability of free water, which subsequently enhances nutrient dispersion and free water available for use by microorganisms for chemical reactions. It has been suggested that mulching along with time of mulching alone and soil moisture can potentially change soil bacterial community composition and soil organic composition due to organic matter break down (Dong et al. 2017). Such biological events can promote growth of specific bacterial genera and change the abundance of soil microflora as well as bacterial pathogen growth and survival profile. These events could also influence *E. coli* survival durations in soils without plastic mulch.

Climatic conditions affect bacterial survival in soil and can be a source or pathway for contamination of produce in the pre-harvest environment. Due to heavy rain events, crops grown in close proximity to the soil could be exposed to pathogens if present in the soil, which may splash onto fruit surfaces or via direct contact with floodwater. Cumulative rainfall affected *E. coli* levels in soils amended with BSAAO without plastic, indicating that increased rainfall provided favorable conditions for bacterial growth and proliferations (Litt et al. 2021), and regular rainfall during an analysis positively influenced growth of epiphytic bacterial populations (Xu et al. 2016).

Similarly, warming air and soil temperatures affected *E. coli* survival in unamended soil samples regardless of presence of plastic mulch (Xu et al. 2016), suggesting that warmer weather supports bacterial survival by providing optimum conditions for growth. Warmer soil temperature and reduced moisture loss by plastic mulch covering along with reduced exposure to excessive UV in sunlight can lead to enhanced bacterial survival, while in bare soil heat and UV irradiation from sunlight coupled with moisture loss could reduce bacterial survival in soil.

In some cases, plants grown in association with plant growth-promoting rhizobacteria have soils with improved water holding capacity, altered soil matric structure, and changes in the effects on enteric pathogens (Markland et al. 2015; Zheng et al. 2018). For example, *Bacillus subtilus* UD 1022 has been shown to protect plants from colonization by human pathogenic bacteria like *Salmonella* and *Listeria monocytogenes* (Markland et al. 2015; Johnson et al. 2020). While pertinent pathogens like *Salmonella* sp. and shigatoxigenic *E. coli* may persist in agricultural soils, their presence and persistence are affected by soil amendment use and may be influenced by other agricultural practices.

As discussed in Chapter 4, another source of organic material applied to soils are biosolids, which are a product of wastewater treatment processes. Microbial pathogens (bacteria, viruses, protozoa, helminths, and fungi) in biosolids originate from human excreta. Composting with a validated time-temperature method can effectively inactivate most pathogens in biosolids and in biological soil amendments. Exposing these materials to high temperatures (e.g., 55°C) for prolonged times in static piles or aerated windrows is an effective means of pathogen reduction (Omar et al. 2023). As described with land application of BSAAO, regrowth or reactivation of bacteria can occur during incubation and storage of dewatered biosolids (Qi et al. 2007). Bacteria in land-applied biosolids will be affected by abiotic factors of the soil and competitive microflora in the soil. In many cases, the alkaline pH of some biosolids will reduce the risk of pathogen survival even more (Wei et al. 2010).

When it comes to foodborne pathogens and heavy metals, wastewater and biosolid production are highly regulated to prevent harmful effects on soil, crops, or animals. The regulations of the U.S. Environmental Protection Agency (EPA) for the quality of biosolids originated in 1993, found in Title 40, Code of Federal Regulations (CFR) in Part 503 Biosolids Rule and includes requirements for use, disposal, and incineration.[2] Biosolids' standards focus on the presence of microbial pathogens, vector attractiveness, and presence of ten inorganic metals.[3] Microorganisms regulated by these standards include fecal coliforms, *Salmonella* spp.,

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[2] U.S. Government Publishing Office. "40 CFR Part 503—Standards for the Use or Disposal of Sewage Sludge." Electronic Code of Federal Regulations. Accessed April 27, 2024. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-O/part-503.

[3] Arsenic, cadmium, copper, mercury, molybdenum, nickel, lead, chromium, selenium, and zinc.

enteric viruses, and helminths. Biosolids can have variable pathogen loads. *Cryptosporidium*, *Giardia*, *Salmonella*, *Listeria*, *Yersinia*, and *E. coli* have been detected at variable levels (Flemming et al. 2017). A portion of the CFR describes pathogen reduction associated with use of biosolids, such as minimum times between land application and harvest of crops (Box 5-6)[4] Biosolids contain several essential micronutrients for plants (e.g., copper, iron, manganese, molybdenum, and zinc) and can therefore be useful in application to micronutrient-deficient soils (Moral et al. 2002; Ozores-Hampton et al. 2011). Use of biosolids with crops may be restricted by the crop commodity and by more stringent restrictions set by the state or buyer.

BOX 5-6
Pathogen Reduction in Biosolids

The U.S. Environmental Protection Agency (EPA) categorizes biosolids into two classes of pathogen reduction: Class A and Class B. Class A biosolid may be applied to lawns, home gardens, or other types of land, or bagged for sale, or land application and requires pathogen densities be reduced to below detection limits. These limits are set at less than three bacterial cells per four grams for *Salmonella* sp., less than one average detectable virus particle per four grams biosolids for enteric viruses, and less than one viable helminth ova per four grams biosolids (dry weight basis) for viable helminth ova (Boczek et al. 2023). Class B pathogen reduction is necessary for any other application and requires a fecal coliform density in the treated sewage sludge (biosolids) of 2 million colony-forming units per gram total solids (dry weight basis) and viable helminth ova are not necessarily reduced in Class B biosolids (Boczek et al. 2023). According to EPA, public access is not restricted for biosolids that meet Class A requirements. Class B sewage sludge still contains considerable pathogens; thus, site restrictions that limit crop harvesting, animal grazing, and public access are required.

SOURCE: Lu et al. (2012).

Even when biosolids meet treatment requirements, pathogenic bacteria can survive these treatment processes and be transmitted to biosolid-amended soils (Badzmierowski and Evanylo 2019). Sagik and Sorber (1978) found that bacterial pathogens die more quickly in hot, dry conditions rather than moist, cold soils. Bacteria usually die off within a few weeks, viruses may persist for months, and protozoa and helminth life stages may survive for up to 10 years (Angle 1994). Microorganisms may leach through soil pores into groundwater (Gerba et al. 1975). Microorganisms have been shown to be transported most rapidly through coarse-textured soils and under saturated flow (Angle 1994).

Beyond microbial pathogens, there is disagreement in the literature regarding the potential for health hazards in land-applied biosolids from other sources of contamination, which can result in contaminated food crops, drinking water contamination, and possible pollutant exposure via inhalation (Schowanek et al. 2004; Lindstrom et al. 2011; Sepulvado et al. 2011; Clarke and Cummins 2015; Lenka et al. 2021; Helmer et al. 2022). While many regulations govern production and application of biosolids, data gaps exist, including emerging chemical

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[4] U.S. Government Publishing Office. "40 CFR Part 503—Standards for the Use or Disposal of Sewage Sludge, Subpart D—Pathogens and Vector Attraction Reduction." Electronic Code of Federal Regulations. Accessed April 27, 2024. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-O/part-503#subpart-D.

pollutants (pharmaceuticals and personal care products, microplastics, and per- and polyfluoroalkyl substances [PFAS]) and potential contamination of soils, crops, and ground and surface water systems (see Chapter 6 for further discussion). The capacity of antibiotic-resistant genes (ARG) in land-applied biosolids to contribute to antibiotic resistance levels in the environment is also a topic of concern. Transmission of ARGs and antibiotic-resistant bacteria along with pathogenic bacteria have been discussed as potential global issues in applications of biosolids to crops (EFSA Panel on Biological Hazards et al. 2021). Transmission of ARGs is not well understood. Several concerns exist, including the potential for ARGs to be concentrated during treatment processes (Munir et al. 2011), the persistence of genes at the application site, and the potential impact on public health (Pepper et al. 2018). Study of bacterial communities in amended soils and resistance genes is worthy of further exploration (Kang et al. 2022).

The microbial communities that live in land-applied biosolids are not well studied. Some microbial communities in fertilizers derived from biosolids have been identified to play active roles in soil enrichment (Hu et al. 2019; Pan et al. 2021), including proteobacteria and planctomycetes that are capable of nitrogen-fixation and ammonia oxidation (Kang et al. 2022).

Soil amendments of animal origin such as manure and biosolids generated from wastewater treatment processes can be effective sources of organic matter and of minimal risk for spreading human pathogens when properly treated and applied. Microbial pathogens may be introduced to the food supply when contaminated biological soil amendments reach the crops or carry run-off into water supplies. Regardless of the commodity or fertilizer type, good agricultural practices[5] should be followed to reduce the risk of contamination (De et al. 2019).

Irrigation

Contaminated irrigation water has been associated with outbreaks of foodborne illness. Irrigation water can become contaminated through a variety of sources, including from cattle manure and poultry litter runoff that can contain harmful pathogens (Markland et al. 2017). The relative safety of irrigation water in terms of microbial food safety risks can be seen as a continuum, where surface water (rivers, streams, irrigation ditches, open canals, ponds, reservoirs, and lakes) has the most risks, followed by groundwater (collected from wells), and then municipal water has the lowest risk of microbial contamination.

Groundwater is generally considered to be a low-risk source of water, but it can become contaminated (Anderson-Coughlin et al. 2021). In a review of enteric diseases attributed to groundwater (Murphy et al. 2017), more than 600 waterborne outbreaks globally were documented that occurred over a 65-year period caused by viral (norovirus and hepatitis A virus), bacterial (*Shigella* and *Campylobacter*), and protozoan (*Giardia*) pathogens. In the outbreaks for which the pathogenic agent could be confirmed or was suspected (n = 169 outbreaks), a variety of bacterial (46 percent), viral (40 percent), and protozoan (14 percent) agents were identified.

Mycotoxins

Soil health influences the vulnerability of plants to colonization of fungi that produce mycotoxins. Mycotoxins are toxic secondary metabolites produced by fungi that reside in soil. They can cause significant health issues and food losses (Box 5-7). Reduction of this food safety

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[5] See FDA (1998) for more guidance on good agricultural practices.

problem in healthy soils is related both to the action of antagonistic soil microbes and fauna (Schrader et al. 2013) and to reduced plant vulnerability associated with reduced water and nutrient stress. Mycotoxins can be grouped into those that result from pre-harvest colonization and toxigenesis and those that primarily accumulate when the food is in storage (Zahra et al. 2019). This section will focus on those mycotoxins that occur in soil and that can accumulate in crops in the field.

BOX 5-7
Burden of Mycotoxins

Mycotoxins are pervasive food system contaminants that cause economic losses and burden public health worldwide (Ostry et al. 2017). They can cause carcinogenic, genotoxic, immunosuppressive, teratogenic, or mutagenic effects, but some can also cause acute toxicity and death if consumed in large quantities (Reddy et al. 2010; Gong et al. 2016; Omotayo et al. 2019). In high-income countries like the United States, regulatory structures protect the public from excessive exposure by ensuring that contaminated foods are detected, repurposed (e.g., for feed), or eliminated. These systems are reasonably effective but at significant expense. One study estimated that losses in U.S. corn, wheat, and peanuts averaged $932 million a year, while costs associated with regulatory processes, testing, and related measures were $466 million a year on average (Vardon et al. 2003). In lower-income countries, regulations may be in place but are likely to be weakly implemented because of the costs involved in effective food-safety monitoring and action. Consequently, mycotoxins exceed regulatory limits in an estimated 25 percent of the global food supply (Eskola et al. 2020).

There are hundreds of structurally diverse mycotoxins (Kabak et al. 2006), but the most agriculturally important mycotoxins are produced by fungi of the genera *Aspergillus*, *Fusarium*, *Penicillium*, *Claviceps* and *Alternaria*.[6] The aflatoxins are the most toxic of the mycotoxins, and of this subset compounds, aflatoxin B1 is the most potent. It is the most carcinogenic naturally occurring compound known, and it causes hepatocellular carcinoma in humans and animals (Kew 2013). It is estimated that consumption of aflatoxin-contaminated food plays a role in 25,200–155,000 cases of hepatocellular carcinoma each year, that is, 4.6–28.2 percent of global cases (Liu and Wu 2010). There is evidence that it is also mutagenic and immunosuppressive (Gong et al. 2004; Zahra et al. 2023). Aflatoxins are produced by *Aspergillus flavus* and *A. parasiticus*. Agricultural soils are the main reservoir for *Aspergillus* inoculum. Spores of mycotoxigenic fungi like *A. flavus* can be transmitted from soil to plants or people by direct contact, movement of dust, splash droplets, or insect vectors (Horn and Dorner 1999; Abbas et al. 2009).

Water stress and high soil temperatures are important drivers of aflatoxin contamination (Horn and Dorner 1999; Jaime-Garcia and Cotty 2010). These environmental parameters may make plants more vulnerable to colonization by *A. flavus*, stimulate greater toxin production, and lead to greater incidence of aflatoxigenic strains of the fungus. Aflatoxin is a particular problem in hot, dry areas, and in cropping seasons affected by drought conditions where corn and peanut

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[6] Various mycotoxins are known or suspected to have a range of negative health consequences for people and animals; see Haque et al. (2020) for an overview of mycotoxins, the fungal species that produce them, and their pathological effects.

are grown, as these crops are especially vulnerable to aflatoxin accumulation (Yu et al. 2022). In the United States, aflatoxin commonly contaminates corn grown in the South and more rarely causes widespread losses in the northern states and Midwest. In drought years, like in 2012, however, mycotoxin levels on corn can be high across North America (Mueller et al. 2016). Peanuts, grown primarily in the Southeast, are particularly prone to pre-harvest aflatoxin contamination when temperatures are high during production and drought occurs late in the season (Butts et al. 2023). Once the fungi are established on the crop host, warm and wet conditions are favorable for pathogen growth and further toxigenesis (Cotty and Jaime-Garcia 2007).

Medina et al. (2017) analyzed the effects of various climate scenarios on the growth and toxigenesis of *A. flavus*, finding that fungal growth was similar across temperature, water, and CO_2 regimes, while aflatoxin production was significantly increased during drought stress. Various studies on modeling of aflatoxin have reinforced the importance of water stress on aflatoxin accumulation in both corn and peanuts (Chauhan et al. 2015; Chalwe et al. 2019a,b). As drought risk increases with climate change, it is likely that aflatoxin will be an increasing risk for the food system. Modeling of future aflatoxin risk suggests that 90 percent of the corn-producing counties in 15 U.S. states will see increases in aflatoxin risk in the future, as the risk of conditions favoring aflatoxin accumulation in the field change with the climate and hot, dry summers become more frequent in northern areas (Yu et al. 2022). Modeling can be especially useful as a tool for bridging scientific disciplines and collaborative data sharing. Systems that coordinate this among multiple scientific disciplines, such as the USDA–Agricultural Research Service's National Predictive Modeling Tool Initiative,[7] can assist producers to make real-time management decisions to mitigate mycotoxin risk in the food and feed supply.

The structure and mycotoxigenicity of the *A. flavus* and broader soil microbial population are influenced by soil temperature and crop rotation (Jaime-Garcia and Cotty 2010). Aflatoxin levels have been associated with soil type (e.g., Smith et al. 2016) and intercropping (Owuor et al. 2018) in surveys. Both surveys and experimental evidence has shown effects of fertilizer application, with an experimental study indicating reduced aflatoxin levels with nitrogen fertilization (Mutiga et al. 2017) and a survey indicating increased aflatoxin with diammonium phosphate fertilization at planting (Njeru et al. 2019).

The health of soils influences nutrient and water-holding capacity of the soil and thus plant stress, which in turn determines the ability of crops to resist colonization and toxigenesis. Soil health may also influence mycotoxin dynamics via the interactions among mycotoxigenic fungi and other soil microbes. Although aflatoxins are remarkably stable in food, resisting heat and many other food-processing procedures, these mycotoxins may be transformed, detoxified, or degraded by other microbes in soil (as reviewed by Pfliegler et al. 2020). Little is known about the ways that increasing levels of aflatoxin in soil ecosystems will influence soil health (Fouché et al. 2020).

Soil organic matter (SOM) serves as a nutrient source for *A. flavus* populations in the soil, so high levels of SOM can thus favor fungal populations. However, the presence of *A. flavus* does not necessarily lead to infection of crops (e.g., Sanders et al. 1984), as host colonization requires environmental stress (Winter and Pereg 2019). Areas with high SOM can show lower aflatoxin contamination levels (Smith et al. 2016), presumably due to better water-holding capacity of soils, and thus lower levels of drought stress on the host crop. In experiments using various levels of compost amendment on peanuts, Chalwe et al. (2019a) observed a strong

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[7] National Predictive Modeling Tool Initiative. Accessed February 8, 2024. https://agpmt.org/.

reduction in aflatoxin levels with increasing additions of compost, while yields were increased. Building soil health is likely to be an effective long-term strategy for both improving yield and reducing mycotoxin accumulation, with positive implications for animal and human health (Figure 5-1).

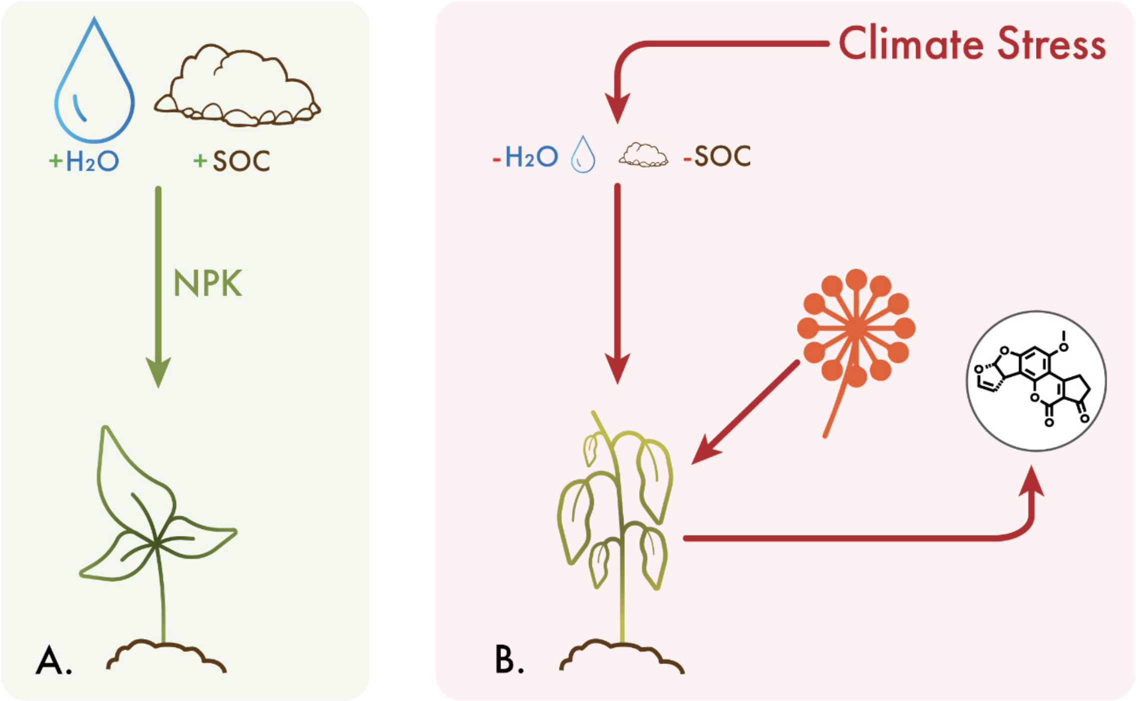

FIGURE 5-1 Influence of soil health on aflatoxin accumulation in crops.
NOTES: Soil health, including both soil nutrients (NPK: nitrogen, phosphorus, and potassium) and soil organic carbon (SOC), is a key driver of mycotoxin accumulation in crops. Soil organic matter influences the water-holding capacity of soil, and thus mediates the effect of drought on plant health and on the risk of aflatoxin accumulation. When water, SOC, and nutrients are sufficient, plants are less susceptible to mycotoxin colonization (a). Water and heat stress increase susceptibility to mycotoxin accumulation (b).

A well-documented approach to reducing aflatoxin is biological control based on the use of atoxigenic strains of *A. flavus*. There are naturally occurring strains of the fungus that do not produce aflatoxin due to deletions in the gene cluster that gives the fungus the ability to make aflatoxin (Horn and Dorner 1999; Ehrlich 2014). Selected non-aflatoxigenic strains have been widely used in the United States and elsewhere to reduce aflatoxin accumulation in corn and peanut (Abbas et al. 2017). Application of atoxigenic strains of the fungus can lead to persistent shifts in the soil fungal community toward the presence of the biological control agent (Lewis et al. 2019).

CONSUMER FOOD CHOICES

Today, farming practices and food production are heavily influenced by consumer preferences and public policy (Lusk and McCluskey 2018). The influence of the consumer constitutes a shift from the preindustrial food market, which was supply-based. Under a supply-based market, consumers have less voice—they choose from the products that are available and the proverbial early bird gets the worm, with latecomers having fewer or lower-quality options from which to choose. As technology improved, the production of raw materials increased, saturating the markets and reversing the production chain. Now, products have to satisfy the demand of consumers to be successful, leading to consumer-driven food product development (Linnemann et al. 2006). Additionally, extrinsic quality attributes, rather than intrinsic factors are becoming more and more important for consumers' food choices (McCluskey 2015). Consumers can easily find multiple products with similar intrinsic factors (e.g., taste, texture, shelf life, nutritional value) and are now more concerned with the extrinsic social and environmental factors of how a food was produced (e.g., organically, fair trade, and absence of child labor) when choosing between products. For some consumers, food consumption and food choice are now driven largely by three major trends: health concerns, sustainability, and convenience (Asioli et al. 2017).

Food choice and human health have direct effects on one another. Diet plays a critical role in the prevention and management of chronic disease, and multiple dietary patterns have been described that promote health and reduce the risk of chronic disease (e.g., the Dietary Approaches to Stop Hypertension eating plan and the Mediterranean diet). Conversely, poor diet is a well-established cause of obesity, hypertension, hyperlipidemia, and chronic disease. Equally, human health also has a direct impact on food choice. Nielsen IQ's 2022 Shopper Health Study found that 31 percent of households report high blood pressure, 25 percent report depression, 24 percent report obesity, 22 percent report cholesterol problems, and 13 percent report Type II diabetes; these conditions are influencing consumer food decisions and interest in food as medicine (Frey 2023). Ninety-two percent of surveyed consumers said sustainability is an important factor when choosing a brand.

Multiple case study examples demonstrate how consumer demand can shift food production. For instance, organic foods are perceived as more nutritious, natural, and environmentally friendly than non-organic/conventional foods by many consumers (Gundala and Singh 2021). Consumers began to link diet, health, and the environment in the 1970s, which created the demand for organic food; the U.S. organic food market has steadily grown over the decades (Carlson et al. 2023). Organic products continue to rise in terms of U.S. market share, though they make up less 6 percent of retail food sales (OTA 2020). Eggs provide a similar example of how rising consumer demand for animal welfare and sustainable food production has been a contributing factor to a shift in the market to cage-free, organic, and enriched eggs that some consumers are willing to pay higher prices for (Rondoni et al. 2020).

Whole grains present an interesting case study where food production has been driven by dietary guidelines and health messaging rather than consumer demand, with a lackluster response in terms of consumption. Numerous studies and surveys have attempted to identify the factors responsible for low whole grain consumption, despite being a focus of dietary recommendations for multiple decades. Potential factors include: lack of consumer awareness of health benefits, difficulty identifying these foods, higher prices (without concomitant demand and willingness to pay), lack of familiarity with preparation methods, and consumer perceptions of inferior taste, texture, and palatability (Kantor et al. 2001; Foster et al. 2020). Given the well-established benefits of whole grain consumption, this seems to be an instance where more needs to be done in terms of food production and marketing to fill this disconnect and benefit human health by influencing consumption patterns (Sogari et al. 2019; Reyneke et al. 2022).

There is potential for consumer demand for sustainability and growing interest in methods such as regenerative agriculture to positively affect soil health. While the organic label has been in the U.S. market since 2003 and is often perceived as designating as a healthy choice, consumers are now becoming aware of products using a regenerative agriculture label and implications for a healthier planet. With growing consumer awareness and public attention on this topic, companies are seeing the benefits of being part of new labeling systems that helps their products stand out and meet consumer demand (Box 5-8). To date, 58 of the top 100 food companies have either made regenerative agriculture commitments or publicly stated regenerative agriculture pilot programs or intentions (Roseboro 2023). However, key challenges remain as there is currently no universal definition or standard for regeneratively grown products. There are at least six main regenerative agriculture labels available, all with different criteria standards (Schwartz 2023; Regenerative Farmers of America n.d.). Not only is the inconsistent messaging confusing for consumers, but it also increases the risk of greenwashing and diluting any current or future trust in a regenerative agriculture label. Nevertheless, this circumstance demonstrates how consumer food choice can influence agricultural management practices and be utilized to help improve soil health.

BOX 5-8
The Expanding Role of the Food Industry in Connecting Soil and Human Health

Soil health and agricultural management practices are being discussed more frequently and openly by food companies. Some food product labels state a commitment to ensure that a percentage of ingredients are grown using regenerative agriculture or other similar approaches. A reason for this is the consumers' concern for sustainability of food products (Tolu 2023/2024). Likewise, and perhaps more importantly in the end, regenerative agriculture can build climate resilience through biodiversity and may lessen risks of loss of shortages of certain ingredients along the supply chain (Tolu 2023/2024). The Institute of Food Technologists recently published a series of articles addressing food production and the environment. The first in the series, focused on soil health, described the interest and intention of large food companies to support practices that support soil health, including carbon sequestering programs, regenerative agriculture, reduced tillage, planting cover crops, and other methods to enrich biodiversity and soil quality (Buss 2023). Innovative methods for measuring soil attributes are being investigated and implemented by major food production companies using genomics and precision agriculture (Buss 2023). It is not yet known what effect this will have on product nutritional quality or on human health; nonetheless, large agriculture commodity companies have committed to greenhouse gas reduction and are enlisting farmers' help in engaging in soil health practices. Companies may become more transparent in the future about the agricultural practices that produce their products and likewise may be more involved with the farmers they source from, possibly providing financial benefits such as credit for carbon sequestration and biodiversity offsets (Tolu 2023/2024).

CONCLUSIONS

Examining human health impacts in response to consumption of foods grown in different soils is complex for multiple reasons. While nutrient deficiencies are a human health challenge that can be studied, food-related health issues predominant in industrialized areas are not due to specific nutrient deficiencies but to overall dietary quality. These health issues are generally characterized as chronic, noncommunicable diseases, such as diabetes, cardiometabolic disease, and cognitive decline. It is generally recognized that these chronic conditions are partly associated with excess intake of calorie-dense foods that are usually low in nutrients and bioactive secondary plant metabolites, including dietary fiber, minerals, protein, essential fatty acids, phenolic compounds, and bioactive lipids, among others.

These are known challenges in the study of human nutrition that researchers and policy makers grapple with when attempting to develop evidence-based guidance on what to eat for optimal health. As elaborated in this report, multiple additional pre- and post-harvest variables—including plant genetics, agricultural management practices, environmental conditions (including soil health), pathogens and pests feeding on crops, harvesting and storage, and food processing—are known to affect the nutritional quality of food consumed, but the complexity of these interactions makes it difficult to identify direct linkages from soil health to crop nutritional quality and on to human health. Although the daily recommended intakes for nutrients (e.g., vitamin A and iron) are well established, a significant challenge for research and policy is lack of consensus for what makes foods better or worse for the human diet in terms of non-nutrient components, sensory characteristics, and other aspects of food quality. Nonetheless, many opportunities exist to further utilize plant breeding and novel food-processing technologies to optimize nutritional, sensory, and food security aspects of foods, including food safety and the ability of plants to produce nutritious food in adverse soil and environmental conditions. Novel approaches to how food production systems are managed can be further developed and utilized to optimize food quality.

Food Composition

Current evidence is weak to link specific soil health factors with food crop macro- and micronutrient content and bioactive compound profile. Furthermore, linking the harvested food crop nutritional composition to human health is difficult due to the large impact that food processing has on the nutritional profile of what is eventually consumed. While some evidence on specific agricultural management practices and nutritional/bioactive compound profile of some food commodities is promising, most research to date has focused on yield rather than on nutrient density or bioactive compound profile as the outcome of interest. Research is needed to identify the relative influence of, as well as interplay among, environmental factors, plant genetics, food-processing techniques, and agricultural management practices on the nutrient density of foods consumed by humans.

Recommendation 5-1: USDA’s National Institute of Food and Agriculture (USDA–NIFA) and the National Science Foundation (NSF) should support translational research to better understand the effect of different agricultural management practices, when used in specific environments, on the nutrient and bioactive density of crops (in the context of yield) consumed by humans.

Recommendation 5-2: USDA–NIFA, NSF, and the National Institutes of Health (NIH) should cooperate to support research on the biosynthetic pathways and the environmental cues (including soil factors) that influence food composition, so that crops can be managed or bred for higher levels of target compounds (especially bioactives) even in the absence of promotive environmental signals.

Recommendation 5-3: USDA–NIFA and NSF should support research, from greenhouse to field scales, to better understand the utility of biostimulants for nutrient uptake and yield under field conditions and considering different ecological factors, including the indigenous soil microbiome.

Food Processing

Food processing is a critical step that not only makes foods safe and palatable but also serves as a major gateway affecting nutritional and health beneficial properties of food crops as accessed by consumers. Therefore, when attempting to identify linkages between soil health, agricultural management practices, crop nutrient composition, and human health, how the food is processed must be considered. Although most food-processing techniques improve bioaccessibility of both macro- and micronutrients, their impact on food nutrient composition can vary considerably. Food processing leads to significant generation of waste streams composed primarily of less palatable plant tissue (e.g., cereal bran, fruit skin and pomace) that are rich in bioactive compounds and micronutrients. Advances in food-processing technologies hold the potential to mitigate these losses and improve nutritional/health profile of foods in ways that are acceptable to consumers. Finally, microorganisms present in the soil as commensals or pathogens are likely important to human health and should be considered in further development of the food system and food-processing technologies.

Recommendation 5-4: USDA–NIFA and private industry should support research in food-processing technologies that enhance the profile of health-beneficial nutrients and bioactive compounds in foods without sacrificing consumer acceptability and that lead to improvements in diet-related indices of public health.

Recommendation 5-5: USDA–NIFA and NSF should support research on innovative technologies that enhance usability of food-processing byproducts as functional food ingredients, sources of valuable bioactive compounds and nutrients, or substrates for production of novel high-value compounds.

Recommendation 5-6: USDA–NIFA and NSF should support efforts to study the survival and microbial fitness of commensal organisms in foods, their response to thermal and nonthermal processes, and their potential impact on host microbiomes.

Food Safety

Agricultural management practices, soil moisture, and precipitation patterns affect foodborne pathogens and mycotoxin production. Better understanding of the conditions under which pathogens and mycotoxins thrive will reduce crop losses and human illness by identifying ways to maximize crop growth potential while minimizing practices conducive to pathogen growth or toxin production.

Recommendation 5-7: USDA–NIFA and NIH should support research studies conducted in controlled environments as well as in field trials that assess persistence of microbial pathogens under varying climatic conditions in order to better

understand factors that may facilitate pathogen survival in soil and transfer onto crops. These studies should incorporate various crops, as well as biostimulants and fertilizer additions, that may alter plant–pathogen interactions and zoonotic pathogen persistence.

Recommendation 5-8: USDA should support efforts, such as the USDA–Agricultural Research Service's National Predictive Modeling Tool Initiative, that use soil monitoring data linked with climate and other environmental data to predict and help control mycotoxin risk in crops and forage species.

Consumers

While there is much more to learn about the specific effects of agricultural management practices on the micronutrient uptake of crops and while soil management is incredibly important from a food safety perspective, it may be that, in contexts such as in the United States, the direct effects of soil health on the nutrition of individuals is small. That is, in locations where diverse types of food are available and foods are often fortified with nutrients post harvest, the nutrient density of any one food is less important to human health than the diversity of the diet consumed. In the case of the United States, the health status of agricultural soils is important to the consumer because it affects food availability and affordability via its impact on crop productivity.

Recommendation 5-9: USDA–NIFA is encouraged to support studies that examine consumer willingness to purchase foods that are more nutrient dense and consumer interest in paying for foods produced with agricultural management practices that support soil health.

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6

Interactions of Soil Chemical Contaminants, Soil Health, and Human Health

Chemical contaminants in soil and other ecosystems are a significant concern for current and future security of the food system. They are also a parameter highlighted by the Planetary Boundaries Framework (PBF), which establishes a set of environmental boundaries that define the safe operating limits for humanity to maintain a stable and habitable planet (Rockström et al. 2009; Steffen et al. 2015). These boundaries represent the critical thresholds, including those related to climate change, biodiversity loss, and chemical pollution, beyond which the environment faces irreversible harm. By identifying these limits, the PBF plays a crucial role in guiding sustainable development and informing environmental policies aimed at ensuring the long-term well-being of the planet and future generations (Rockström et al. 2009).

Regarding contaminants, the PBF is concerned about the “amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in the global environment, or the effects on ecosystem and function of Earth system thereof” (Rockström et al. 2009, 473). Initially referred to in the literature as “chemical pollution,” this planetary boundary category has been further expanded to “novel entities” (Steffen et al. 2015), which include newly developed chemicals, engineered materials, and previously undiscovered organisms within the Earth system as well as naturally occurring substances such as heavy metals that are released into the environment due to human activities. Persson et al. (2022) argued that humanity has exceeded its planetary boundary concerning contaminants and novel entities. This assessment is attributed to the escalating production and release of contaminants, coupled with the challenges in evaluating and monitoring associated risks. In the context of soil, a significant repository for pollutants, chemical contaminants pose substantial threats to both human health and the environment, as summarized in Figure 6-1.

Each year, a vast and diverse array of chemicals enters the soil. These contaminants are often in complex mixtures, which significantly complicates the assessment of potential exposure and associated health risks, as highlighted by Persson et al. (2022). These inorganic and organic chemicals—varying in chemical composition, concentration, and behaviors—enter the soil through routine agricultural practices, industrial activities, waste disposal, atmospheric deposition, and accidental spills. Among these releases, some are intentional, such as the application of pesticides and fertilizers, while others are unintentional, leading to severe negative consequences, as seen with microplastics and per- and polyfluoroalkyl substances (PFAS).

This chapter delves into the interactions between soil processes and contaminants, exploring their impact on exposure and how soil health influences these processes. The committee recognizes that contaminants affect all soil, not just soil used to grow crops. The committee is also aware that “chemical pollution” or “novel entities,” as defined by the PBF, encompass hundreds of thousands of substances (Steffen et al. 2015). It is not within the committee’s capacity to review the interaction of the soil microbiome with all soil contaminants. Some sources of contamination, such as pesticides, are discussed briefly but are primarily addressed in Chapter 4. In this chapter, after reviewing how humans may be exposed to contaminants in soil and how, in general, soil health can mitigate exposure, the committee provides details about three major classes of contaminants: heavy metals, plastics, and PFAS. The committee selected these three classes as case studies because heavy metals have been a long-standing concern in food production and because plastics and PFAS are emerging soil contaminants with potential repercussions for food production and beyond. The case studies provide overviews of the contaminants' sources, their fate and transport, their repercussions on human health and soil ecosystems, and strategies for mitigation and remediation. Although these contaminants enter the soil (or may be magnified in the soil) through agricultural production, the committee notes that contact with soil, crop production, and food consumption are not the only routes of exposure for all the contaminants discussed.

FIGURE 6-1 Impacts of soil contaminants on key soil functions.
SOURCE: Food and Agriculture Organization of the United Nations. Reproduced with permission.

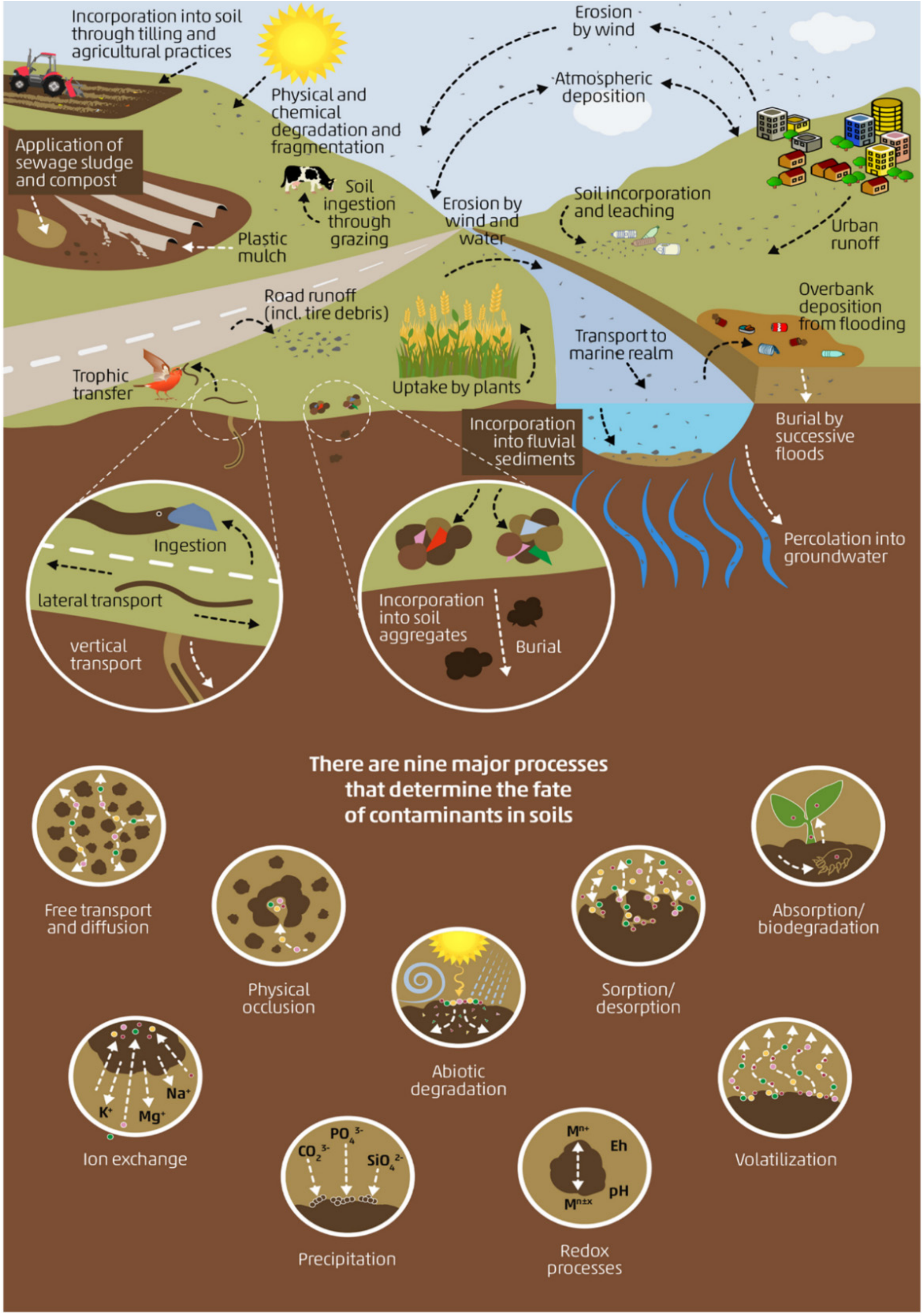

FIGURE 6-2 The route of entrance and fate of contaminants in soils, and nine major soil processes determining the fate of soil contaminants.
SOURCE: Food and Agriculture Organization of the United Nations. Reproduced with permission. Adapted from *Current Opinion in Environmental Science & Health*, 1, Hurley and Nizzetto, "Fate and Occurrence of Micro(nano)plastics in Soils: Knowledge Gaps and Possible Risks," 6-11, 2018, with permission from Elsevier.

HUMAN EXPOSURE TO CONTAMINANTS IN SOIL

Contaminant Fate and Transport in Soil

Once chemicals enter the soil, their movements and potential impacts are determined by a range of physicochemical characteristics, such as solubility, volatility, and sorption potential, as well as their interaction with specific soil properties. These interactions and processes (Figure 6-2) govern whether contaminants will migrate deeper into the soil through percolation, escape into the atmosphere via volatilization, or remain bound to soil particles (Jury and Godhrati 1989; Linn et al. 1993; Schnoor 1996).

Transformation of contaminants—loss or removal of certain substances (e.g., reactants) and the generation or formation of new substances (e.g., products)—can occur via both abiotic and biotic processes (Linn et al. 1993; Scow and Johnson 1996; Al-Mamun 2017). Physical and chemical transformation processes include photolysis and hydrolysis reactions (Figure 6-3). Coupling or polymerization reactions, mediated by certain mineral oxides and fungal extracellular enzymes, can also transform and alter the availability of some organic contaminants (Linn et al. 1993). Biodegradation specifically refers to the transformation of a contaminant by metabolic reactions carried out by the soil organisms, primarily the microbiome. Given that the soil microbiome, with its strong connection to soil health, is a major focus of this report, the committee chose to focus on biodegradation and its role in contaminant removal.

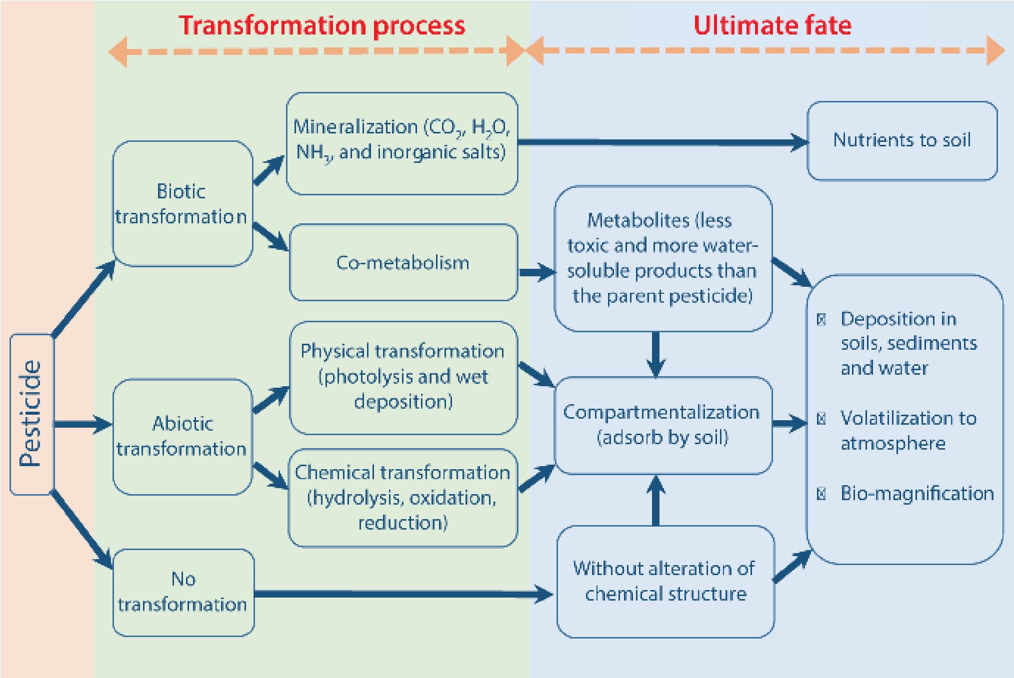

FIGURE 6-3 Transformation processes affecting the fate of pesticides and their degradation products in the environment.
NOTE: In this example, a pesticide stands in as an example of an organic contaminant.
SOURCE: Adaptation used with permission of Spring Nature BV, from "Pesticide Degradations, Residues and Environmental Concern" in *Pesticide Residue in Foods: Sources, Management, and Control*, Al-Mamun, 4, 2017; permission conveyed through Copyright Clearance Center, Inc.

Biodegradation

Biodegradation is defined as the alteration of the chemical structure of a compound by a biological process (Scow and Johnson 1996; Al-Mamun 2017) and often provides a source of carbon and energy to the organisms responsible. In soil, these primarily microbial processes lead to the destruction, and thus either complete removal or change in chemical composition of the original contaminant. Many organic contaminants can be metabolized by the soil microbiome in a process known as mineralization, in which case the contaminant is converted into harmless byproducts, such as carbon dioxide (CO_2) and nutrients, and into microbial biomass (Scow and Johnson 1996; Scow et al. 1995; Figure 6-3). Examples of mineralizable contaminants include many pesticides and petroleum products. In other cases, however, a contaminant may be chemically transformed into other chemical forms, some of which may persist in the environment (Scow et al. 1995). Often, metabolites are less toxic than the parent compound. Sometimes, however, metabolites are more toxic than the parent compounds (e.g., trichloroethylene to vinyl chloride) (Yoshikawa et al. 2017).

Numerous metabolic pathways for contaminants have been identified, some very specific to particular chemicals (Kolvenbach et al. 2014). The University of Minnesota Biocatalysis/Biodegradation Database (Gao et al. 2010) is a comprehensive, publicly accessible resource that provides information on the biodegradation and biotransformation of organic compounds, including many contaminants, by bacteria and fungi (Ellis and Wackett 2012). Among the data compiled are enzymatic pathways, metabolites of degradation, and organisms involved. The database is valuable for bioremediation research, assessment of contaminant degradation potential, and the study of microbial metabolic pathways (Gao et al. 2010).

Human Exposure to Contaminants in Soil

The level of threat that a contaminant poses to human health is thus determined by the complex interplay between the contaminant and the unique soil conditions at a particular location. In general, the enhancement of soil quality (for instance, increasing the level of soil organic matter) can serve as a means to mitigate the adverse effects of soil contamination. The overall health of the soil plays a pivotal role in determining the extent to which contaminants may pose harm to human health.

Exposure assessments (NRC 1991; Swartjes 2015) are frameworks used to identify potential exposure pathways for humans for specific chemicals. An important part is evaluation of how contaminants move and persist and where they end up (e.g., in water, air, or soil) after they enter the environment. From this information, the most likely pathways for human exposure can be identified (Figure 6-4). There are multiple routes by which soil is involved in human exposure (NRC 1991; Swartjes 2015). For instance, individuals near contaminated areas can be exposed directly through dermal contact of the skin with soil or through ingestion of soil, which may occur from incidental ingestion, from consumption of soil particles remaining on foods, or through consumption of contaminants concentrated in foods and animal products. Apart from these direct health effects, contaminants may also be leached through the soil into groundwater and surface water, which can affect drinking water quality and accumulate in seafood. Finally, contaminants on the soil surface may be aerosolized, leading to exposure through inhalation. Whatever the route, estimates are made of contaminant concentrations in exposure media using monitoring data, environmental fate models, or both. These estimates are then used to gauge the potential contaminant intake by individuals, considering factors such as ingestion and inhalation rates (NRC 1991; Swartjes 2015).

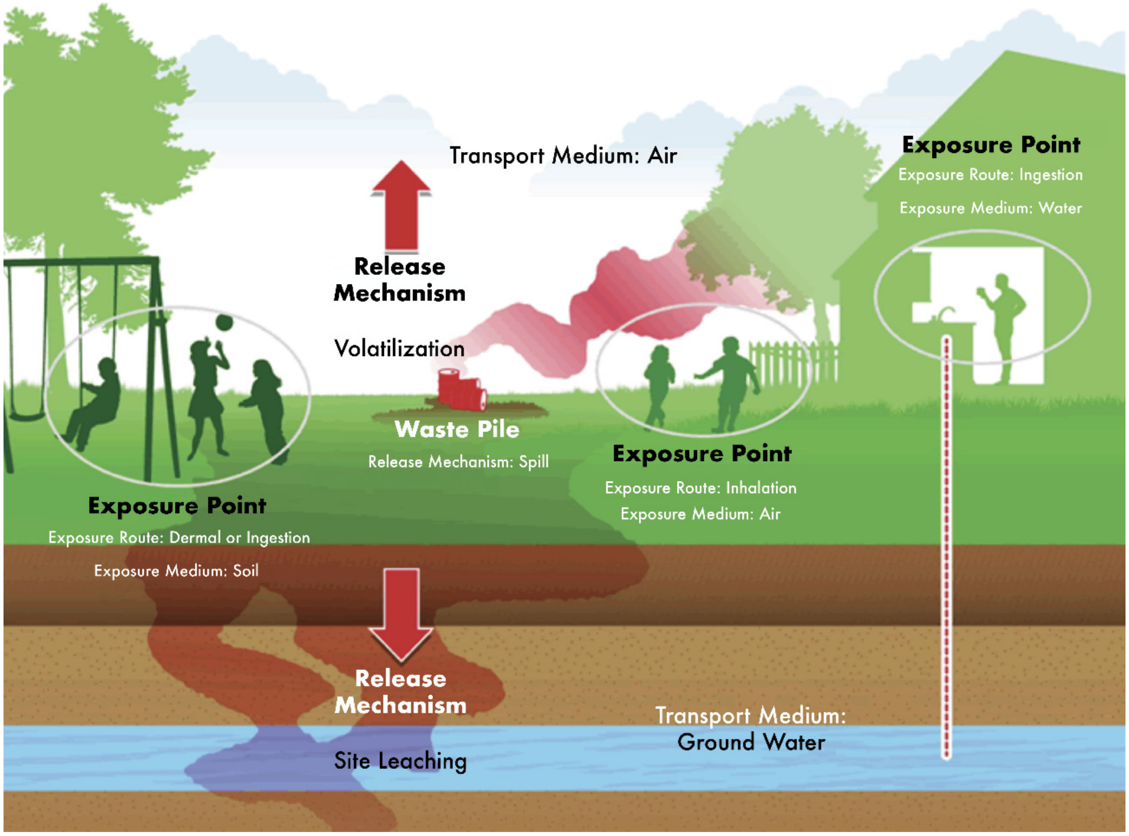

FIGURE 6-4 An example of contaminant source, fate, transport, and exposure setting.
NOTE: Leaking drums are the source of contamination in this figure. Chemicals are released into the air via volatilization, soil via leakage, and water via leaching. The chemicals are transported through air and water to humans and other organisms in the environment.
SOURCE: U.S. Environmental Protection Agency. "Exposure Assessment Tools and Approaches: Indirect Estimation (Scenario Evaluation)." EPA. Accessed April 27, 2024. https://www.epa.gov/expobox/exposure-assessment-tools-approaches-indirect-estimation-scenario-evaluation.

Bioavailability of Soil Contaminants

Bioavailability refers to the propensity of a contaminant to be taken up (e.g., absorbed by various biota, including plants, microorganisms, and human receptors. Bioavailability in soil is a multifaceted concept influenced by physical, chemical, and biological factors, as examined by the National Research Council (NRC 2003). These factors encompass a wide range of interactions that include soil properties (e.g., texture and pH), contaminant properties (e.g., chemical form and solubility), and biological factors, notably microbial activity. Bioavailability can vary over time due to evolving environmental conditions and processes. Considering bioavailability is paramount in the assessment of risks at contaminated sites and in the development of effective remediation strategies.

Barriers presented by soil and plants can diminish the transmission of contaminants to humans. The "soil–plant barrier" concept (Chaney and Ryan 1994; Basta et al. 2005;) aids in discerning the relative significance of food chain versus soil ingestion exposure pathways, particularly for contaminants such as metals. The soil barrier, for instance, can reduce contaminant bioavailability through robust absorption mechanisms. Conversely, for the majority of plants, the plant barrier comes into play when contaminants exhibit phytotoxicity, potentially harming food crops before reaching levels detrimental to human health. Contaminants strongly adsorbed to soil, such as lead, encounter the soil barrier and do not pose a risk via the food chain; instead, ingestion of contaminated soil or dust becomes the primary risk driver. Conversely, highly mobile and weakly adsorbed contaminants such as cadmium bypass the soil–plant barrier, contaminating food crops and elevating the risk associated with the food chain pathway.

Soil properties and components, such as clay and organic matter content, exert substantial influence on contaminant solubility, mobility, and bioavailability. Soil pH, in particular, can modify contaminant bioavailability and mobility by regulating heavy metal dissolution/precipitation, by influencing the ionization of pH-dependent ion exchange sites on organic matter and metal oxide clay minerals, and by regulating strong adsorption of heavy metals and oxyanion metalloids (e.g., arsenate, arsenite) on soil clay minerals. Furthermore, pH-dependent functional groups on soil organic matter affect the formation of stable organometallic complexes. For organic contaminants such as pesticides, bioavailability varies, with nonpolar organic chemicals primarily adsorbed via partitioning to soil organic matter. Polar organic compounds, for example, perfluoroalkyl acids (a type of PFAS), exhibit anionic characteristics within the environmentally relevant pH range. The length of the hydrophobic chain controls the extent to which PFAS contaminants are adsorbed by soil organic matter.

The type of adsorption significantly shapes the environmental fate and long-term exposure of contaminants (Table 6-1). Significant advances have been made to characterize the type of metal contaminant adsorption to soil. Application of synchrotron spectroscopy including X-ray absorption near edge structure and extended X-Ray absorption fine structure for lead and arsenic have been reviewed (Sparks 2013). Limited studies have reported the relationship between metal speciation in soil and their bioavailability or bioaccessibility for lead or arsenic (Scheckel et al. 2009; Noerpel et al. 2020). Over the last two decades, in vitro gastrointestinal (IVG) soil extraction methods have been reported to be highly predictive of lead and arsenic bioavailability (Drexler and Brattin 2007; Basta and Juhasz 2014; Diamond et al. 2016; Whitacre et al. 2017). The IVG extraction methods have been shown to be more predictive of bioavailability than chemical speciation methods via synchrotron spectroscopy (Stevens et al. 2018). Weak adsorption processes, such as electrostatic and hydrophobic partitioning to organic matter, reduce bioavailability and mobility in the short term but not over the long term. In contrast, strong and irreversible sorption is desirable for persistent contaminants like heavy metals and PFAS, effectively reducing long-term human exposure.

In addition to adsorption reactions, metal contaminants can be sequestered as minerals or in soil minerals. Formation of double layer hydroxides (LDH) have been shown to sequester metals including cobalt, nickel, and zinc. Sequestration of these metals in LDH has been reviewed (Siebecker et al. 2018). This sequestration mechanism has not been reported for the metals of concern (lead, arsenic, and cadmium) in this chapter.

TABLE 6-1 Bioavailability and Strength of Adsorption of Select Contaminants to Soil Adsorbent Phases

Contaminant	Examples	Soil adsorbent	Strength of adsorption [a]	Bioavailability
Heavy metal cations	Lead, cadmium, copper	Soil organic matter	Weak or strong	Low to high
		Reactive iron, aluminum, manganese oxide clays	Strong	Low
Heavy metal oxyanions	Arsenic, selenium	Reactive iron, aluminum, manganese oxide clays	Strong	Low
Organic chemicals (nonpolar)	Nonpolar pesticide	Soil organic matter	Weak	Low to high
Organic chemicals (polar)	Perfluoroalkyl acids	Clays	Weak	High
		Soil organic matter	Weak to moderate	Moderate to high
	Polar pesticides			
	Glyphosate		Weak	High
	Paraquat		Strong	Low

[a] Weak adsorption is nonspecific adsorption. Strong adsorption is specific adsorption or chemisorption.

Role of Soil Health in Remediation and Mitigation of Contaminants

Remediation strategies encompass a wide range of methods crucial for managing contaminated soil environments. These approaches play a pivotal role in reducing the concentrations and accessibility of harmful contaminants, thus mitigating potential harm to human and ecosystem health. Remediation, as a comprehensive term, refers to processes directed at lessening the presence, bioavailability, mobility, and potential human exposure to contaminants. It includes a spectrum of approaches, from complete removal to reducing contaminant bioavailability and mobility. Strategies primarily focus on reducing the bioavailability of contaminants in soil, making them less accessible to organisms, especially humans who may be exposed. These approaches often involve altering the chemical and physical properties of the soil to decrease contaminant mobility and uptake.

Bioremediation is defined as “the intentional use of biodegradation processes to eliminate environmental pollutants from sites where they have been intentionally or inadvertently released” (Madsen 1997). In most cases, the treatment process harnesses the metabolic activities of indigenous microbial populations to break down contaminants into less harmful forms (Seagren 2024). Biostimulation involves adding limiting nutrients to support indigenous microbial communities in metabolizing contaminants, while bioaugmentation introduces microbial strains with the potential to degrade specific contaminants (Scow and Hicks 2005).

Chemical remediation methods, such as adsorption and precipitation, aim to reduce bioavailability by binding contaminants to soil particles or transforming them into less mobile forms; these practices are commonly used for metals and inorganic contaminants (Scheckel et al. 2009). For metals (and some organic pollutants), immobilization is the only option since complete removal is not possible. This strategy involves transforming contaminants into forms (e.g., changing oxidation state, solubility) that form strong, irreversible chemical bonds that remain stable in the environment. Contaminant aging is a natural process where contaminants become more strongly sorbed to soil particles over time, making them less bioavailable, involving both fast, reversible sorption reactions and slow, irreversible sorption reactions.

Incorporating organic matter into the soil, such as plant residues, animal manures, and biochar, improves soil physical, chemical, and biological properties (Attanayake et al. 2015). Organic inputs stimulate microbial activity, supporting the biodegradation of organic contaminants and enhancing soil health (Kästner and Miltner 2016). Soil organic matter, influenced by organic amendments, can adsorb metals and organic chemical contaminants, reducing their bioavailability. Additionally, soil pH adjustment resulting from organic matter additions can decrease the bioavailability of metal contaminants (Brown et al. 2004). The use of biochar can be particularly valuable for immobilizing metals and organic pollutants, contributing to the overall effectiveness of contaminant mitigation strategies (Zhang et al. 2013).

In summary, practices that improve soil health not only enhance the overall health of the soil but also play a crucial role in facilitating remediation and mitigation efforts. Improved soil health can effectively reduce the bioavailability of contaminants, ultimately protecting human and ecosystem health. In the "Contaminant Case Studies" section below, greater detail regarding the potential for remediation in soil is provided for various contaminant classes.

CONTAMINANT CASE STUDIES

In this section, the source, fate and transport, exposure pathway, and impacts of major classes of soil contaminants on soil ecosystems and human health are summarized. Although not exhaustive, these examples represent some of the most pressing soil contamination issues that pose a risk to human health. While contaminant sources and exposure routes are not exclusive to agriculture production, both the sources and solutions have, in many cases, a direct connection to agricultural management practices and soil health.

Heavy Metals and Metalloids

Many heavy metals and metalloids can be toxic to humans and the environment, depending on exposure routes, concentrations, and bioavailability. Lead and arsenic are ranked as the top two substances found at national priorities sites determined to pose the most significant potential threat to human health due to their known or suspected toxicity and potential for human exposure.[1] Lead is the most common heavy metal soil contaminant worldwide (Hettiarachchi et al. 2023). The environmental chemistry of lead (a cation) and arsenic (usually an oxyanion) are used here to demonstrate behavior and health impacts of these toxic trace elements. Cadmium is included as an example because it is a highly mobile toxic metal that concentrates in food crops.

Sources of Lead in the Soil Environment

Lead occurs naturally in soils, but most soil lead contamination is a consequence of anthropogenic activities. Mining, smelting, refining activities, and coal combustion have resulted in widespread contamination of soil (Rieuwerts et al. 1998; Tchounwou et al. 2012; ATSDR

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[1] The 2022 Substance Priority List of the U.S. Department of Health and Human Services' Agency for Toxic Substances and Disease Registry. Accessed January 22, 2024. https://www.atsdr.cdc.gov/spl/index.html#2022spl.

2020). Leaded gasoline and paint are also major sources of soil contamination (ATSDR 2020). Ash deposits from solid waste incineration prior to the U.S. Solid Waste Disposal Act of 1965 have been found to be a source of lead contamination in soil as well (Bihari et al. 2023).

In agriculture, lead-containing inorganic pesticides such as lead arsenate (PbHAsO4) were extensively used because of its immediate effectiveness, low cost, and easy handling (Hettiarachchi et al. 2023). Lead arsenate was widely used in U.S. agriculture until the 1950s; its heavy use in orchards over many years caused the buildup of lead as well as arsenic in the soil environment (Schooley et al. 2008). Inorganic fertilizers, manure, compost, and biosolids are alternative sources of accumulation of lead, either in soil or plants (Alengebawy et al. 2021).

Sources of Arsenic in the Soil Environment

Similar to lead, arsenic is found naturally in soil, but most contamination of soil with arsenic is primarily related to anthropogenic sources. These sources include nonferrous metal mining and smelting, wood and coal combustion, wood preservation, pesticide application, and waste incineration (ATSDR 2007). Irrigation water containing high concentrations of arsenic can also be a significant source of soil contamination in India, Bangladesh, and east Asian countries (e.g., Vietnam, China) (Mitra et al. 2017). Arsenic contamination of rice, especially brown rice, from arsenic-tainted irrigation water has been reported in the U.S. Southeast (Meharg et al. 2009) and in California (Carrijo et al. 2022). Arsenic contamination in the southeastern soils is likely from the historical use of arsenical pesticides for cotton production before these pesticides were banned in the 1980s and 1990s; conversion of land from cotton production to rice production has resulted in elevated levels of arsenic in rice in the Mississippi Delta and Texas (Zavala and Duxbury 2008).

Sources of Cadmium in the Soil Environment

Cadmium is one of the most toxic heavy metals and negatively affects essential biological processes of humans, plants, and animals (Kabata-Pendias 2010). Major sources of cadmium pollution in soil include zinc mining, processing, and smelting and the use of phosphate fertilizer produced from rock phosphate ore with elevated cadmium (Kabata-Pendias 2010). Smelter emissions from zinc and cadmium production facilities have contaminated downwind environments (Chaney and Ryan 1994; Zhou et al. 2022). Land application of phosphate fertilizer can result in significant soil pollution with cadmium that impairs crop quality (Kabata-Pendias 2010). However, long-term application of phosphate fertilizer with low cadmium content does not increase soil cadmium or impair wheat grain quality (Basta et al. 1998). Cadmium can also reach soil through land-applied biosolids (ATSDR 2012).

Impact on Soil Ecosystems

Heavy metals change soil microorganism community structures and diversity (Konopka et al. 1999; Khan et al. 2010; Rodríguez Martín et al. 2014; Gutiérrez et al. 2016). Khan et al. (2010) determined that the high levels of cadmium and lead in soils caused decreases in microbial biomass carbon, inhibited acid phosphatase and urease enzymatic activity, and changed community structure based on denaturing gradient gel electrophoresis banding patterns. They also found that bacteria are more sensitive to heavy metal concentrations than actinomycetes and fungi. Konopka et al. (1999) found lead soil content to correlate with microbial biomass and determined that some bacteria populations contained lead-resistance genes. They noted that heavy metal–contaminated soils also have reduced plant biomass that could affect microbial community composition and activity. Others have noted that the diversity and function of soil invertebrates, such as earthworm and nematodes, can be altered by cadmium and lead (Žaltauskaitė and Sodienė 2010; Rodríguez Martín et al. 2014; Gutiérrez et al. 2016; Kavehei et al. 2018).

Fate and Transport: Human Exposure Pathways

Fate and transport of heavy metals is complex and varies greatly between metals. Three exposure pathways important to human health are: soil/dust ingestion and inhalation, ingestion of contaminated food, and ingestion of contaminated drinking water. The first two pathways, which relate to soil, are reviewed here.

Soil and Dust Ingestion One of the major exposure pathways for lead, arsenic, and other heavy metals to humans is through the incidental ingestion of soil or dust. Ingestion is of special concern for children due to their increased hand-to-mouth activity and enhanced pharmacokinetics. Many heavy metals, including lead and arsenic, often have low water solubility in the environment. Low solubility reduces the transport of metals from soil to crops and from soil to source waters. The exception is cadmium, which escapes the soil–plant barrier and easily contaminates food crops (Basta et al. 2005). Many of the heavy metals in ingested dust or soil are dissolved in the acidic conditions (e.g., pH 1.5 to 2.5) of the upper gastrointestinal tract.

Soil properties and agricultural management practices can affect bioavailability and exposure to lead and arsenic. Lake et al. (2021) reported key soil properties reduced the bioavailability of arsenic by 17–96.5 percent and of lead by 1.3–38.9 percent associated with soil human ingestion. For both arsenic and lead, bioavailability decreased with increasing content of aluminum oxide and iron oxide. Soil amendments that add aluminum oxide and iron oxide to soil (e.g., via biosolids) will decrease arsenic and lead bioavailability.

Contaminant Transport from Soil to the Food Chain In general, transport of many heavy metals from contaminated soil to plants to humans is small when compared to incidental ingestion (Chaney and Ryan 1994; Attanayake et al. 2015). However, small amounts of heavy metal absorption into crops that are diet staples (e.g., wheat, rice) can result in significant human exposure. For example, root crops such as carrots, radishes, and beets can accumulate soil lead, and surface contamination of crops with soil can affect human exposure (Attanayake et al. 2014, 2021). Human exposure from ingestion of soil adhered to vegetables has been found to be greater than amounts in those vegetables. Best management practices to reduce heavy metal exposure include washing crops thoroughly before consumption to get rid of adhering soil particles.

Diet is the largest source of exposure to arsenic, largely from grains, produce, seafood, and drinking water. Rice, in particular, is an important source of dietary arsenic because it is cultivated under flooded conditions leading to an anoxic soil environment that liberates arsenic from its minerally bound form and allows it to be taken up and concentrated in the grain. Notably, a recent study found that arsenic availability, uptake, and allocation in rice increases in warmer temperatures; therefore, global warming may increase the risk of arsenic exposure through consumption of rice in production systems that were previously considered low risk (Farhat et al. 2021).

For non-smokers, diet is the largest exposure route for cadmium (ATSDR 2012). However, the concentration of cadmium in the soil is not predictive of the concentration of cadmium in food grown in the soil; soil properties, the type of crop and its genetics, crop rotation, and fertilizer and irrigation management practices all affect the ultimate concentration of cadmium in food (Schaefer et al. 2020).

Impacts on Human Health

Lead exposure primarily occurs through incidental ingestion of contaminated soil and dust, with children being particularly vulnerable. Unlike respiratory and dermal pathways, incidental ingestion involves unintentional swallowing due to hand-to-mouth contact. Studies have consistently highlighted the significance of this pathway, with exposure typically occurring through hand-to-mouth transfer of contaminated soil or dust (Mielke and Reagan 1998; Glorennec et al. 2010; Oulhote et al. 2011; Zahran et al. 2013; Henry et al., 2015). Once lead is absorbed into the body and enters the bloodstream, it can rapidly distribute to the kidneys and liver or be slowly absorbed by soft tissues. The majority of the body's lead burden is stored in teeth and bones. Lead is highly toxic and can affect nearly every organ, especially the nervous system. At elevated exposure levels, lead can lead to comas, convulsions, and even fatalities. There are no safe blood lead levels, and any concentration of lead can be associated with decreased IQ levels in children and behavioral challenges. These effects are considered permanent. Additionally, lead exposure can cause symptoms such as dizziness, irritability, fatigue, impaired cognition, anemia, hypertension, kidney damage, and reproductive organ toxicity (Wani et al. 2016; ATSDR 2020). Lead exposure during pregnancy has been linked to maternal health risks, including hypertension and pre-eclampsia. One study found that women living in areas with higher soil lead levels were more likely to suffer an eclampsia event (Zahran et al. 2014). Even low levels of exposure during pregnancy have been found to lead to poor birth outcomes including low birthweight and preterm birth (Bellinger 2005).

Inorganic forms of arsenic like As(III) (i.e., arsenite) and As(V) (i.e., arsenate) are associated with more severe health effects from exposure as compared exposure to organic arsenic. Ingestion of arsenic can cause gastrointestinal symptoms, decreased production of white and red blood cells leading to bruising, impaired nerve function leading to burning sensations in the hands and feet, and skin changes (Mandal and Suzuki 2002; ATSDR 2007). The U.S. Environmental Protection Agency (EPA) and International Agency for Research on Cancer have also listed arsenic as a human carcinogen because it has been linked to cancer of the liver, skin, bladder, and lung. Fetuses, infants, and children are particularly vulnerable to the potential harmful effects from arsenic exposure, and exposure during times of active brain development has been linked to learning disabilities, behavioral problems, and lowered IQ.

As described above, the impact on human health can vary based on the timing duration, route of exposure, and host variability. Notably, recent research has shown that gut microbiota can increase the bioavailability of soil-bound arsenic thereby enhancing its toxicity (Yin et al. 2017; McDermott et al. 2020; Griggs et al. 2022). While research in humans is limited, studies using in vitro models such as the Simulator of the Human Intestinal Ecosystem have shown that human gut microbiota may increase the bioavailability of arsenic in contaminated soil samples (Laird et al. 2007; Van de Wiele et al. 2010). Despite this individual variability, the U.S. Food and Drug Administration has issued guidance to industry on acceptable levels of arsenic in foods often consumed by infants and children. It recommends that inorganic arsenic levels do not exceed 100 parts per billion (ppb) in infant rice cereal (FDA 2020) and 10 ppb of inorganic arsenic in single-strength (ready-to-drink) apple juices (FDA 2023).

Recent research has also described the impact of heavy metals and metalloids on the gut microbiome, which is important for human health. Studies using animal model systems have shown significant alterations of gut microbiomes to arsenic exposure (K. Lu et al. 2014; Gokulan et al. 2018). One study in mice showed that arsenic exposure not only caused shifts in the composition of the gut microbiota but also led to impairment of the immune response and higher inflammation. Further, these changes were dose-dependent and differed according to the age of the animals (Gokulan et al. 2018). The function of the gut microbiome also is impacted by arsenic exposure, which in one study inhibited the fermentation rate of rumen bacteria by almost one third (Forsberg 1978).

Information about the effect of arsenic on the human microbiome is scarce, but vast shifts in the composition of gut microbial communities have been observed in populations exposed to arsenic (McDermott et al. 2020). For example, in Bangladesh, there was a significantly higher abundance of Proteobacteria as well as multidrug and arsenic resistance microbial genes in children exposed to arsenic than their unexposed counterparts (Dong et al. 2017). In the United States, urinary arsenic was correlated with several taxonomic groups in naturally exposed infants, although none of them were in the Proteobacteria phylum (Hoen et al. 2018). Significant compositional shifts were also observed in a mining community in China with prolonged exposure to heavy metal contamination when compared to a community with little exposure to these pollutants. Paradoxically, metal exposure was also correlated with microbial richness in the human gut (Shao and Zhu 2020).

Evidence supports adverse effects on the kidneys and bone density from chronic dietary cadmium exposure, although in some studies, the populations also lived in areas polluted with cadmium. Studies of the effects of dietary cadmium exposure on human health have found mixed results on cardiovascular disease. Consumption of cadmium at high concentrations is known to cause gastrointestinal distress (ATSDR 2012).

Mitigation and Remediation

Remedial approaches for lead are based on removal or reducing the bioavailability of lead. Bioavailability-based remediation is a cost-effective in situ approach that does not remove the contaminant but does reduce the contaminant's bioavailability. The use of soil amendments to remediate lead-contaminated soils focuses mainly on changing existing soil lead chemistry in situ. It is done by inducing the formation of sparingly soluble lead solids or enhancing chemisorption. Many soil amendments have been used successfully for bioavailability-based remediation (Henry et al. 2015; Wang et al. 2021; Hettiarachchi et al. 2023). Commonly used soil amendments reported to reduce lead bioavailability are summarized in Table 6-2. Other amendments are in development including formation of plumbojarosite (Sowers et al. 2023) and the use of modified biochars (Yang et al. 2019).

Several of the above soil amendments are applied to agricultural fields through additions of phosphorus fertilizer, manures, compost, biochar, and liming materials. These amendments decrease lead bioavailability and exposure to human and ecosystem receptors. Many amendments are green and sustainable remediation (GSR) strategies, which are holistic approaches that maximize environmental, social, and economic benefits (Wang et al. 2021).

TABLE 6-2 Commonly Used Soil Amendments for Bioavailability-Based Remediation of Lead-Contaminated Soil

Soil amendment	Examples	References	Suggested mode of stabilization
Phosphate materials	Triple super phosphate, bone meal, poultry litter	Scheckel et al. 2013 Martin and Ruby 2004 Kumar et al. 2020 Zeng et al. 2017 Liu et al. 2018 Bolan et al. 2014 Kumpiene et al. 2008 Gong et al. 2018	Formation of pyromorphites
Organic materials	Biosolids, biochar, manure, compost	Laidlaw et al. 2017 Martin and Ruby 2004 Kumar et al. 2020 Liu et al. 2018 Yang et al. 2019 Bolan et al. 2014 Kumpiene et al. 2008 Gong et al. 2018	Sorption of lead on organic surfaces
Clay minerals	Zeolites, vermiculite	Kumar et al. 2020 Liu et al. 2018 Bolan et al. 2014 Li et al. 2017 Gong et al. 2018	Sorption of lead on clay mineral surfaces or formation into clay minerals
Metal oxides	Iron oxides and iron rich wastes, manganese oxides, aluminum oxides	Laidlaw et al. 2017 Martin and Ruby 2004 Kumar et al. 2020 Liu et al. 2018 Bolan et al. 2014 Kumpiene et al. 2008 Gong et al. 2018	Formation of lead-metal and sorption on to oxide surfaces
pH	Lime, fly ash, calcium hydroxide	Martin and Ruby 2004 Kumar et al. 2020 Liu et al. 2018 Bolan et al. 2014 Kumpiene et al. 2008 Gong et al. 2018	Formation of metal precipitates

Phytoextraction is using hyperaccumulator plants that absorb metals (e.g., more than 10,000 mg/kg) from soil followed by harvesting of the hyperaccumulator plants. Phytoremediation of cadmium, zinc, selenium, and arsenic from contamination soil has been reviewed (Chaney et al. 2014). Hyperaccumulator plants for lead do not exist. Application of chelating ethylenediaminetetraacetic acid solution to lead-contaminated soil planted with *Brassica juncea* (e.g., Indian mustard) was able to accumulate more than 1 percent of the lead in plant tissue (Blaylock et al. 1997). However, this practice contaminated groundwater (Nowack et al. 2006).

Remediation strategies vary depending on the form of arsenic in the environment. Often, the dominant form of arsenic contamination in aerobic soil is arsenate. The majority of in situ remediation methods are designed to adsorb or precipitate arsenate and reduce its bioavailability and mobility (Gong et al. 2018). In particular, iron oxide clay minerals strongly adsorb arsenate and reduce arsenate bioavailability (Violante et al. 2010). More recently, GSR soil amendments for remediation or arsenic-contaminated soils include biochar (Wang et al. 2021) and biochar modified with iron oxide (Yang et al. 2021). These treatments improve soil health while remediating arsenic.

Mitigating cadmium in the food supply is complicated by the properties of the soil the food is grown in, the type of amendments that may be applied to the crop, and the genetics of the crop. Cadmium can also be introduced to the food supply from utensils, plastics, and cookware that contain cadmium. When it comes to steps to reduce cadmium uptake in the field, better understanding of geogenic sources and specific plant uptake would help mitigate cadmium in food, as would minimizing the application of phosphate fertilizers and irrigation water that contains cadmium (Schaefer et al. 2020). Producers would benefit from research that provides evidence for management strategies tailored to specific soils and specific crops that prevents plant uptake of cadmium (Schaefer et al. 2020).

Microplastics

Microplastics (MPs) are defined as small plastic particles measuring less than 5 mm in size (Masura et al. 2015). MP pollution includes primary MPs (e.g., microfibers, textiles) and secondary MPs, which are defined as degradation products of larger plastic products (Petersen and Hubbart 2021). Approximately 90 percent of synthetic polymers produced are polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), or polyethylene terephthalate (PET) (Andrady and Neal 2009). MPs exist in a variety of physical forms that include fibers, foam, film, and particles (Rillig et al. 2019a). Found in diverse ecosystems worldwide, MPs have become a pervasive and global environmental issue (Bolan et al. 2020; Büks and Kaupenjohann 2020) and a major reason the planetary boundary for category of contaminants (i.e., novel entities) is being exceeded (Persson et al. 2022).

Sources

Microplastics reach soil through direct and indirect pathways, which vary based on location, land use, and management practices (Figure 6-5; Yadav et al. 2022). In agriculture, the primary sources are compost (Bläsing and Amelung 2018), biosolids (Bläsing and Amelung 2018; Crossman et al. 2020), irrigation with untreated wastewater (Bläsing and Amelung 2018; He et al. 2018), and polymer coatings of slow-release fertilizers (Lian et al. 2021). Worldwide, plastic mulch use in agricultural production is a growing source as well (He et al. 2018).

Once in soil, MPs tend to accumulate near the soil surface due to their low density and small particle size. MPs can also become incorporated into soil aggregates or immobilized on to soil particles as a function of the particular soil's texture, organic matter content, and moisture levels (Rillig and Lehmann 2020). MPs can be transported within and out of soil through processes such as surface runoff, erosion events, and leaching to groundwater and via biological activities such as earthworm burrowing and root growth.

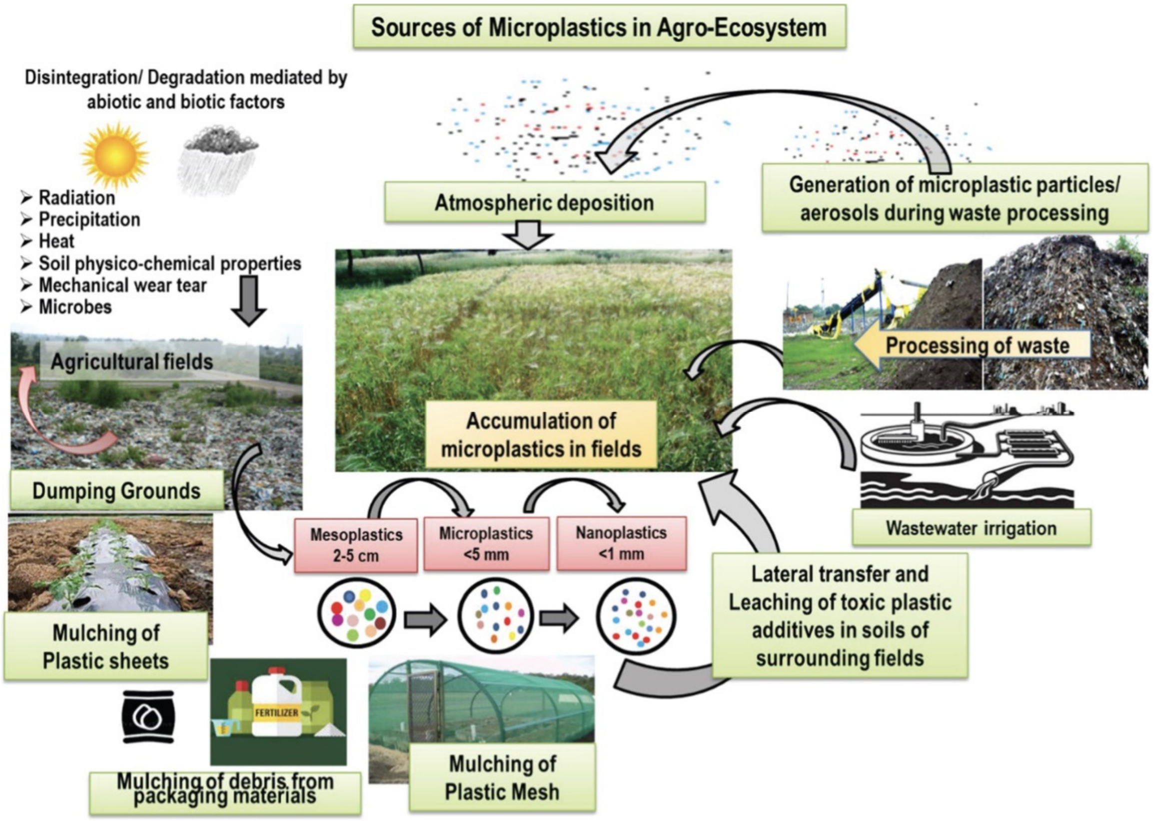

FIGURE 6-5 The source, movement, and fate of microplastics in the environment.
SOURCE: Used with permission of Springer Nature BV, from "Unravelling the Emerging Threats of Microplastics to Agroecosystems", Yadav et al., *Reviewers in Environmental Science and Biotechnology* 21 (3), 2018; permission conveyed through Copyright Clearance Center, Inc.

Fate and Transport

The persistence and degradation of plastics and MPs in soil environments have been reviewed by Krueger et al. (2015), Restrepo-Flórez et al. (2014), and Bläsing and Amelung (2018). Plastics, synthesized to be durable and withstand deterioration, accumulate in soil (Bläsing and Amelung 2018) despite being susceptible to degradation by abiotic and biotic processes (Figure 6-5). Degradation rates are dependent on the type of MPs, location in soil, management practices, climate, and other factors. Degradation pathways via ultraviolet (UV) radiation are known, particularly in aquatic ecosystems, but in soil only materials near the surface are susceptible and degradation rates are generally slow. Over time, UV exposure and weathering processes cause larger MPs to fragment into smaller particles, which then move through soil and become more susceptible to both uptake and degradation (Hooge et al. 2023).

With respect to biodegradation, a microbial process, most plastics degrade very slowly (if at all) in soil, with persistence estimated to range from several years to several thousand years (Chamas et al. 2020). The usually low surface-to-volume ratio of most forms of microplastics physically limits their bioavailability to microorganisms, who need to maintain close proximity to surfaces for reactions (Hooge et al. 2023). Field studies reviewed by Bläsing and Amelung (2018) indicate minimal soil degradation of MPs with far less than 1-percent loss by weight of

PE over 2.5 year (Albertsson 1980) and PP after 1 year (Arkatkar et al. 2009), and no detectable PVC degradation after 10–35 years in soil (Otake et al. 1995; Santana et al. 2012; Ali et al. 2014). Thus, although large and visible pieces of plastics may fragment over time, most data confirm that MPs are persistent in soil (Krueger et al. 2015; Bläsing and Amelung 2018). Unfortunately, rates of inputs of MPs greatly exceed their rates of removal in soil (Petersen and Hubbert 2021).

Impact on Soil Ecosystems

Physical–chemical MPs are redistributed throughout the soil by tillage, by physical mixing from wet-dry or freeze-thaw cycles, or by soil organisms (Hooge et al. 2023). MPs can affect soil structure and porosity, leading to changes in water infiltration, retention, and drainage (Figure 6-6; de Souza et al. 2019; Lehmann et al. 2019) and, in turn, influence nutrient availability, root growth, and plant productivity. Due to their larger size (around 2 mm), fiber, foam, and film MPs can potentially increase soil aeration and microporosity (Sun et al. 2022). MP microfibers can decrease the water stable macroaggregates via both physical effects and biological effects on soil biota that contribute to soil aggregation (Boots et al. 2019). MPs can also modify soil chemical properties by adsorbing and releasing contaminants, such as heavy metals and organic pollutants, thereby influencing their bioavailability and potential toxicity to soil organisms and plants (Sajjad et al. 2022).

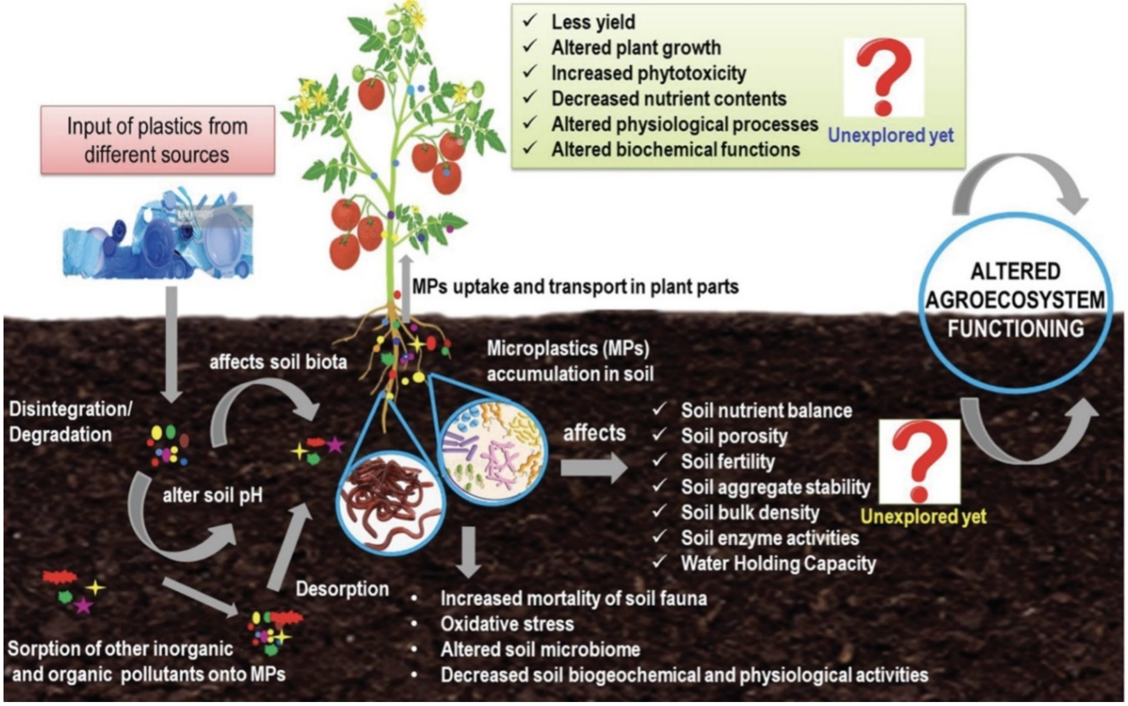

FIGURE 6-6 A schematic diagram of microplastic interaction with plant-soil systems.
SOURCE: Used with permission of Springer Nature BV, from "Unravelling the Emerging Threats of Microplastics to Agroecosystems", Yadav et al., *Reviewers in Environmental Science and Biotechnology* 21 (3), 2018; permission conveyed through Copyright Clearance Center, Inc.

Impacts on soil communities MPs have been documented to change the diversity, abundance, and functions of soil microbial communities (Rillig et al. 2021b); the extent of impact is often proportional to concentration (Sun et al. 2022). Overall effects on soil biota can be negative, positive, or neutral and occur via both direct (e.g., absorption of MP nanoparticles) and indirect (e.g., altering soil structure) pathways. Though not well understood, the impacts are many (Rillig et al. 2021b), such as shifting the composition of microbial communities and altering microbial processes, including carbon storage, organic matter decomposition, and greenhouse gas emissions (Rillig et al. 2021a,b). MPs are made up primarily of recalcitrant carbon and can slow down overall organic matter decomposition rates (Rillig et al. 2021a). MP fibers in soil resulted in an increase in CO_2 fluxes and a decrease in nitrous oxide emissions, especially after urea fertilizer application, which is attributed to increased soil aggregation and air permeability (Rillig et al. 2021a).

The plastisphere—defined as the soil surfaces influenced by plastic—has a different microbial community than bulk soil. For example, more pathogens and antibiotic resistance genes are present as compared to bulk soil (Zhu et al. 2022; Rillig et al. 2024). Furthermore, plastics have been found to change soil bacteria community structure and interfere with microbial lipid metabolisms and the biosynthesis of secondary metabolites (Wu et al. 2022). MPs can detrimentally affect the growth, reproduction, lifespan, and overall survival of soil fauna through various mechanisms, including ingestion, bioaccumulation, oxidative stress, reproductive and neurotoxic effects, metabolic disruptions, and gut microbiota imbalances (Wang et al. 2022). Some soil fauna play a role in the formation and degradation of MPs, modify their movement in soil, and can potentially transfer accumulated MPs up the food chain. (Helmberger et al. 2020; Wang et al. 2022).

The indirect effects of MPs on plant growth include alteration of soil structure, bulk density, and water-holding capacity, which in turn influences plant development (Helmberger et al. 2020). These effects are varied and can be both positive and negative, heavily dependent on the characteristics of the MPs (like their chemical additives) and the specific types of soil and plants in the environment (Rillig et al. 2021b). MPs can impair plant seed germination, reduce root elongation, and negatively affect plant biomass and reproductive capacity (Boots et al. 2019; de Souza et al. 2019). MPs may also interfere with plant nutrient uptake and induce oxidative stress, leading to physiological disorders and decreased overall plant performance (Rillig et al. 2019b). These impacts could have a cascading effect on other biophysical processes in the soil and may pose a threat to soil biodiversity and ecosystem functioning (Boots et al. 2019).

Human Exposure Pathways

MPs in soils can pose potential risks to human health through several exposure pathways such as direct soil ingestion, particularly by children during outdoor activities as well as inhalation of MP particles suspended in the air due to wind erosion or dust generation from contaminated soils. Consumption of contaminated foods is also possible; most research to date has focused on MPs in food that is not directly related to soil, such as seafood, fish, salt, honey, and water (Karbalaei et al. 2018). One study that investigated the quantity of MPs in fruits and vegetables found that MPs <10 micron ranged by 52,050 to 233,000 particles/g, and that apples were the most contaminated samples (Conti et al. 2020). These estimated daily intakes are smaller than the estimated daily intakes from plastic bottled mineral water (Zuccarello et al.

2019), therefore the committee concluded that consumption from soil-related agricultural produce may be less of a concern.

Impacts on Human Health

The human health effects of MPs can be categorized into chemical, physical, and biological effects, as illustrated in Figure 6-7. Chemical effects refer to the impact of additives and dyes that may be toxic, teratogenic, or carcinogenic. For example, phthalates are commonly used as plasticizers to provide flexibility to plastics. Because they are additives, they are not chemically bound (covalently bonded) and are more likely to be released and transferred to the environment (Blackburn and Green 2022). Similarly, polybrominated diphenyl ethers are used as flame retardants in many commercial products and, because they are not chemically bound, can leach during production and recycling, bioaccumulate, and cause endocrine disruption and impaired neurological development in animal models. Secondary toxins include persistent organic pollutants that can lead to immunotoxicity and secondary toxicity through interaction with other chemical pollutants. For example, plastic mulching sheets used in agriculture can both absorb pesticides and increase risks for human exposure (Huang et al. 2020, Wang et al. 2020).

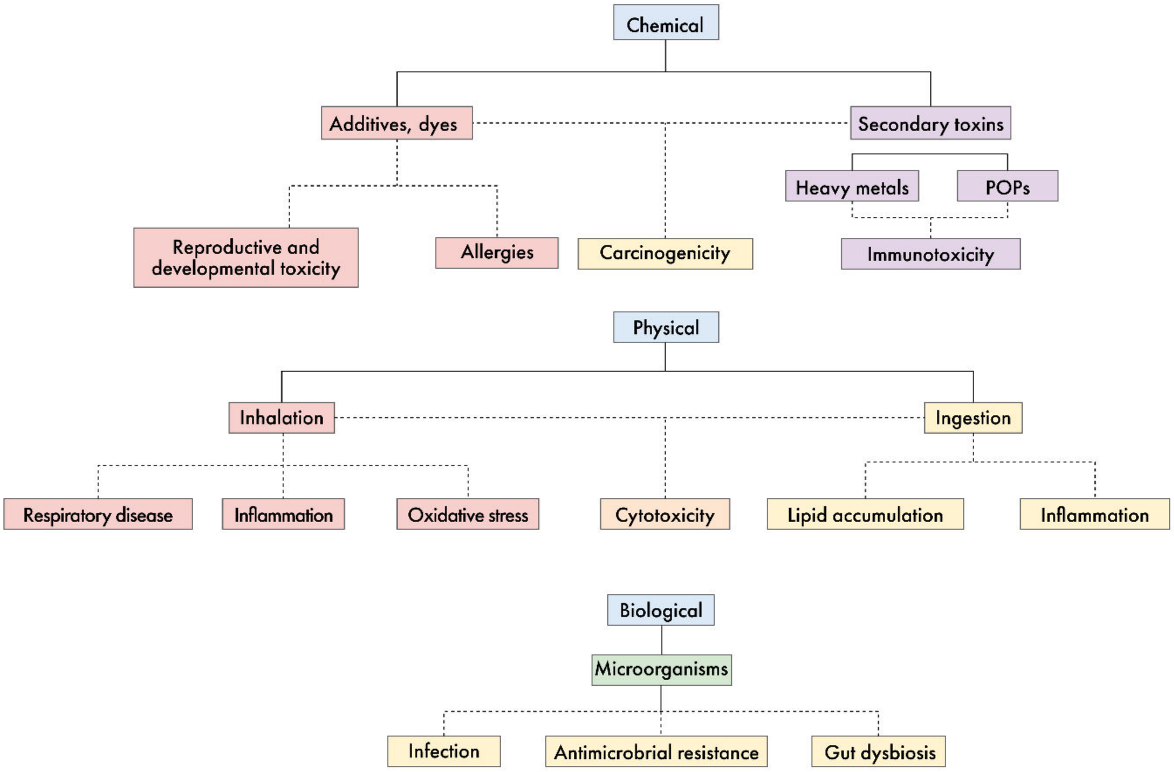

FIGURE 6-7 A flow diagram illustrating the potential human health effects of microplastics.
NOTE: The dotted lines represent current speculative research.
SOURCE: Used with permission of Springer Nature BV, from "The Potential Effects of Microplastics on Human Health: What is Known and What is Unknown", Blackburn and Green, *Ambio: A Journal of the Human Environment* 51 (3), 2022; permission conveyed through Copyright Clearance Center, Inc.

Physical effects include inhalation and ingestion of MPs and subsequent immunotoxicity. Small MPs are common in the atmosphere and can be readily inhaled; however, the health effects remain poorly understood. Eyles et al. (2001) found that, once inhaled or ingested, MPs could also translocate to other tissues; fluorescent polystyrene microspheres delivered intranasally to mice were found in the spleen 10 days later. MPs have also been shown to impair gastrointestinal function and alteration of hepatic lipid metabolism in animal models, (Y. Jin et al. 2019; L. Lu et al. 2019); this may also be the case for humans.

Finally, there are biological effects that primarily refer to the impact on the microbiome. Evidence thus far, mostly stemming from animal models, has shown that nano and microplastics alter microbial community structures in the gut (both alpha and beta diversity), which may in turn underlie immune impairment, as previously reviewed (Fackelmann and Sommer 2019; L. Lu et al. 2019; Santos et al. 2022).

As an additional burden, microplastics from soil may carry pathogens and other pollutants that pose a threat to human health potentially through alterations in gut microbial communities (Fackelmann and Sommer 2019). A mice study found that when co-ingested with polyethylene particles, the bioavailability of arsenate increased, and this seemed to be mediated by the metabolite output of the gut microbiota (Chen et al. 2023). Also, impacts of MPs on soil communities may translate into effects on the food system and have negative consequences for human health (Daghighi et al. 2023).

Few studies have comprehensively assessed the impact of microplastics on health concurrently with their presence in the environment. A recent study compared the soil, air, nasal, and gastrointestinal microbiomes of two populations, one with high exposure to microplastic pollution and the other with low exposure. They found overlap in the microplastic species found in gut microbiome samples and soil samples in the high exposure area, along with inverse correlations between microplastic exposure and the abundance of taxonomic groups that may be beneficial for human health (Zhang et al. 2022).

Mitigation and Remediation

The reduction of plastic use in agriculture is an essential step toward more sustainable and environmentally friendly farm management. To address these issues, the “3 R” waste hierarchy concept of reducing, reusing, and recycling plastics, before considering disposal, is crucial (Hofmann et al. 2023). Similarly, the United Nations’ Food and Agriculture Organization (FAO) has promoted the 6R model (Refuse, Redesign, Reduce, Reuse, Recycle, and Recover) for reduction of use of plastics in agriculture (FAO 2021). Both approaches advocate for plastic applications that have circular end-of-life treatment options and stress the importance of innovative material design to ensure plastics can be completely collected, recycled, and reused. Use of non-biodegradable polymer-coated fertilizers and mulching films, in particular, should be minimized and, if used, be collected after use. Additionally, in situations where plastics cannot be collected after use, or where recovered plastic is too degraded or soiled to be reused or recycled, polymers that are more biodegradable or less toxic should replace conventional persistent polymers (Galati and Scalenghe 2021; Hofmann et al. 2023).

Biodegradable polymers offer potential solutions for reducing environmental impacts of plastics for short term uses (e.g., cutlery). Biodegradable plastics can break down through composting or exposure to UV radiation. However, uncertainties concerning biodegradable polymers involve their complex waste management, including requirement for specific collection and composting facilities, and the low volumes produced that may not justify the waste management efforts (Prata et al. 2019). Additionally, some degradable plastics produce non-degradable by products (Prata et al. 2019).

The possibility of significant and consistent biodegradation of conventional plastics in the environment remains uncertain (Krueger et al. 2015). Some strains of bacteria and fungi have been demonstrated in the laboratory to be capable of degrading many polymers via enzymatic hydrolysis or oxidation (Sivan 2011; Krueger et al. 2015). Some conventional plastics can biodegrade under lab conditions when exposed to specific plastic-degrading organisms, such as *Zalerion maritimum* (Paço et al. 2017); how successful these organisms would be in soil is not known.

PFAS

Per- and poly-fluoroalkyl substances are a large group of synthetic, organofluorine chemicals that are of increasing concern as environmental contaminants. Their characteristic carbon–fluorine bond is one of the strongest single bonds in chemistry, so PFAS molecules are extremely hard to break down. Thus, they are highly persistent in the environment and are often referred to as “forever chemicals.” There are thousands of PFAS compounds[2] of concern with respect to the health of people and the environment.

PFAS give desirable properties to industrial and consumer products because they resist water, oil, and heat. They are used to make waterproof and stain-resistant garments, nonstick pans, and oil-resistant containers. Teflon is a well-known example. They are also used to make firefighting foams, fabrics that resist fire and stains, and a great many other products and industrial processes.

The different PFAS species vary in their length of the carbon chain, their branching structure, the number of fluorine molecules and their positions, attached functional groups, and so on (Buck et al. 2011). The large and diverse PFAS family of molecules can be divided into the polymer and non-polymer classes, with the latter most commonly found in biological and environmental samples. This non-polymer class includes per- and polyfluoroalkyl substances; the carbon chains of the perfluoroalkyl substances are fully fluorinated, while the carbon chains of the polyfluoroalkyl substances are not fully saturated with fluorine atoms. The perfluoroalkyl acids (PFAAs) are one major group of the perfluorinated subclass of the non-polymer class of PFAS. Because of their saturation, they are the most stable and thus most persistent in the environment. Their non-saturated precursors can be transformed into PFAAs through biological or chemical cleavage of their non-fluorinated moieties.

Sources

PFAS molecules are created through industrial processes. They have been manufactured since the 1940s and widely used since the 1950s. They are spread from both point sources (where they are made or used) and diffuse sources (such as water, soil, and air). Point sources include industrial sites where PFAS is made and used, such as fluorochemical production plants (Gebbink and van Leeuwen 2020).

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[2] U.S. Environmental Protection Agency. “PFAS Structure Dashboard.” EPA. Accessed April 27, 2024. https://comptox.epa.gov/dashboard/chemical-lists/PFASSTRUCT and “PFAS Developmental Dashboard.” EPA. Accessed April 27, 2024.https://comptox.epa.gov/dashboard/chemical-lists/PFASDEV1.

Several studies have found soil to be a major environmental reservoir of PFAS (Strynar et al. 2012; Brusseau et al. 2020). Soils can receive PFAS from applied biosolids, contaminated irrigation water (Pepper et al. 2021), aqueous film-forming foam used extensively at military bases and airports (Yan et al. 2024), and rainfall (Pfotenhauer et al. 2022). PFAS in biosolids can come from many sources, including landfill leachate. Landfill leachate is a rich source of PFAS because of the discarded domestic products (e.g., cookware, clothing, carpets, and furniture) and industrial products deposited in these sites (Lang et al. 2017; Capozzi et al. 2023). Landfill leachate is typically treated at the municipal wastewater treatment plants where other wastes, including excreta and industrial wastes, are processed (Masoner et al. 2020; Helmer et al. 2022).

Because the biological and other treatment processes implemented through conventional wastewater treatment do not destroy PFAS, biosolids (the stabilized solids that result from municipal wastewater treatment, also known as sewer sludge) may be contaminated. Longer-chain PFAS molecules (e.g., those with an 8-carbon backbone or C8) are typically enriched in biosolids relative to liquid effluent (Helmer et al. 2022).

Fate and Transport

PFAS are highly mobile in the environment (Brunn et al. 2023). As noted above, their forms can change in the environment as non-fluorinated moieties are cleaved, yielding stable (saturated) PFAAs (Evich et al. 2022). Greater amounts of some PFAS molecules are thus found in the effluent from wastewater treatment plants than in the influent (Coggan et al. 2019; Thompson et al. 2023). Short-chain PFAS are more mobile in soils than longer-chain forms (Brusseau et al. 2020). General pathways are indicated in Figure 6-8.

Biosolids have long been used as a soil amendment, adding carbon and nutrients to agricultural and other lands (Lu et al. 2012). While it is desirable to regard organic wastes as resources, concern is rising about PFAS contamination of biosolids leading to contamination of farmland (Lowman et al. 2013; Mason-Renton and Luginaah 2018). Plants can take up PFAS, with short-chain forms showing greater mobility in plant tissues than longer-chain forms (Costello and Lee 2020). Maine recently banned the land application of biosolids after some farms were found to have high levels of contamination (Perkins 2022).

Impact on Soil Ecosystems

Studies of the effects of PFAS on soil microbiomes have shown that PFAS changes community composition and metabolite production (Xu et al. 2022; Senevirathna et al. 2022; Wu et al. 2023). Several studies have reported that PFAS reduce microbial abundance, including in laboratory experiments (Xu et al. 2022) and field studies comparing contaminated and noncontaminated sites (Senevirathna et al. 2022). Xu et al. (2022) found that soil treated with the PFAS compounds perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) had bacterial reduced gene abundance as compared to the control treatment and that PFAS exposure altered soil microbial composition. The researchers speculated that the increase in Proteobacteria was due to Proteobacteria's greater tolerance for PFAS (Xu et al. 2022). Increases in Proteobacteria have also been observed in other studies (Wu et al. 2023). Modeling also predicted that exposure to PFAS inhibited numerous microbial metabolism processes in soil. Wu et al. (2023) found that soil microorganisms downstream of a Teflon production plant had reduced lipid biosynthesis and possibly decreased metabolic activity.

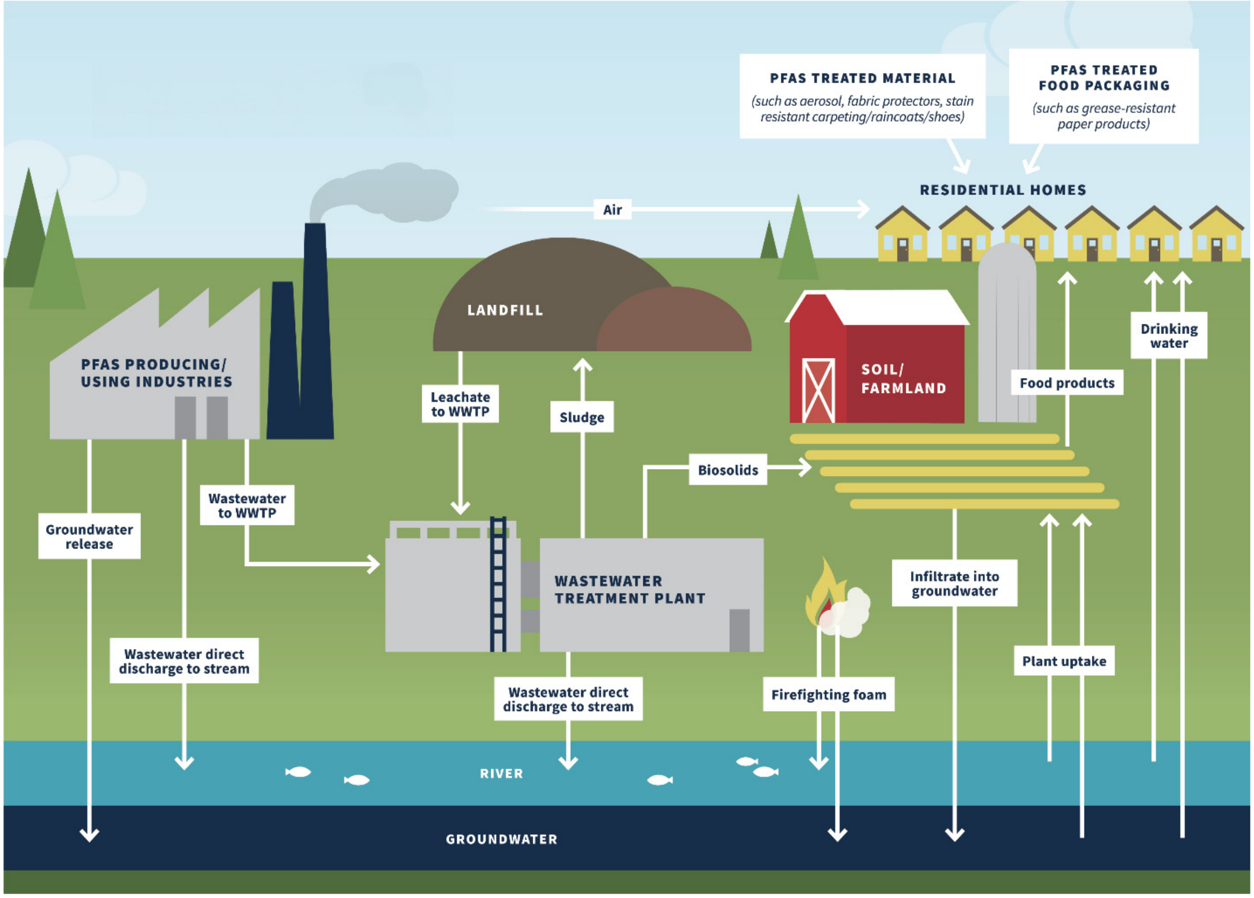

FIGURE 6-8 A diagram illustrating the sources of PFAS and pathways for their release into the water cycle and the environment.
SOURCE: Diagram courtesy of Michigan Department of Environment, Great Lakes, and Energy.

Findings with regard to effects of PFAS on soil pH and microbial diversity have varied across studies. Xu et al. (2022) did not find a change in soil pH between soil treated with PFOA and PFOS and a control sample. while Xu et al. (2023) found a significant increase in soil pH in another laboratory experiment. The latter results were likely because PFAS increased litter decomposition rather than PFAS having a direct effect on soil pH. The latter researchers also found that soil aggregate stability was not affected by PFAS but water-stable aggregates decreased.

The direction of change in microbial diversity and richness of soil microorganisms exposed to PFAS is unclear, possibly due to differences in PFAS concentration and species across studies. Xu et al. (2022) found that microbial diversity and richness of soil microorganisms increased in the treatment cases as opposed to the control in a laboratory study, whereas Senevirathna et al. (2022) observed a decline in soil bacterial community population and diversity in soils collected from contaminated sites versus uncontaminated environmental samples. PFOS (a C8 molecule) had a greater effect than PFOA (a molecule with a 7-carbon backbone), suggesting the type of PFAS may influence impacts on soil microbial communities. Cai et al. (2019) also found that the type of PFAS influenced in its effect on microbial diversity and richness, with longer chains having greater toxicity than shorter chains.

Additionally, PFAS may negatively affect plant growth. Xu et al. (2022) found that PFOA and PFOS inhibited the abundance of *Azospirillum*, a plant-growth promoting rhizobacteria. PFOS also enriched *Hydrogenophaga*, which are resistant to organic pollutants, while *Methyloversatilis* was more abundant under PFOA exposure. The abundance of *Methyloversatilis* suggests that it may be able to degrade PFOA. Wu et al. (2023) also determined that PFAS contamination affected the fungal community in soils. The authors noted that mycotoxin concentrations were higher downstream of the Teflon plant.

Human Exposure Pathways

People are exposed to PFAS through many pathways, including via occupational exposures, consumer and household products, environmental contamination, and ingestion. Occupational exposures are myriad and may include occur where PFAS-containing products are manufactured, in the construction industry, among food workers that handle PFAS-containing food packaging, and among firefighters. PFAS are used in thousands of consumer products ranging from personal care products like sunscreen, makeup, and dental floss to textiles, artificial turf, and paint. A recent review found that exposure from contaminated household dust could account for up to 25 percent of blood concentrations but that there were many methodologic flaws in the existing studies and that more research on household exposure pathways is needed (DeLuca et al. 2022).

Environmental contamination of soils and groundwater is also thought to be an important source of PFAS exposure. Most research in nonoccupational settings has focused on ingestion of PFAS, which can occur through drinking contaminated water or eating contaminated seafood, vegetables, game, or dairy products (Domingo and Nadal 2017; Death et al. 2021). In April 2024, EPA established a regulation for maximum contaminant levels for six PFAS compounds for public water systems in the United States (EPA 2024a). It estimated that 6–10 percent of the country's 66,000 public drinking water systems would have to take action to reduce PFAS to meet these levels (EPA 2024b). PFAS may also be ingested through food contaminated by PFAS-containing materials including food packaging, microwave popcorn bags, and cookware. PFAS can be transferred intergenerationally through the mother's body to a developing fetus and through breastfeeding (Manzano-Salgado et al. 2015; Gao et al. 2019; Zheng et al. 2021). Exposure pathways may also include inhalation of aerosolized or volatile PFAS, which have been detected indoors and near factory emissions. The impact of inhaled and transdermal exposures, for example through bathing in contaminated water, have been less well studied (Sunderland et al. 2019).

Impacts on Human Health

PFAS are known to affect human health in multiple ways (Sunderland et al. 2019; Brase et al. 2021; Chambers et al. 2021). A recent review by the National Academies summarized the health effects of PFAS and found that cancers, endocrine effects, dysregulation of immune function, and impacts on fertility were the health effects most frequently mentioned by speakers at that committee's information-gathering meetings (NASEM 2022a). After a systematic synthesis of the evidence, that report concluded that there was sufficient evidence to support an association with decreased antibody response (in adults and children), dyslipidemia (in adults and children), decreased infant and fetal growth, and increased risk of kidney cancer (in adults).

The report also found suggestive evidence for the following diseases and health outcomes: increased risk of breast cancer (in adults), liver enzyme alterations (in adults and children), increased risk of pregnancy-induced hypertension (gestational hypertension and pre-eclampsia), increased risk of testicular cancer (in adults), increased risk of thyroid disease and dysfunction (in adults), and increased risk of ulcerative colitis (in adults).

Mitigation and Remediation

As PFAS have been found in drinking water, foods and food packaging, and the bodies of people and animals around the world, awareness and concern become increasingly palpable. This increased awareness has led to pressure for companies to stop making these compounds. After half a century of production, companies are beginning to phase out production of certain PFAS compounds. 3M began phasing out production of PFOS in 2000 (EPA 2000) and recently paid $10.3 billion to settle a multidistrict lawsuit (Kluger 2023). The company stated in 2022 that it would work to cease manufacturing PFAS by the end of 2025 (3M 2022). Reduced production has led to some decrease in the human body burden in the United States and Australian populations (Gomis et al. 2017). Although some PFAS forms are being phased out, there is evidence that companies are making replacement compounds with likely hazardous properties (Brase et al. 2021).

EPA recently published a roadmap related to PFAS contamination (EPA n.d.). As part of the roadmap, EPA is conducting a risk assessment for two specific PFAS compounds, PFOA and PFOS, in biosolids. The risk assessment is scheduled to be completed by December 2024.[3] Given the large number of PFAS molecules, their persistence and potential to accumulate in the environment, their individual and collective hazards, and the difficulties of regulating them individually, some authors argue that they should be regulated as a class (e.g., Kwiatkowski et al. 2020). Others suggest that, because of the differences in toxicity among PFAS species, each PFAS subgroup and compounds within should be evaluated (Singh and Papanastasiou 2021). Cousins et al. (2020) argued that a rational approach to phasing out PFAS production would eliminate most applications but would recognize certain “essential uses.” Eliminating most uses but allowing exceptions for the most essential, such as certain medical applications, would likely be the most feasible approach.

Because of the extreme strength of the carbon–fluorine bonds that are the defining feature of PFAS, it is notably difficult to fully mineralize PFAS (that is, to break PFAS down to their elemental components rather than to smaller species of PFAS) (Shahsavari et al. 2021). Sorption of PFAS can block the movement of contaminants such as PFAS in the ecosystem. Porous, high-carbon materials such as activated carbon and biochar can be used to remove PFAS from drinking water (Box 6-1; Xiao et al. 2017). Granulated activated carbon is the most widely used sorbent for purification of air and water. Fecal biochar (e.g., made from biosolids) has been shown to be an effective sorbent for PFAS (Krahn et al. 2023).

That said, it is possible to degrade PFAS in soil and in amendments that might reach soil. A few alternatives are emerging, each with potential to address the issue in certain niches. Mechanochemical treatment by ball milling can be used to eliminate PFAS (Turner et al. 2021); this might be useful for extremely contaminated soils, though the committee finds it is difficult to

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[3] U.S. Environmental Protection Agency. "Risk Assessment for Pollutants in Biosolids." EPA. Accessed April 27, 2024. https://www.epa.gov/biosolids/risk-assessment-pollutants-biosolids#pfas.

BOX 6-1
Biochar as Decontamination Possibility

Some of the environmental concerns about the land application of biosolids can be addressed by converting the material into biochar (Krounbi et al. 2019). The pyrolysis of biosolids can strongly reduce the presence of organic contaminants such as PFAS, hormones, and pharmaceuticals, which are destroyed at the high temperatures that are used to produce biochar (Hoffman et al. 2016; Kundu et al. 2021; Mercl et al. 2021). In addition, biochar can bind and immobilize contaminants such as heavy metals (Park et al. 2011) and PFAS, preventing their movement through soil (Krahn et al. 2023). Biochar produced from biosolids is particularly good at binding PFAS (Krahn et al. 2023).

envisage this being conducted at large scale in an economically viable way. Although bioremediation is challenging and generally not considered as a practical approach to PFAS remediation, there is hope that microbes can contribute to breaking down PFAS (LaFond et al. 2023). Another new biological approach involves use of enzyme-catalyzed oxidative humification reactions carried out by fungal extracellular enzymes (e.g., peroxidases and laccases). These processes can potentially lead to break down of certain PFAS molecules (Grgas et al. 2023; Kumar et al. 2023). Thermochemical transformation is an approach that has shown promise under certain conditions (Weber et al. 2023). Incineration can destroy PFAS but can lead to the emission of fluorinated byproducts (Stoiber et al. 2020).

There is evidence that pyrolysis at high temperatures (over 600°C) can be effective for removing PFAS from biosolids. Thoma et al. (2022) showed that 21 PFAS compounds detected in biosolid samples (ranging from 2 ug/kg–85 ug/kg) were undetectable in the biochar resulting from pyrolysis at 650°C. Kundu et al. (2021) demonstrated greater than 90-percent removal of PFOA and PFOS from sewage sludge after pyrolysis at temperatures between 500 and 600°C. McNamara et al. (2023b) showed more than 99-percent removal of target PFAS and PFAS precursors at pyrolysis temperatures up to 800°C. However, PFAS may be present in byproducts of pyrolysis (McNamara et al. 2023a,b). Further research and development is needed to assess the potential of pyrolysis as a general solution to the problem of PFAS in biosolids (Wallace et al. 2023). Other high-temperature treatments, plasma, and combustion under specific conditions, can also be effective at breaking down PFAS (Singh et al. 2021; McNamara et al. 2023a,b; Weber et al. 2023). High energy electron beam technology is also being tested to break down PFAS in soils and groundwater (Lassalle et al. 2021).

Integrated strategies for dealing with sources and flows of contamination are needed. These are likely to bring together elements of the strategies mentioned above, as well as selective mobilization of PFAS (Bolan et al. 2021). Figure 6-9 presents an overview of elements of remediation strategies that can be integrated.

CONCLUSIONS

The properties of soil facilitate the capture and remediation of many contaminants. In some cases, the soil microbiome can mitigate the risk contaminants pose, such as through the attenuation of heavy metals via sequestration, ion efflux, and extracellular chelation (Hou et al. 2020). In other cases, the physical and chemical properties of soil can trap contaminants, making them unavailable to volatilize, leach into water, or be taken up by a plant. As alluded to in Chapter 3, the degradation of contaminants is one of many soil-derived nature's contributions to people.

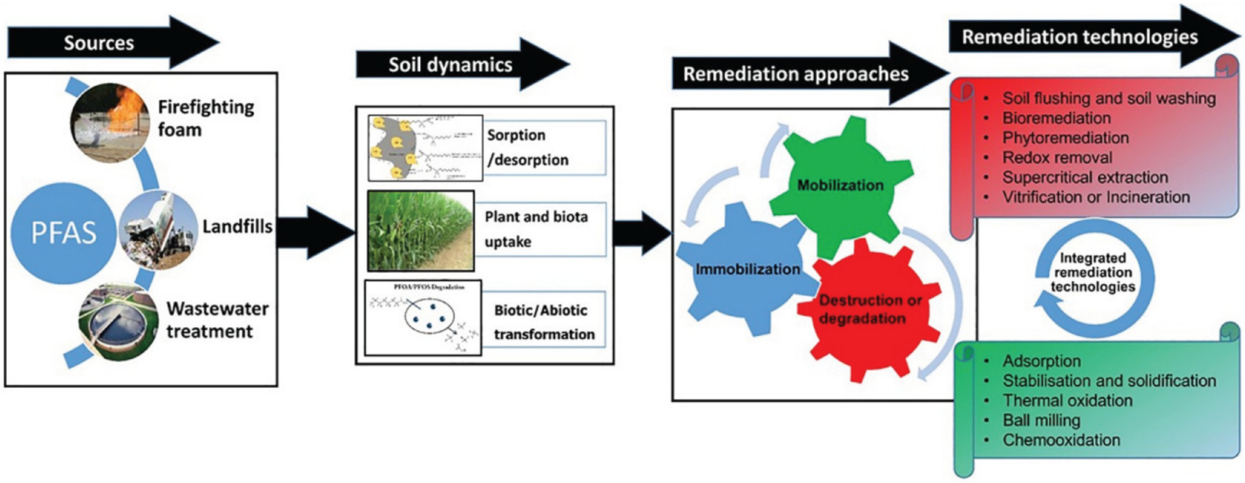

FIGURE 6-9 Elements of a remediation strategy for PFAS.
SOURCE: Reprinted from *Journal of Hazardous Materials*, 401, Bolan et al., "Remediation of Poly- and Perfluoroalkyl Substances (PFAS) Contaminated Soils–To Mobilize or to Immobilize or to Degrade?" 123892, 2021, with permission from Elsevier.

Soil health is key to this contribution. As reviewed in the case studies, soil organic amendments can increase the absorption of metals and organic chemical contaminants. Changes to pH can reduce the bioavailability of some contaminants. Conversely, contamination can overwhelm the capacity of soil to mitigate risk. High levels of lead and cadmium in soils reduce microbial activity and plant biomass. Microplastics can change soil structure and thereby affect water-holding capacity. The enrichment of pathogens and antibiotic resistance genes in soil microbial communities influenced by microplastics may have implications for human health, but this possibility has not yet been explored.

It is important to note that the contaminants in the case studies presented above were discussed in isolation from one another. Each contaminant class is diverse with heterogeneous impacts based on the nature and quantity of the material and the characteristics of the soil in question. The reality of soil contamination is even more complex because of the potential for co-contamination with multiple compounds. It is likely that the examples of contaminants provided here, along with contaminants found in agricultural inputs such as manure and synthetic fertilizers and pesticides, interact with one another in ways that compound the adverse effects on soil health.

Furthermore, these interacting contaminants are affected by global change factors, such as water stress and high temperatures (Rillig et al. 2019c). There is little available evidence about the effects of many combinations of soil contaminants, in part because it is prohibitively difficult to systematically test the combinatorial effects of large numbers of anything, including contaminants and stressors affecting soils. Given the practical impossibility of testing large numbers of specific combinations, Yang et al. (2022) tested a range of numbers of soil stressors under experimental reactor conditions, drawing at random from a roster of stressors that included various soil contaminants. They found that the positive ecosystem functions of soil microbial diversity were systematically compromised by the action of multiple environmental stressors, including heavy metals, pesticides, plastic film residues, and surfactants as well as nitrogen deposition, heat, drought, salinity, and compaction.

Soil plays a vital role in the cycling of nutrients, where products that are waste to humans, such as manure and biosolids, can be used as sources of energy and nutrients for soil biota and plants. However, soil can no longer be a receptacle for the untreated waste products of agricultural and industrial processes. To incorporate considerations about soil health into decisions about material processing and disposal, the committee suggests that action be taken in the following areas.

Source Identification and Targeted Surveillance

Soil contaminants have not been strategically mapped in the United States. As part of its North American Soil Geochemical Landscapes Project, the U.S. Geological Survey (USGS) mapped the spatial distribution of lead, arsenic, and cadmium (among other chemical elements) in the conterminous United States (Smith et al. 2014), but this low-density effort (one sample site per 1,600 km^2) did not target agricultural lands. USGS has also recently conducted a survey of PFAS in the United States, but collection was from tap water and soils were not included in the survey (Smalling et al. 2023). To the committee's knowledge, no comprehensive sampling effort of microplastics in U.S. soils has taken place.

Thus, there is a lack of comprehensive knowledge regarding the geographic distribution of these contaminants in U.S. soils and the specifics of their co-occurrence in mixed forms. This gap in understanding underscores the need for more detailed research and mapping of soil contaminants to better address soil and environmental health challenges.

> **Recommendation 6-1: Federal agencies should work collaboratively to support surveys of soil chemical contaminants informed by systematic risk assessments to identify where contaminant levels in soil may be particularly high (e.g., locations around, downwind, or downstream of PFAS point sources). These surveys can be used to build contaminant maps (e.g., of lead, arsenic, persistent organic pollutants) that can be viewed individually or overlaid to assess the status of contamination, identify locations of concern, and, over time, evaluate the effectiveness of interventions.**

Exposure Science

The effects of heavy metals on the health of soil organisms, plants, and humans have been studied for decades. Research on the same effects of novel entities such as PFAS and microplastics is just ramping up. There is still a great deal to learn about the effects of new and old chemical contaminants on soil organisms, plants, and humans, including thresholds of exposure and compounding effects of more than one contaminant. The degree to which exposure routes from soil (e.g., through inhalation, dermal contact, or direct or food consumption) affect bioavailability and how they compare to exposure routes from other sources (e.g., water or personal care products) are also unknown.

> **Recommendation 6-2: Federal agencies should support interdisciplinary research to reduce gaps in knowledge about exposure pathways from soil and the compounding health effects on soil biota, plants, and people from exposure to multiple chemical contaminants.**

Mitigation

The emergence of PFAS and microplastics as contaminants of concern this century and their interplay with contaminants from the last century that have yet to be addressed indicate that contaminant issues will continue to mount unless explicitly curtailed. A recent report by the National Academies on the U.S. role in ocean plastic waste recommended that "the United States should substantially reduce solid waste generation (absolute and per person) to reduce plastic waste in the environment and the environmental, economic, aesthetic, and health costs of managing waste and litter" (NASEM 2022b, 6). The committee of this report on soil health and human health wholeheartedly endorses this recommendation for reduced plastic use; this includes in agricultural production systems, as has been called for by the FAO. Use of plastic in agriculture needs to be substantially reduced by finding alternatives as well as reusing it when possible, removing it after use if persistent, stopping use of forms with toxic byproducts, and developing biodegradable plastics.

Reducing the production and use of other contaminants, such as PFAS, for all but the most essential applications, is also in order. The committee recognizes that soil is not the only exposure pathway for these contaminants to humans, but the extent to which production of these products is reduced mitigates all exposure pathways to humans and decreases their potential to enter soil.

> **Recommendation 6-3: The United States should mitigate the entry of plastic and PFAS contaminants into soil by reducing their overall production and use.**

Biosolids can be an important source of organic matter to agricultural land and a means of recycling rather than disposing of waste. However, they can also be a route of soil contamination because water treatment processes leave heavy metals, PFAS, microplastics, and other contaminants in biosolids. The entry of contaminants into soil could also be mitigated by improvements to the processing of landfill leachate and the treatment of wastewater. Landfill leachate contains PFAS, microplastics, and many other contaminants from discarded materials, which includes municipal biosolids. Wastewater treatment plants vary in their ability to remove these contaminants during treatment. Processing landfill leachate before it enters wastewater treatment plants would be a first line of contaminant reduction.

Some PFAS precursors may be broken down in the wastewater treatment process, but the strength of the carbon–fluorine bond often means that treated water has more, shorter-chain PFAS molecules than the influent. Technology to remove PFAS during treatment needs to be advanced. Limited research has reported pyrolysis of biosolids reduces PFAS content and possibly bioavailability. The U.S. Department of Agriculture–Natural Resources Conservation Services' recent soil carbon amendment standard (code 336) does not support application of non-gasified or non-pyrolyzed biosolids, while the standard does allow land application of biosolids biochar. Research is needed to provide information on manufacture of biochar from biosolids and the ability of pyrolysis to reduce the content and bioavailability of PFAS.

The technology exists to effectively remove microplastics from wastewater. Unfortunately, most of the plastic ends up in the biosolids (Carr et al. 2016). Pyrolysis of biosolids can result in the elimination of plastics as well as PFAS and other organic pollutants because of the high temperature attained in the process. Converting biosolids into biochar would be a means of continuing to use waste as a soil amendment while mitigating the contamination of the soil with more plastic. Biochar can also immobilize other contaminants, including PFAS and heavy metals. The carbon in biochar is stable over long periods of time, so it also has the benefit of sequestering carbon.

Recommendation 6-4: EPA should continue pursuing research and technology to remove PFAS from wastewater and biosolids.

Recommendation 6-5: EPA should pursue research to establish a threshold for plastics in land-applied soil amendments. Revisiting heavy metal thresholds would also be in order.

Remediation

Soils, especially those rich in organic matter and with healthy microbial communities, have the capacity to absorb and eliminate (e.g., through bioremediation) some, but not all, contaminants. Enhancing soil's ability to remediate contaminants is crucial for protecting human health. Using soil organic amendments to increase organic matter as well as recycle waste can move agricultural production to a more circular approach to nutrient management. Wastes that can serve as sources of soil organic matter include food waste, agroindustrial byproducts, and human and animal excreta. The use of source-separating, container-based sanitation can enable the recycling of carbon and nutrients in excreta without the contamination risks that arise in conventional wastewater handling.

Organic amendments can be designed to be more targeted. Modified biochars with functionalized surface chemistry ("designer biochars") can reduce contaminant bioavailability. For example, including iron in biochar production can enable greater binding of heavy metals for soil remediation while improving water holding and nutrient cycling. Research is needed to identify or produce functionalized designed biochars for soil remediation.

Recommendation 6-6: Public sector investment should be made to develop affordable technologies for converting biosolids into biochar that can be applied to agricultural land and/or used for wastewater treatment.

Recommendation 6-7: Producers and other land managers should adopt practices that increase the organic matter content, biodiversity, and other health parameters of their soils.

Recommendation 6-8: Public and private entities should invest in Green and Sustainable Remediation techniques, including the application of designer biochars and biosolids biochar, to manage soil contamination effectively.

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7

Microbiomes and the Soil–Human Health Continuum

Given their well-established importance in maintaining the biochemistry inherent to health, there is strong motivation to include soil microorganisms, and other biota, in assessments of health from soils and humans. In fact, in soils today nearly a third of tests recommend microbial measurements of soil respiration, biomass, or nitrogen mineralization to characterize biological properties in assessment of health (Lehmann et al. 2020). Similarly, there is mounting evidence that the human microbiome plays an important role in human health (Turnbaugh et al. 2006; Lynch and Pedersen 2016). Given the higher resolution information on microbial content and processes provided by high-throughput sequencing technologies and mass spectrometric methods, microbiome-derived content could be untapped sentinels of soil and human health.

Microbes are likely to be among the key factors explaining how the environment affects human health. While there has been substantial work on understanding how the microbiome of the built environment can affect health (NASEM 2017; Gilbert 2018), far less work has specifically linked soils and their microbiomes to human health outcomes. Most of the evidence linking soil health and human health by way of the microbiome focuses on direct ingestion of soil or contaminated food, aerosolized dust, and percutaneous transfer. Areas of interest in this research include the role of diet as modulated by the gut microbiome, toxins and pollutants derived from microbial metabolisms, and soil-derived pathogens or toxins on human health (see Chapters 3, 5, and 6). There is also indirect evidence that soil health may be tied to human health via the beneficial role of exposure to microbes in human development and the maintenance of health, notably on the immune, metabolic, and central nervous systems. Both exposure to environmental microbes, and colonization of the human gut, oral cavity, lung, skin, and urogenital tract are essential for normal function of these organ systems (Thompson et al. 2017). The link between the soil microbiome and human health is particularly compelling because it offers the potential as a modifiable factor and health indicator that can reduce health inequities; this is in contrast to environmental and social determinants of health such as access to greenspace and biodiversity that require long-term investment to change.

This chapter focuses on the microbiomes of soils and humans and their relationship to health in each compartment (soils and humans) and across compartments. The focus is on the coordinated invisible ecosystem of microorganisms and less on specific microorganisms, as these are covered in other areas of this report (Figure 7-1). For instance, Chapter 2 introduces how the microbiome can be incorporated into a One Health framework, provides linkages between soil, plant, and animal systems, and includes a cross-system taxonomic analysis that highlights the shared and unique members (see Figure 2-9). Chapter 5 discusses the direct linkage between soil microbes and human health in their role as soil-borne pathogens (such as *Escherichia coli*, *Clostridium tetani*, and *Coccidioides*) and mycotoxins. Additionally, in Chapter 6, the effects of microbial transformations of soil chemical contaminants on health are discussed. Additional human health benefits conferred by soil microbiota, such as their ability to produce antibiotic and therapeutic agents (Chapter 3) or their roles as inoculants for soil management (Chapters 4 and 5) are also detailed in other chapters of the report.

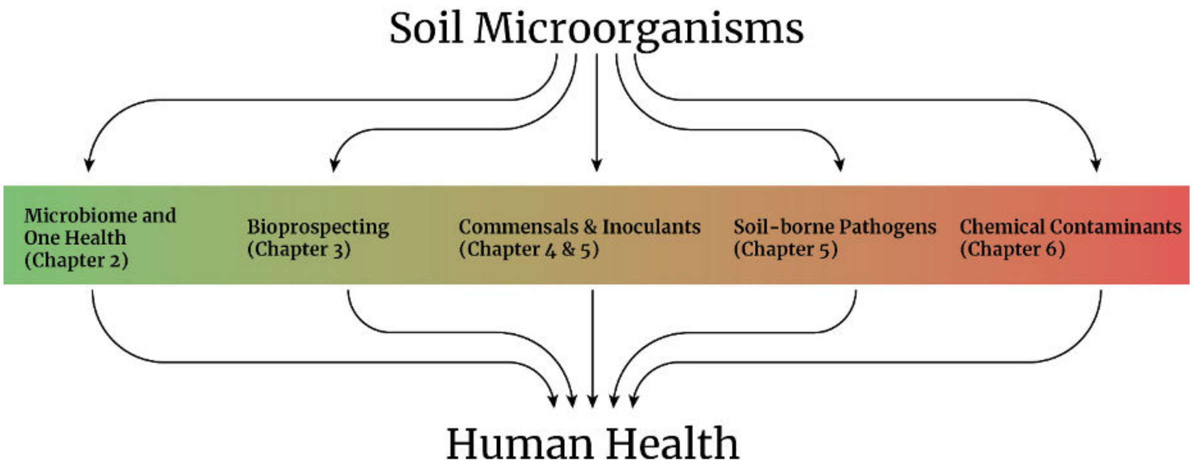

FIGURE 7-1 Discussions of specific microorganisms or microbial processes that relate to human health in other chapters of the report.

Instead, this chapter offers a forward-looking perspective of the role for the microbiome in the soil–health continuum (Figure 7-2). The approach taken in this chapter underscores the identification of two primary knowledge gaps. Firstly, there is a pressing need to determine which microbial features, if any, contribute to quantifying or fortifying health in both human and soil systems. The ultimate goal for this knowledge is to leverage this understanding for the development of improved and rapid diagnostics or for new biotic-inspired therapeutics such as inoculants or probiotics. Secondly, there is a necessity to comprehend the direct and indirect roles of soil, alongside other environmental factors, in influencing human microbial colonization and subsequent health outcomes. Such investigation involves delving into the relatively sparse or disconnected research regarding the microbiome continuum that links soil and human systems.

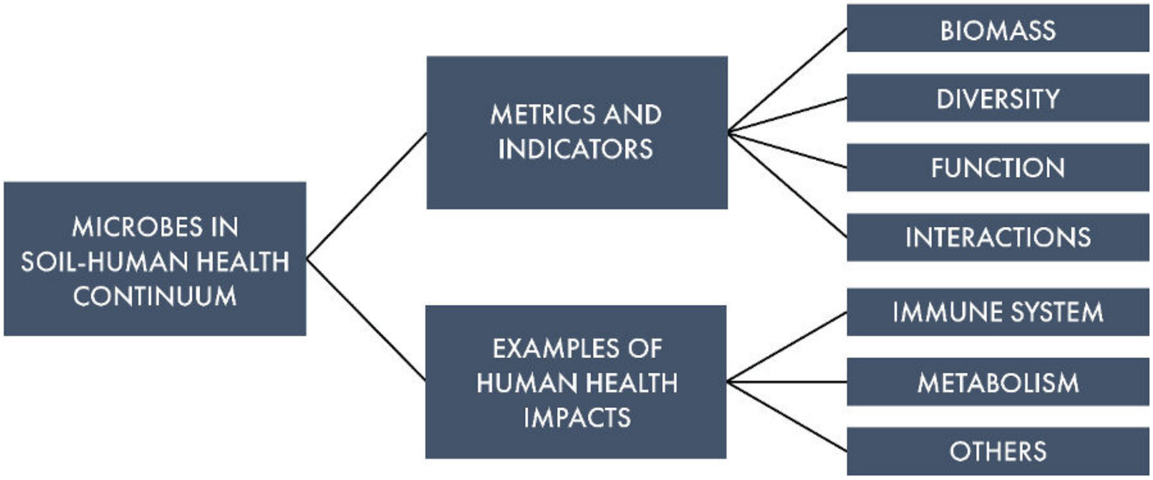

FIGURE 7-2 Organization of Chapter 7.

This chapter addresses two overarching research needs (Figure 7-2). The first section explores the current utilization of microbiome content to assess health status both in human and soil systems. This segment concludes with an examination of emerging technologies and analyses showing promise in identifying new microbiome-derived indicators for health or disease status in humans, crops, and soil systems. The second part of the chapter assesses the existing evidence regarding the microbiome continuum linking soil systems and human systems. It focuses on areas with the most compelling research evidence today: (1) the connection of environmental microorganisms to immune development and allergic disease and (2) the role of gut microbes in modifying or extracting nutrients from food for human health. In summary, by exploring the microbiome continuum from soils to human systems, the valuable insights that will inform diagnostics and interventions and promote health across both ecosystems can be unlocked.

MICROBIOME FEATURES AS INDICATORS OF HEALTH STATUS

Microbiomes as Modulators of Soil and Human Health

Structurally speaking, host systems such as the human gut microbiome and the plant rhizosphere (soils attached to or impacted by plant roots) exhibit numerous physical and chemical similarities. For example, both communities are partially shaped by host activity. In the human gut, microbial composition can be altered by dietary shifts, medication usage, host health status, and environmental factors, while the host also generates compounds such as mucin to nourish and facilitate microbial colonization (Fassarella et al. 2021). Similarly, microorganisms in the rhizosphere respond to root exudation, where plants secrete metabolites, influencing microbial activity and community dynamics (Seitz et al. 2022). However, there are critical differences between these two habitats, as outlined below. Together these shared principles and unique drivers influence the way microbiomes are analyzed and collected and how they are interpreted in a health context.

Broadly, both gut and soil microbiomes provide benefits to their hosts through decomposition (e.g., fiber, proteins), nutrient extraction, and hormone production. As detailed later in this chapter, the human gut microbiota metabolizes proteins and fiber from the diet, generating short-chain fatty acids for the host energy. Similarly, soil microbiomes decompose litter and process metabolites from root exudation, shaping carbon and nitrogen pools crucial for maintaining soil biotic and abiotic structure as well as for plant health. In the gut microbiome, microbiota synthesize vitamins (e.g., vitamins B and K) and produce metabolic products that nurture human host cells (Nicholson et al. 2012). Similarly, soil microbiomes, particularly bacteria and fungi in the rhizosphere, play critical roles in extracting nutrients from soil and transferring them to host plants. Bacteria excrete compounds or enzymes that mobilize iron and other metals, acquire nutrients such as phosphorus and nitrogen, and produce phytohormones with regulatory properties for host plants (Chepsergon and Moleleki 2023). Additionally, mycorrhizal fungi can extend nutrient uptake beyond the plant roots by a factor of 1,000 (Larcher 1995) and alter phytohormone concentrations to promote drought tolerance (Bahadur et al. 2019). In return, the plants allocate a substantial amount of carbon to the underground fungal network, roughly equivalent to one-third of the annual CO2 emissions from fossil fuels (Hawkins et al. 2023). Thus, gut and soil microbiomes play vital roles in hormone regulation and nutrient acquisition.

In both humans and rhizosphere soils, beyond providing nutritional benefits, the microbiome acts as a formidable barrier against the invasion and proliferation of pathogenic microorganisms (Nakatsuki et al. 2017; Zheng et al. 2020; Gu et al. 2022). In humans, microbiomes confer this resistance by induction of an immune response, competitive exclusion to make colonization inaccessible to other pathogens, production of antimicrobial substances, maintenance of intestinal barrier function, and immune training in early life (Zheng et al. 2020). In plants, commensal microbes can serve as a passive barrier by occupying niches that become inaccessible to pathogens, but current evidence also suggests that the plant immune response may be partially suppressed to allow for commensal colonization (Durán et al. 2018). Taken together, these findings highlight the complexity of microbial interactions in promoting host health and defense mechanisms, offering valuable insights for both human health and agricultural practices.

This report commonly refers to microbiomes associated with their broad habitat categories such as the gut and rhizosphere, but it is important to acknowledge that each habitat comprises vast microheterogeneity. Therefore, generalizing shared features may oversimplify the diverse metabolic regimes that exist in each compartment and span small physical distances or fluctuate over daily temporal scales. For instance, within the intestinal lumen, microbial density increases from the stomach to the colon, and there are distinct gradients of microbiota and metabolic lifestyles between the lumen and the adjacent mucus layer (Li et al. 2015). Similar nutrient gradients are observed between the bulk soil and rhizosphere, and even within the rhizosphere, where specific taxonomic compositions and functionalities are associated with different microenvironments (Ling et al. 2022; Fitzpatrick et al. 2023).

The committee also recognizes that there are differences across gut and rhizosphere systems, which provide unique challenges in the microbiome methodologies and their analyses, a feature highlighted below in Table 7-1. For example, rhizosphere systems are external to their host and embedded within the environment, which means these microbiomes experience diurnal and seasonal fluctuations in temperature, nutrients, and water availability and are open to microbial dispersal. In contrast, the gut system is internal and is well modulated by the host in temperature and pH, with dispersals only happening via ingestion. These differences contribute to differences in the active and dormant members in each system, with proportionally more dormant cells in the soil and rhizosphere than in the gut (Lennon and Jones 2011), a finding that has ramifications for how the communities are composed, structured, and buffer perturbations. In summary, the committee has attempted to provide threads of comparison and context for identifying areas of synergy and perhaps knowledge transferability, while still recognizing the domain specifics that contribute to these unique microbiota, their derived processes, and host relationships across soil and human habitats.

Microbiomes as Diagnostic Agents for Health

Given the shared roles as modulators of chemical transformations and host-interactions in human and soil systems, the potential exists to use microbiome content as health indicators in soil, crop, and human systems. Because microbial catalysis is responsible (either directly or a few steps removed) for many of the chemical indices used today as health indicators, it is also believable that the microbiome functional content underpinning these transformations could serve as an even earlier indicator of health changes prior to measured chemical differences. In this scenario, microbiomes themselves may act as canaries in the coal mine, providing early warning signals for other desirable or undesirable outcomes (Gu et al. 2022). While the soil and human microbiomes have considerable potential to serve in this capacity, the ability to define and interpret microbial health indicators is limited today by sparse understanding of the ecology and function of microorganisms in both soil and human systems. Bridging this gap, along with experimental design and methodological advances for sampling and analyzing microbiome content along health states will improve the incorporation of microbiome data in health monitoring (Wilhelm et al. 2023).

This section provides an inventory of microbiome features that are used to infer health in both human and soil systems and is organized based on different microbial units that have been used, or proposed to be used, as health indicators. The committee categorized the microbiome into four constituent classes that can be used to inform health status: (i) biomass, (ii) compositional, (iii) functional, and (iv) interaction. Measurements derived from these framing categories can be used as indicators themselves (e.g., biomass) or used to calculate new indices (e.g., diversity metric) of health status in human, soil, and plant microbiomes. Table 7-1 summarizes a selection of these microbiome features that are used or proposed for use in diagnosing human and soil health conditions. The table outlines assumed relationships between the microbial measurement and health status and identifies some caveats with the application. Examples included in this table are not meant to be exhaustive, and they are organized first by microbiome measures that are actively used in clinical human diagnostics or soil health assessment frameworks today (as denoted by [in use]). Approaches under development today are indicated in the bottom half of the table. The interaction framework for health is nascent such that it is described in the text but not included in Table 7-1.

Discerning health metrics within and between the biological categories of biomass, composition, and function has relied on a variety of methods based on cultivation (e.g., colony forming units), molecular (e.g., quantitative PCR, amplicon sequencing), functional (e.g., enzyme and physiological assays), and -omics inspired approaches (e.g., metabolomics, metagenome, metatranscriptome, metaproteome). As such, Table 7-1 is not organized by method, as many of them measure different aspects of biomass, taxonomy, and functional components of the microbiome. For example, cultivation-based approaches can provide microbial load (biomass insights) as well as specific types of microorganisms (compositional insights). Similarly, both amplicon sequencing and metagenomics uncover the microbial membership and distribution in a sample. In the text below the table, the four microbiome constituents are described in subsections, articulating the importance of diversity metrics (composition), chemical catalysis (function), and food webs (interaction) as promising diagnostic indicators of ecosystem health and functioning, providing examples from soils to humans. This section is ultimately written to highlight microbiome indicators in use today but also highlight the promise of emerging technologies for deriving new microbiome-informed indicators. Although enthusiasm is universally shared across human and soil systems, the practice and quantifiable metrics of health using microbiome-derived information are not well defined at present.

TABLE 7-1 Microbiota-Based Content and the Use of This Information for Establishing Health in Human, Soil, and Plant Systems

Microbiota class types	Methods of measurement	Human systems	Soil and plant systems	Assumption	Caveats
Microbial biomass-Total mass of organisms per mass of sample [in use]	Chloroform fumigation, PLFA, SIR, fungal hyphal quantification, direct counts, qPCR, ergosterol (DeLuca et al. 2019)	Overall microbial biomass is not commonly estimated in human health assessments.	Bacterial and fungal biomass in soils is a commonly used metric of health (Ghimire et al. 2023).	In soils, greater biomass is commonly considered a positive health status.	(i) More biomass is not necessarily positive, as it does not provide information on which organisms are present (e.g., pathogen). (ii) Biomass does not equate to increased rates of desired chemical reactions. (iii) High methodological variation in biomass estimation from soils.
Microbial biomass-pathogen enumeration [in use]	Plate counts, direct counts, culturing, qPCR, 16S rRNA/ITS marker genes of relative biomass.	Isolated or identification of infectious agents using cultivation approaches (Washington 1996), growing appreciation for molecular diagnostics (Hodinka and Kaiser 2013).	Isolated or identification of infectious agents using molecular or cultivation approaches (Hariharan and Prasannath 2020; Khiyami et al. 2014; Põlme et al. 2020).	In host systems (mainly humans but also plant), greater pathogen loads are considered detrimental to health.	(i) Pathogen presence or abundance does not always equate to disease, (ii) other factors contribute to severity of disease (stress, wellness status, immunity).
Targeted functional assays using known gene, enzyme, or process-based targets [in use].	Targeted approach (qPCR, qRT-PCR, enzyme assays, analytical profile index [API]) to quantify genes or enzymes that catalyze chemical reactions important to health in soils and humans.	API profiles and biochemical approaches and anti-microbial susceptibility to diagnose microorganisms associated with disease (Altheide 2020).	Acetylene reduction for nitrogen fixation, assay for potentially mineralizable nitrogen, or defined enzyme assays for carbon use are used in soil health assessments (Ferrocino et al. 2023).	Health status is specific to the enzyme selected, but increased activity is often considered a positive health outcome.	(i) Assays often have high internal variability cofounding interpretation, (ii) results can be impacted by methodology and environmental matrix (e.g., mineral content) that limit cross study comparisons, (iii) requires a priori knowledge of the target, or health or disease agent, (iv) typically a bulk, single enzyme measurement that may not accurately represent the process. For example, beta-glucosidase enzyme activity may not accurately capture all soil carbon metabolism.

continued

TABLE 7-1 *continued*

Microbiota class types	Methods of measurement	Human systems	Soil and plant systems	Assumption	Caveats
Microbial membership and abundance: alpha diversity [under development]	16S rRNA/ITS rRNA gene (via amplicon sequencing or qPCR) provide information on microbial types/sample (richness), their distribution (evenness) or can calculate diversity metrics per sample. Metagenomics is increasingly being used for compositional insights as well as functional diversity metrics (discussed below).	Decreased microbial richness of human gut microbiome was associated with increased disease metabolic markers (Le Chatelier et al. 2013).	Greater richness or diversity of mycorrhizal fungi and bacteria contribute to plant health, diverse soil communities have higher and more stable nutrient cycling (Fierer et al. 2021).	In both soils and human systems, increased species richness, evenness, and diversity metrics are thought to be associated with positive health outcomes.	(i) not all DNA comes from intact or active cells (relic), (ii) relationships between diversity and health in both humans and soils is context dependent, and not uniformly maintained across diverse hosts or sample types making interpretation challenging, (iii) greater richness from unwanted taxa may not contribute positively to health, (iv) sequencing technology may be a barrier to early adoption, requiring trained personnel to analyze and interpret microbiome information in health context.
Microbial membership and abundance: beta diversity [under development]	Amplicon 16S rRNA/ITS rRNA provide taxonomic identity and relative abundance assess changes in beta diversity across samples or treatments. Metagenomics is increasingly being used for compositional content as well as functional beta diversity metrics (discussed below), e.g. how gene relative abundance patterns change with health status.	Microbiomes of disease patients fluctuate more than healthy patients, which can be associated with healthy plane (Halfvarson et al. 2017; Brooks et al. 2017). Core functional processes or members contribute to stability in face of changing conditions (Eisenstein 2020)	Greater abundance of mycorrhizae or plant beneficial microbes are associated with health (Fierer et al. 2021), some taxa inform lower health scoring soils. CST are associated with disease suppression in crops (Fujita et al. 2023).	Certain community state types (CST) or microbiome membership will be associated with health, and these can be distinguished from unhealthy microbiomes.	(i) Not all DNA comes from intact or active cells (relic), (ii) multiple stable states exist in microbial communities without associated health change (Borton et al. 2023), (iii) overall community response or lack of response may mask changes in disease etiological agents, and (iv) sequencing technology may be a barrier to early adoption, requiring trained personnel to analyze and interpret microbiome information in health context.

continued

TABLE 7-1 *continued*

Microbiota class types	Methods of measurement	Human systems	Soil and plant systems	Assumption	Caveats
Untargeted functional gene diversity, content, or expression [under development]	Next-generation sequencing untargeted metagenomic, metatranscriptome, or metaproteome profiling of microbial communities.	Gene abundance and diversity predicted cardiovascular risk (Borton et al. 2023), functional shifts with inflammatory bowel disease (Lloyd-Price et al. 2019).	Genomic traits and environmental bioindicators of soil health were discovered (Wilhelm et al. 2023).	The relative abundance of genes or their expression, or aggregated traits derived from this content can inform health status.	(i) There is a small set of genes known today where biochemical knowledge that gene or gene product results in a directed health outcome, yet opportunity for discovery of new markers is desired, (ii) greater abundance of gene or its product does not dictate process rates, and (iii) this is an emerging technology with data difficult to analyze and interpret in health context today.
Untargeted microbial derived metabolites diversity, content, or quantification [under development]	Targeted or untargeted - nuclear magnetic resonance, high-pressure liquid chromatography, or mass spectrometric based methods (GC-MS, LC-MS, FT-ICRMS) (Aderemi et al. 2021).	Specific metabolites can indicate disease, while profiles can be used to indicate wellness or carbon processing (Martinez et al. 2017).	Targeted phytohormone panels (Šimura et al. 2018) and untargeted metabolomics for soil quality functional assessment (Withers et al. 2020).	Microbial metabolism produces metabolites that can impact human, plant, and soil systems; these metabolites or suite of metabolites can be an indicator of health of system.	(i) Due to travel through the body or solubility/mobility through soils, measurement of the metabolite may be distant from production site, thus distorting signal interpretation, (ii) host and microbiome factors control metabolite conversions and consumption, such that metabolite may not be master regulator of disease, (iii) improved identification of metabolites and demonstration that they elicit health effect is needed, and (iv) newer technology with data difficult to analyze and interpret in health context.

SOURCE: Adapted from Fierer et al. (2021).

Biomass Measurements of Health

Quantification or enumeration of biomass and its inferences to health varies across soils and human systems. In soil systems, microbial biomass, a measure of the mass of microbes both active and dormant per gram of soil, is a parameter often used to assess soil health. In fact, a third of soil health assessment tests, such as those from the European Commission or Soil Management Assessment Framework, recommend microbial biomass measurements as a critical estimate of the biological properties of soils (Lehmann et al. 2020). This metric is estimated using a variety of methodologies with lipid measurements or a chloroform fumigation-incubation being the most prescribed. Because microbial biomass accounts for a large proportion of total soil carbon and nitrogen, higher microbial biomass content or carbon is often considered as soil fertility constituent (Sparling 1997).

Fungal biomass is used as a biological indicator of soil health, as not only are these eukaryotic organisms vital to carbon and nutrient cycling but their hyphae and products play critical roles in improving soil structure and water retention. Typically, fungal biomass is assessed through lipid-based or ergosterol content or through microscopic quantification of hyphal biomass. While conventionally managed soils are reported to exhibit decreased fungal biomass relative to more regenerative management strategies, a response thought to be due to tillage, high rates of fertilization, and fallow, this response is not always uniform (Frąc et al. 2018). In addition, the number of fungi versus bacteria in given soil, expressed as the fungal:bacterial ratio, has been historically used as an indicator of soil health, with higher ratios indicating a more sustainable soil system with higher carbon accrual. However, recently this ratio has received criticism as it is affected by methodological constraints that particularly impact fungal assessment in soils and it does not reflect current ecological understanding of complex, multi-trophic soil food webs (Fierer et al. 2021). For instance, some fungi and bacteria have overlapped or syntrophic functionalities in soils, functionalities that will not be captured by this ratio.

While biomass or its derivatives is one of the most used metrics for assessing soil health, the application of microbial biomass in health assessment has confounding interpretations. Recently, it has been debated whether biomass provides a useful, or readily interpretable, assessment of soil health (Fierer et al. 2021), as there are many biotic and abiotic factors that could contribute, directly or indirectly, to changes in soil microbial biomass. For instance, biomass does not account for the types or diversity of microbes present in a sample, such that overgrowth of a pathogen or single microbial type would increase overall biomass but would not necessarily be considered healthy. Additionally, more biomass does not necessarily equate with specific "healthy" catalytic properties of microorganisms. Despite these concerns, microbial biomass or microbial biomass carbon remains one of the commonly recommended biological-based indicators of healthy soils in use for soil health assessments.

Demonstrating how microbiome indicators are often ecosystem specific, broad measurements of microbial biomass were not commonly used as an indicator in host health in past human research. However, current work is increasingly recognizing the need for assessments of absolute abundance in addition to relative abundance of microbes in a microbiome. Specifically quantifying populations of microorganisms associated with disease, such as pathogen loads, is used to diagnose health in human and plant systems. Pathogen biomass can be enumerated using cultivation-based approaches to measure the amount of a specific type of microbe in sample mass or volume (e.g., selective media or most probable numbering techniques) as well as with molecular approaches that determine the abundance or relative abundance of a taxon in sample mass or volume (e.g., quantitative PCR and 16S or internally transcribed spacer region [ITS] ribosomal amplicon sequencing). Given that some taxa are obligately pathogenic, the presence of these members can be easily ascribed to poor health conditions observed in plants or human individuals. Yet, interpreting pathogen content is not always so clear-cut, as pathogen abundance does not necessarily correlate to disease severity (Genin and Denny 2012; Swanson et al. 2007; Leggett et al. 2012; Yadav and Pandey 2022). Further, many pathogens are opportunistic, meaning they can be present and active in healthy individuals, and disease severity is controlled instead by other conditions, such as stress or host immunity (Kaper et al. 2004). Thus, the biomass of targeted taxa is not always a robust indicator of health and depends on the taxon and the ecosystem.

Measuring Diversity and Composition of the Microbiome

Amplicon sequencing is a targeted approach that uses deep sequencing of a single gene to provide information on the diversity and composition of the microbiome. The sampling of bacteria and archaea (16S rRNA gene), fungi (ITS), and eukaryotes (18S rRNA gene) has provided new dimensions on the microbial community constructs that contribute to health across ecosystems. Data from amplicon sequencing projects can provide three lines of microbial information: (1) measurements of diversity such as richness (number of types of microbes in a sample) or evenness (their distribution in a sample), (2) the microbial composition (which microbes are present in a sample), which provides insights into taxa that are indicators of disease or health status (Wilhelm et al. 2022), and (3) the relative abundance of each member in a sample, which describes the distribution of microbial members (e.g., enrichment or dominance that can occur along a health axis).

Today, because of increased affordability and streamlined data analytics, there is widespread adoption of amplicon-based analyses of microbial communities across habitats from soil to plant and human microbiomes. This reduced cost per sample, and the ability to process hundreds to thousands of samples, allows researchers to better contextualize heterogeneity with a sample site, developing more robust temporal and spatial awareness of microbial diversity and membership dynamics. For example, it is now warranted to sample microbial communities during different temporal stages of soil management or crop and human development, both in health and disease, to capture monthly and yearly scale changes in the microbiome (Lauber et al. 2013) or even hourly responses to daily routines and fluctuations (e.g., temperature and feeding). Similarly, more intensive sampling of soil compartments (e.g., rhizoplane from rhizosphere) or anatomical sites (e.g., different sections of the gastrointestinal tract) will further discern microbiota responsive signals from natural variation (Singh et al. 2020; Chinda et al. 2022). Additionally, in soils, regional differences in climate and soil type, as well as local land management differences, can make comparisons of microbiome diagnostic patterns across studies or even samples within closely related plots confounding. Similarly, human genetic backgrounds, the history of clinical treatments, and variations in diets, age, and other factors confound universal microbiome metrics for human health (Falony et al. 2016). Amplicon sequencing today is an important tool for allowing researchers to sample this heterogeneity in microbiomes across different gradients of variation.

Metrics derived from amplicon sequencing, either organismal or diversity-based indicators, are being evaluated as diagnostic tools that could be incorporated into formalized health assessments in the near future. In this chapter, the committee focuses on compositionally defined diversity as an indicator of health as it is used in both soil and human microbiomes. Yet, the committee recognizes that diversity can be measured on any level of biological organization

(Whittaker et al. 2001) and that microbiome diversity calculated using gene diversity, gene expression, or metabolite profiles may become more commonplace indicators of health status in the future as these methods have greater development and adoption as well (see the section "Functional Components of the Microbiome" below).

The explanation of how compositional diversity can relate to health is best understood through the lens of the insurance hypothesis. Originally proposed by Yachi and Loreau (1999), this hypothesis suggests that increasing biodiversity can insure ecosystems against functional declines in response to environmental perturbations (see also Box 3-1). This stability is achieved because different species respond differently to environmental fluctuations, but they can have overlapping functions within an ecosystem (i.e., functional redundancy). Therefore, greater species diversity increases the likelihood of maintained functionality stability in response to perturbations. With advancements in measuring functional diversity directly (through gene content or expression, see the discussion in the next section), it may no longer be necessary to be inferred from compositional richness, which may or may not be directly related to functional content at the scale required to withstand environmental perturbations.

Diversity measurements based on compositional data are often touted as indicators of health (Lozupone et al. 2012). In the human gut, the presence of a higher number of microbial members (richness) is inferred to make the microbial community more resistant to stressful events, such as antibiotic treatments (Lozupone et al. 2012). Moreover, it has also been shown that richer and more diverse microbiomes can guard against pathogen proliferation (Zheng et al. 2020; Bertola et al. 2021). On the other hand, decreased compositional diversity in the microbiome has been linked with chronic conditions such as obesity and type 2 diabetes, gastrointestinal diseases, and neurodegenerative diseases, among others (Cho and Blaser 2012; Fan and Pedersen 2021). Compositional diversity metrics may be used to assess health status more broadly. For example, gingivitis (gum inflammation) is associated with a lower diversity of the oral microbiome and the dominance of the pathogen, *Porphyromonas gingivalis* (Hajishengallis et al. 2012). The findings suggest that microbiome compositional diversity could be an indicator of health in adult humans.

Microbial communities are structured by a few more dominant members followed by thousands of rare members. These rare members are thought to act as a seedbank, preserving genetic diversity until it is needed. Although not abundant, these rare members can become provisionally enriched under specific environmental conditions, maintaining ecosystem performance in the face of changing conditions (Shade et al. 2014; Jousset et al. 2017). It is regarded that increased microbial compositional diversity or richness, often due to a large number of rare taxa, contributes to higher nutrient-cycling rates (Fierer et al. 2021). Additionally, in the rhizosphere, as in humans, increased microbial (both fungal and bacterial) diversity is associated with pathogen suppression for crop wellness (Bollmann-Giolai et al. 2022; Ling et al. 2022). Conversely, heavy metal contamination has been associated with a decrease in bacteria, fungi, and protist diversity due to both a loss of rare members and the increased dominance of a few select taxa that can resist changes in the abiotic conditions (Qi et al. 2022). In fact, the four most common threats to soil microbial diversity are cited as intensive human exploitation, land use change, soil contamination, and climate change (Jeffery and Gardi 2010; Tibbett et al. 2020). Thus, as emphasized in other chapters of this report, there is an ever-increasing interest in maintaining soil microbial diversity to maintain soil functionality and health.

Beyond microbial compositional richness and diversity, the relative abundance and taxonomic identity of members can serve as indicators of health status. For example, in the vaginal microbiome, the genus *Lactobacillus* play a major role in maintaining female health—such that increased lactobacilli prevent against vaginal infection and reduce the risk of acquisition of HIV and sexually transmitted pathogens (Das Purkayastha et al. 2020). Despite these clear linkages in research publications, not enough is known about the vaginal microbiome and disease to be able to add lactobacilli probiotics to reliably shift in the direction of improved health (France et al. 2022). Also, large cohort studies of healthy and unhealthy individuals combined with machine-learning approaches are paving the way for discovering new microbial classifiers of health (Lee and Rho 2022). Despite compelling results from individual studies, further investigation is needed to reveal the roles of human microbiota in all body habitats in order to support the development of microbiome-based diagnoses and therapeutics (Hou et al. 2022).

Compared to the human microbiome, specific microbiome-derived indicators of health are less defined in soil systems. There are generally regarded plant beneficial microbes that are used as inoculants (see Chapters 4 and 5), but more extensive studies assessing the presence, plant colonization, and persistence of biostimulants in the rhizosphere are warranted. It is also unknown whether taxa extant in soils can respond to land management to serve as indicators of health. To investigate this possibility, a study surveyed more than 900 agricultural soils from diverse geographic locations and management types across the continental United States, with each soil ranked with a health score based on biological, physical, and chemical measurements encompassed by the Comprehensive Assessment of Soil Health (CASH) framework (Wilhelm et al. 2022). Researchers identified microbial taxa that differentiated soils with low and high health scores, and these new organismal indicators also predicted conventional metrics of soil health. Although it is a single study and not partitioned for regional or crop differences, the results indicate that, as with the human gut, microbiomes compositional information obtained through amplicon sequencing could inform measures of health status.

However, in human and soil systems, using ribosomal RNA (rRNA) and ITS-based metrics for assessing health in microbiomes is not without constraints (Ames et al. 2017; Matchado et al. 2024). Firstly, these methods provide limited taxonomic resolution and cannot differentiate well-known pathogens (e.g., S*almonella typhi* from *E. coli*), necessitating higher resolution for accurate identification of health-associated microbial taxa. Secondly, biases in data processing and reliance on incomplete databases can skew detection and interpretation of microbial groups in the microbiome. Additionally, while taxonomic composition may offer some limited insights into potential functional roles (Nguyen et al. 2016; Douglas et al. 2020), these methods do not fully represent the overall metabolic activity or functional potential of the microbiome. Moreover, using DNA as input material fails to distinguish active from dormant microbes or extracellular DNA (Lennon and Jones 2011; Carini et al. 2016), which are prevalent in soils and the human gut and could further overrepresent inactive members. Understanding the distinction between active and dormant microbiota, along with their functional capacities, may become crucial indicators when assessing implications for soil and human health. While rRNA and ITS sequencing provide valuable insights into microbial community composition, diversity, and dynamics, their use in health assessment could be bolstered with other methods discussed below and careful consideration of their limitations.

Functional Components of the Microbiome: A Promising Indicator of Health

Assessing Metabolic Potential There is broad recognition that harnessing microbiomes for improving plant, human, and soil health requires decoding the genetic underpinnings of the microbiome and how these molecular constituents are translated into chemical changes and ecosystem outputs. This is no trivial task, but newer -omics technologies, such as metagenomic sequencing, and other multi-omic technologies, such as metatranscriptomics, metaproteomics, and metabolomics, can provide advanced functional insights into the microbiome (Figure 7-3). This section defines these methods and begins to illuminate how these tools and their measurement of the functional aspects of the microbiome may be called upon to assess health status in human and soil systems in the future.

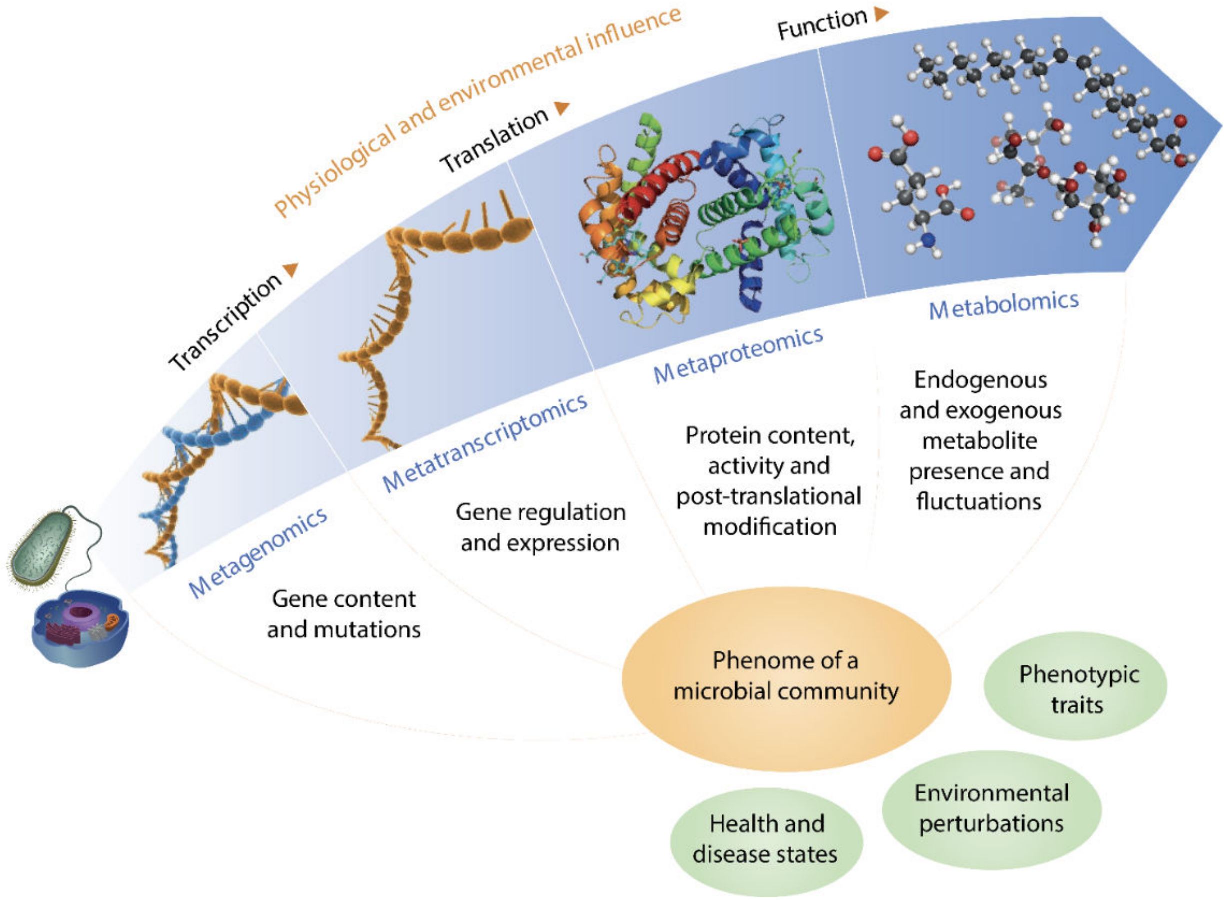

FIGURE 7-3 A schematic illustrating the information gained from each -omic technology and how their integration is essential to fully understanding the phenome.
SOURCE: Used with permission of Springer Nature BV, from "A Multi-omic Future for Microbiome Studies", Jansson and Baker, *Nature Microbiology* 1 (5), 2016; permission conveyed through Copyright Clearance Center, Inc.

It is increasingly possible to use untargeted sequencing approaches to inventory the cache of gene content in a microbial community, an approach known as metagenomics (Jansson and Baker 2016). Metagenomics approaches are best developed for bacteria and viruses (Kang et al. 2017; Emerson et al. 2018; Leleiwi et al. 2023), where results have showed greater ability to predict ecosystem outputs and health status. These methods are still in development for eukaryotic members like fungi and protists (Donovan et al. 2018). Instead of community-wide genomics (metagenomics) for eukaryotes, valuable insights into the functional attributes or traits of fungi have been gleaned from genomic approaches that sequence specific taxa individually or map environmental sequences to genomes derived from relevant isolates (Treseder and Lennon 2015; Ravn et al. 2021; Zhang et al. 2023). Microbial gene information derived from genomic sequencing not only yields taxonomic content (although not as deeply sampled as amplicon-based sequencing) but also provides critical measurements on the genes that govern metabolic or functional capabilities in a microbiome.

Specifically, metagenomics has advanced knowledge of human health, uncovering new metabolic assignments for previously uncultivated lineages (Wrighton et al. 2012; Di Rienzi et al. 2013), identifying potential for microbially derived antibiotics and secondary metabolites with health-promoting benefits (Crits-Christoph et al. 2018), and outlining the metabolic wiring underpinning the functional outputs critical for soil and human health (Table 7-1). Advances in data processing (software), decreased sequencing cost, and improvement of databases for data processing (Pasolli et al. 2019) have made it possible to apply metagenomics to larger cohort sizes and to utilize sequencing more effectively within a sample. The metagenomic-derived functional gene profiles derived from fecal microbial genomic content can predict human heart disease (Borton et al. 2023) and various types of cancers, from colon to prostate (Banerjee et al. 2015; Gao et al. 2022). Additionally, metagenomics can rapidly identify infectious disease-causing pathogens, such as bacteria, viruses, and fungi in a single test without the need for culturing (d'Humières et al. 2021), thereby playing a promising role in the clinical diagnoses of disease (Box 7-1). Yet, to date, there remain few FDA-approved microbial therapies (Jain et al. 2023).

In comparison to human clinical assessments, metagenomic studies have not been used to study soil health as often (Duque Zapata et al. 2023), and larger cohort studies with paired genomic insights and robust physical, chemical, and biological soil health indicators are needed. To these ends, genome-resolved metagenomic databases from soils are on the rise both in the public (Woodcroft et al. 2018) and private sectors,[1] however, developing an open, collective database infrastructure, such as the Human Microbiome Project, and targeting agricultural soils with paired soil health data specifically, could advance the discovery of microbial gene indicators in these soils. These efforts are buoyed by additional large-scale global soil microbiome catalogs, such as the Earth Microbiome Project (Thompson et al. 2017) and the federally funded Genomic Encyclopedia of *Bacteria* and *Archaea* project (Whitman et al. 2015). Yet, more studies are needed across geographic and agricultural landscapes with paired microbiome and soil health measurements (Wilhelm et al. 2022) to begin fortifying the predictive capabilities of the microbiome for soil health and fertility. The federal government has taken steps to develop the necessary infrastructure for sharing data across projects with a project called the National Microbiome Data Collaborative, which supports a Findable, Accessible, Interoperable, and Reusable (FAIR) microbiome data sharing network, through infrastructure, data standards, and community building (NMDC 2022).

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[1] See, for example, "Pattern Ag Announces World's Largest Metagenomics Database," September 18, 2023. Accessed April 30, 2024. https://www.pattern.ag/news/pattern-ag-announces-worlds-largest-metagenomics-database.

BOX 7-1
Human Microbiome Project

In 2007, the National Institutes of Health, through its Common Fund, established the Human Microbiome Project. In its first phase, the project used 16S rRNA sequencing to characterize microbial communities in the human body and metagenomic sequencing to learn about microbiome functions. In Phase II of the project, studies that focused on pregnancy and preterm birth, inflammatory bowel diseases, and stressors affecting individuals with prediabetes began to elucidate mechanisms of host-microbiome interactions (HMP 2019).

This novel undertaking spurred taxonomic sequencing and eventually molecular profiling of microbial gene content from the major ecological niches of the human body. Research has expanded from a focus on the gut microbiome to touch on many diverse sites of microbial colonization including oral, respiratory, vaginal, cutaneous, and ocular microbes. It has been found that a combination of an individual's genetic background and current state of health, the molecular function and personalized strain-specific makeup, and environmental factors are all important predictors of a range of health outcomes. For example, a recent study profiled the bacterial composition, function, antibiotic resistance, and virulence factors in the gut microbiomes from a three-generation Dutch cohort and found that a larger proportion of variation in the gut microbiome is associated with cohabitation and environment than genetic relatedness (Gacesa et al. 2022). These large-scale studies, sampling thousands of humans over time and assessing the microbiome at different levels of biological units from composition to functional attributes, as well as their individual and coordinated relationship to health, can provide inspiration for the kind of research needed in soil and human systems.

However, reusing microbiome data collected across many different studies for machine-learning approaches (Box 7-2), especially those spanning analyses across soil and human compartments, is not trivial today. Barriers include that the data are often housed without meta-data standards, hindering reprocessing of the data to create uniform analysis metrics. Public microbiome data are also not housed with health outcome data, and the latter is often linked within studies rather than housed in public repositories. Beyond data organization, while many artificial intelligence approaches may uncover genes or sets of genes linked to disease, many times these "predictors" lack accurate biochemical annotations with unknown functional outcomes. Thus, both from a data-mining point of view and a biochemical knowledge perspective, empowering gene content into health frameworks will require ongoing research. Yet, there are enough promising studies, especially on the human microbiome side, highlighting the promise that this content can be used for microbiome-inspired diagnostics and interventions.

Activity Assessment of the Microbiome While metagenomics provides insights into the gene-encoded metabolic potential of a microbial community, it may not fully capture the dynamic responses to environmental perturbations (Jansson and Baker 2016). Instead, functional assays, which measure or attempt to measure active processes in the microbiome, may be more direct indicators of health. These can include either (1) targeted approaches that use process-based assays or (2) untargeted approaches that measure expressed gene products, such as transcripts or enzymes. In soil health assessments today, enzyme assays are commonly used as biological indicators. For example, beta-glucosidase and cellobiohydrolase assays are employed to estimate carbon decomposition activity in the Soil Management Assessment Framework (SMAF) (Stott et al. 2010), an assessment tool to evaluate impacts of land management on soil

BOX 7-2
Machine Learning and Artificial Intelligence for the Microbiome

With the tremendous progress in multi-omics approaches and the popularity of their adoption, both the type and amount of data are increasing at an astronomical pace. Consequently, data wrangling, storing, and management have become an important part of microbiome projects as well as long-term information archiving. Data processing using artificial intelligence tools is also becoming popular in microbiome science. One such tool that has seen a surge in use is machine learning, which is a flexible set of tools that can tackle large datasets to identify, group, and predict patterns (Hernández Medina et al. 2022). Machine learning can be broadly classified into two groups: unsupervised machine learning and supervised machine learning. Unsupervised machine learning attempts to group observations and identifies major structures in a new dataset when a priori information or hypotheses are not available. On the other hand, supervised machine learning attempts to generate predictive models from training data when answers are known and a priori hypotheses are available (Asnicar et al. 2023). Deep learning is also a type of machine-learning tool that utilizes artificial neural network architectures. The networks are composed of nodes or neurons, which are essentially functions that can perform operations and forward the results to other nodes.

In recent years, machine learning has been applied to a wide range of microbiome questions, including assessing the complex physical and chemical interactions between the microbiome components, selecting microbiome features such as the abundance and distribution of biomarkers, predicting an environmental or host phenotype, and examining for changes in the microbiome composition (Hernández Medina et al. 2022). For human microbiomes, machine-learning tools are enabling clinicians with accurate prognosis and diagnosis in precision medicine. For example, Calderone et al. (2015) used supervised machine learning on a large dataset comprising 2,357 human proteins and 453 viral proteins and predicted interactions between human proteins and viral proteins with up to 80-percent accuracy. Another study employed machine learning and cross-validation on 969 fecal metagenomes to predict colorectal cancer with over 80-percent accuracy (Thomas et al. 2019). Recently, Weis et al. (2022) used a clinical dataset comprising 300,000 mass spectra with 750,000 antimicrobial resistance phenotypes to detect resistance of potent pathogens such as *Escherichia coli*, *Klebsiella pneumoniae*, and *Staphylococcus aureus*. Machine-learning tools have also been used to predict pancreatic cancer using fecal microbiome signatures, determining the success of fecal transplantation, and assessing the mortality risks in melanoma patients (Asnicar et al. 2023).

Soil microbiome studies are also utilizing different machine-learning algorithms. One of those algorithms that is routinely used is random forest analysis, which has detected macroecological patterns of soil bacteria (Ramirez et al. 2018), identified microbial predictors of soil multifunctionality (Delgado-Baquerizo et al. 2016b), predicted keystone taxa (Trivedi et al. 2017), identified global soil microbial carbon, predicted assembly of seedling microbiomes (Walsh et al. 2021), and found drivers of soil microbiome complexity (Yang et al. 2023). Nonetheless, fundamental soil science studies are also utilizing random forest analysis to predict soil parental materials (Heung et al. 2014), soil carbon stocks (Wiesmeier et al. 2011), soil texture (Chagas et al. 2016), soil respiration (Delgado-Baquerizo et al. 2016a), and optimal soil health parameters (Wilhelm et al. 2022).

While artificial intelligence tools have been adopted and implemented in human health and soil health studies separately, the linkage between the two health components has yet to leverage such efforts. The stage is indeed set for such exploration; however, enhanced data integration and interoperability will facilitate these linkages. Given that biochemical and microbiome signatures of health can be "nuanced" and challenging to distill from the deluge of data, the aforementioned tools can be particularly useful in establishing hypotheses for further investigation.

quality. While these process-based assays provide valuable insights into targeted processes like nitrification or potentially mineralizable soil nitrogen, their interpretation may be complicated by soil matrix effects, the inability to effectively capture all relevant processes, and the need for further validation persist (see Table 7-1 for a detailed discussion).

Untargeted approaches, such as metatranscriptomics (the sequencing of the transcribed cellular content in a sample) and metaproteomics (mass spectrometric analysis of proteins), sample the expressed gene content in soils and human microbiome (Aguiar-Pulido et al. 2016). These methods offer opportunities to identify new, more comprehensive targets beyond those represented in the handful of established enzyme assays today, but they also can be more responsive than metagenome methods (or other DNA-based approaches) because they reveal an immediate response to perturbations (e.g., land management, diet interventions, disease onset). In both human and soil systems, metatranscriptomics and metaproteomics are technological advancements that could be leveraged for measuring and monitoring health aspects, offering new directions for research and clinical diagnosis and management (Berg et al. 2020; Bertola et al. 2021). While promising and growing in their application in soils (McGivern et al. 2021; Starke et al. 2021) and human microbiomes (Long et al. 2020; Borton et al. 2023; Wang et al. 2023), these methods are often only as robust as their underlying database used to contextualize the expression data, which can be challenging in samples with high strain diversity. The data collection can be affected by the heterogeneity of the matrix, and, compared to other methods, the cost to process and analyze at scale to identify health outcomes is limiting (Issa Isaac et al. 2019). These or other methods, such as quantitative stable isotope probing (Hungate et al. 2015; Wilhelm et al. 2021), probe-based functional profiling (Whidbey and Wright 2019), or flow cytometric single cell metabolic assays (Salazar et al. 2019), may further quantify the abundance of active and dormant microbes and processes in the future, providing better descriptions of microbial traits relevant to soil and human health outcomes.

Likewise, metabolomics—the study of low-molecular-weight organic compounds—can be targeted (directed at specific chemical compounds) or untargeted (simultaneous measurement of large number of compounds in a sample). This approach offers insight into the metabolic status of a sample, measuring the chemical products of the biological community. In humans, the detection of metabolites produced by gut microbes from dietary metabolism has been linked to pathologies such as hypertension, atherosclerosis, heart failure, obesity, kidney disease, and type 2 diabetes (German et al. 2005; Tang et al. 2019). In soil systems, metabolite approaches are used but trail studies in humans (Ellenbogen et al. 2024; Song et al. 2024) and are less developed for measuring health status. However, a recent study using nine different topsoils along a land use gradient with paired chemical and physical soil health data showed that the untargeted detection of more than 400 soil metabolites had discriminatory power as a potential soil quality indicator (Withers et al. 2020). Additionally, measurements of soil metabolomes from 188 backyard soils across 14 U.S. states demonstrated that soil metabolomes reflected the effects of local factors such as temperature, light level, and human activities on the soil (Nguyen et al. 2020). However, methodological improvements, including overcoming extraction biases from matrices, enhanced annotation and identification of soil metabolites, and discerning the fate of metabolites due to transient fluxes, will be necessary to identify the close relationships between microbiota and metabolomes in a wellness context from complex microbiomes in soils and the human gut (Song et al. 2024).

Both in human and soil microbiomes, multi-omics or the complementary use of multiple methods (metabolite, proteomic, genomic, transcriptomic approaches, see Figure 7-3) can provide more definitive evidence on the microbial metabolic pathways related to health status. The next step is to establish metrics to evaluate performance aspects of metabolomic and other multi-omic methods, under a wide range of health and disease conditions, as well as management regimes, so that they can be used for the quantitative assessment of human health or soil health (Withers et al. 2020).

Interactions: An Unstudied Metric of Health

Biodiversity includes not only the number and type of species and their abundances but also the complex interactions among different species. There is growing appreciation for network-based analyses that incorporate taxonomic (co-association or abundance network) or functional (co-expression network) content to estimate the interactions that occur among different species and their contributions to ecosystem functioning (Harvey et al. 2017; Wagg et al. 2019; Box 7-3). It should be noted that these networks do not provide explicit evidence for species interactions but suggest that organisms or the gene content co-occur over space and time, hinting at a possible interaction potential. Networks constructed from taxonomic or functional information can be assessed for their connectivity, network size and structure, and relationship to health or ecosystem properties (Shi et al. 2016; Banerjee et al. 2019; Dundore-Arias et al. 2023). It is hypothesized that more complex and connected networks are more robust to disease and other biotic perturbations as well as abiotic stressors (Barabási et al. 2011). In support of this, a recent study of bacterial rhizosphere networks in tobacco plants strongly affected by the pathogen *Ralstonia* showed that disease-suppressive soils had greater network complexity and that the bacterial abundances of highly connected keystone taxa within disease-suppressive soils were negatively correlated with pathogen density (Zheng et al. 2021). Similar network approaches have been used in human gut microbiomes to identify coordinated species and pathways associated with inflammatory bowel disease that are absent in obese and healthy population cohorts (Chen et al. 2020). While nascent, network analyses that use culturing and multi-omics approaches to capture the interactions of phenotypes could be indicators of health in the future.

Building on the ideas of trophic structure comprising all soil biota, not just viral, archaeal, bacterial, or fungal members, it is increasingly apparent that biodiversity maintenance is an essential constituent for soil health. Here, the idea in soils is that preserving belowground biota from microbes to protozoan to animals such as nematodes and earthworms are critical not only for soil functioning today but also for their long-term management with repercussions extending to human health. Collectively, a loss of soil diversity (microbes, fungi, protozoa, and fauna) has been associated with lower plant diversity and crop yields, leading to reduced food security, erosion that reduces air and water quality, and increased soil-borne pathogen and pest load, which all can have indirect and direct human health impacts (Wall et al. 2015). Consequently, current research initiatives across global organizations, such as the Global Soil Biodiversity Initiative, are committed to inventorying and maintaining soil biodiversity to protect soil and human health. Beyond microbial biomass, taxonomic, and functional metrics, soil biodiversity management should target the ecological complexity and food web architectures necessary to provide robustness of soil ecosystem services. In summary, an ecosystem management approach to health in soils can be extended to managing humans and plant health more holistically. As stipulated in the One Health framework, there is a recognized need to move beyond managing a single aspect of health, with biodiversity stewardship and overall ecosystem wellness being increasingly realized as a metric unto its own (FAO, UNEP, WHO, and WOAH 2022).

While promising, most of the modern -omics-based metrics are exploratory and have not been readily incorporated into human clinical or soil health assessments (Table 7-1). Similarly, interactions as a measurable unit of health is a newer concept not widely adopted today. Given the complexity of microbiomes, the reality of creating a robust, scalable health index using a single microbiome measurement (e.g., gene, organism, metabolite, interaction network) is unlikely. This situation is not entirely different from applications of health assessments in humans and soils today, which use a handful of metrics derived from physical, biological, and chemical measures for a more comprehensive picture of wellness. To discover new indicators or features of the microbiome that can predict health in humans and soils (see Box 7-2), enhancing the spatial and temporal resolution of the data stored in collections, moving beyond a handful of 10–100 samples per study to thousands, will help resolve localized responsive “signals” across a background of heterogenous “noise.” Additionally, these analyses need to be performed when there is a clear health outcome or gradient to compare to, to detect capacity of microbiome-derived indicators to predict different health status. Artificial intelligence approaches will likely play a critical role in this discovery given the deluge of data produced from modern -omics methods. Rather than being derived from genes or sets of gene content, it is likely that microbiome functional estimates of health will be distilled to aggregate properties that capture more responsive indicators that may function as a final single health index (Lehmann et al. 2020).

BOX 7-3
Viruses

Viruses are key members of Earth’s microbiomes, shaping microbial community composition and metabolism. There is growing interest that bacteriophages that infect bacteria may be additionally sentinels of health in soil, cropping, and human microbiomes. This perspective is spurred by the fact that in the past decade the field of viral ecology has moved from quantifying virus-like particles in different environments to community-wide measurements where sequencing the DNA or RNA from a sample (using metagenome or metatranscriptomes) offers the capacity to sample the genomic diversity of viruses living in soils, plant, and human systems (Sharma et al. 2021; Bhagchandani et al. 2023; Ma et al. 2024). These studies have reported that viruses are highly diverse and very abundant, infect a significant portion of their microbial host communities, and influence major biogeochemical processes mediated by microbes (Roux and Emerson 2022). Across human and terrestrial microbiomes, correlations between viral abundances and ecosystem services (e.g., climate-relevant biogeochemical indices [Emerson et al. 2018; Rodríguez-Ramos et al. 2022; Jansson and Wu 2023], agricultural practices [Santos-Medellin et al. 2021; Liao et al. 2022], and human health lifestyle, status, or outcomes [Gregory et al. 2018; Chen et al. 2023]) are often more informative than bacterial correlates alone, suggesting that further interrogation of viral communities can yield a more comprehensive understanding of microbiome functional networks and ecosystem processes. Thus, understanding the role of phages offers a promising avenue for predicting and maintaining health in both human and soil ecosystems.

SOILS, MICROBES, AND HUMAN HEALTH

Though microbes are often associated with disease and infection, the relationship between microbes and human health is far more complex. Research over the past few decades has unveiled the indispensable role of exposure to microbes in human development and the maintenance of health, notably on the immune, metabolic, and central nervous systems. Both exposure to environmental microbes and colonization of the human gut, oral cavity, lung, skin, and urogenital tracts appear to be important for normal function and protection against pathogenic microorganism and toxins (Thompson et al. 2017). Microbes outnumber human cells in the body, and their metabolic products make up over a third of the small molecules in the peripheral blood, many of which affect physiology (Wikoff et al. 2009).

To what extent exposure specifically to the soil microbiome influences human health is as yet unknown. Despite the growing capacity to characterize taxa and study the functions of microbiomes in humans and other systems through next-generation sequencing, the full continuum between soil health and human health by way of microbiome influence is not established in the literature. Additionally, even when skipping past the soil microbiome for which the metrics are under development, the committee found limited research that spans the investigation on how soil health more broadly may influence the nutrient density of foods in a way that would affect the gut microbiome's metabolic capacity or human health (Chapter 5). Further, the committee found inconclusive support for the direct linkage of soil microbiomes to human gut microbiomes leading to human health outcomes. As such, this section focuses on areas where promising linkages have been made for (1) environmental microbes as immunomodulators for human health, (2) soil microbiomes and gut microbiomes in animal models, and (3) the gut microbiome as a connector between nutritional inputs and human health.

The Hygiene Hypothesis and the Importance of Balancing "Good" and "Bad" Microbial Exposures

Humans, like all eukaryotic life forms, have evolved from microbes and have co-evolved to form a symbiotic relationship with microbes (Domazet-Lošo and Tautz 2008). For example, the immune system is dependent on receiving appropriate inputs from microbial interactions, and these must be received early in life and then maintained and updated throughout life (Bach 2018; Rook 2021). It has been shown that maternal and familial transfer of microbiota is crucial for the development of an infant's microbiota, and that lifestyle factors that reduce this transfer and correlate with increased immunoregulatory disorders include caesarean deliveries, lack of breast feeding, antibiotic use, and diet (Penders and van Best 2022). Environmental exposures, including proximity to green space and farms, has also repeatedly been shown to be influential (von Mutius 2021). For example, Hanski et al. (2012) showed that environmental biodiversity based on land use data was correlated with a greater diversity of commensal skin bacteria commonly found in soil and vegetation, which translated into functional measurements of serum immune markers and lower rates of allergic disease.

Exposure to the environment and microbes is essential to the selection of a repertoire of cells that can eliminate pathogens while tolerating the microbiota and avoiding self-recognition and autoimmunity. Therefore, each individual develops an immune repertoire that is matched to the microbial world into which he or she is born and resides (Rook 2021, 2022). The individualization of this process has important implications for health. For example, purposeful infection with soil-transmitted helminths[2] has shown some efficacy in early-stage trials for treating autoimmune diseases in humans, but later-stage clinical trials have not confirmed these results (Ryan et al. 2020). It may be that the elimination of helminth exposure during childhood in some parts of the world plays a role in the response (or lack thereof) to exposure to helminths later in life to treat autoimmune diseases (Rook et al. 2015).

The hygiene hypothesis, first proposed in the late 1980s based on data showing an inverse correlation between hay fever and the number of older siblings, suggests that reduced exposure to infections and microbes during childhood may contribute to the increasing prevalence of allergic and autoimmune diseases in developed countries (Strachan 1989). The hypothesis, popularized by the media, highlights the paradox that while hygiene is needed to avoid exposure to dangerous pathogens, humans also need exposure to "beneficial" microbes. Rook (2022) suggests a framework for reconciling these conflicting needs, as illustrated in Figure 7-4.

A common interpretation of the hygiene hypothesis is that humans have become "too clean for our own good." Early humans lived in shelters built from natural products that were likely to provide beneficial microbial exposures. In contrast, modern homes are largely built from synthetic products, and bacterial and fungal microbiota frequently invade damp and deteriorating modern homes and can produce infections (Rook and Bloomfield 2021). Therefore, upkeep and cleanliness are important. However, this hygiene must be balanced against the risks of exposure to cleaning agents that may have immunostimulatory properties. Exposure to antigens via sites like the gut, airways, or skin in the presence of toxins, common in cleaning products, activate TH2 immune responses and can result in allergies and autoimmune disease (Akdis 2021; Rook and Bloomfield 2021). Therefore, both building products and household cleaners are likely to influence escalating rates of allergic and autoimmune disease.

Another common misconception is that childhood infections are necessary to "strengthen" the immune system. Today's common infections of childhood are mostly crowd infections that were not present during most of human evolution, and the risks of infection likely outweigh any potential benefits of long-term and nonspecific immunity (Rook and Bloomfield 2021). Moreover, many infections can now largely be replaced by vaccines, which have been shown to have disease-specific benefits and to improve resistance to other infectious agents (Dagenais et al., 2023).

Putative Role for Soils as Influencers of Gut Microbiomes

From animal models, there is evidence that soil biodiversity is interrelated with the mammalian gut microbiome. For example, a study assessing the impact of different lifestyles on the development of mouse gut microbiomes found that mice in contact with soils and dust harbored a gut microbiome with greater diversity and richness (Zhou et al. 2016). While this diversity was not correlated to nutritional performance or overall health, it was found that these mice had lower serum immunoglobulin. Such results indicate that contact with soils could enhance gut microbial diversity and innate immunity, in support of the hygiene hypothesis by way of the gut microbiome and soils. Supporting the stimulatory role of soil biodiversity for gut

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[2] Helminths are worm-like parasites, such as flukes, tapeworms, and roundworms. Hookworm is an example of soil-transmitted helminth for which infection was common in the southern United States until eliminated by a public health campaign the early 20th century. Worldwide, hookworm continues to cause hundreds of millions of infections in humans each year.

microbiome diversity, another study found that gut microbial diversity increased in mice that were in contact with non-sterile soil, while it was unaffected when the mice were in contact with sterile soil (Zhou et al. 2018). The study also showed that non-sterile soils were a key factor influencing the gut microbiota and its effect was comparable to the effect caused by diet, which is recognized to have an impact on human health (see the section "Gut Microbes, Nutrition, and Human Health" below). Given the positive health impacts illustrated by having a more rich and diverse gut microbiome, it is promising but not conclusive that contact with soil and its microbiome could be beneficial for animal health.

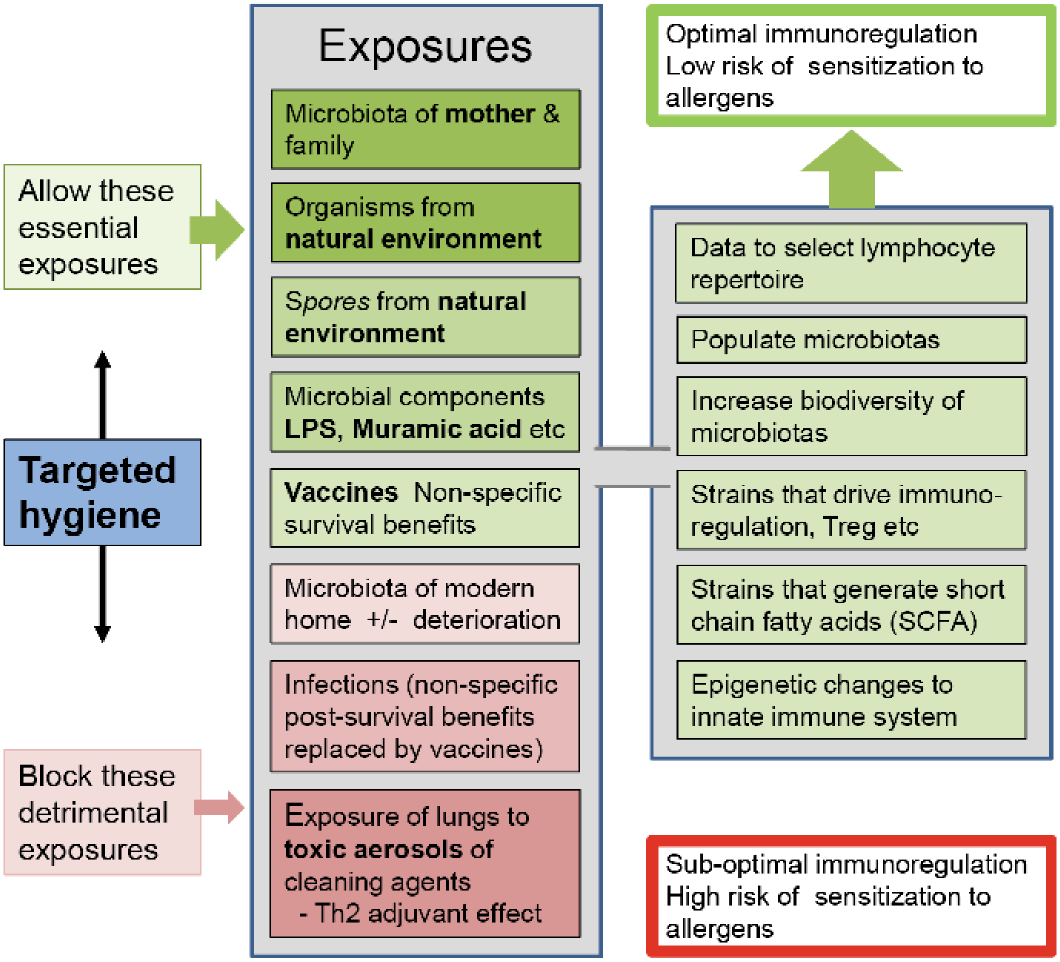

FIGURE 7-4 Essential microbial exposures and nonessential or detrimental exposures.
NOTES: The essential exposures include the microbiota of mothers, family, and the natural environment. Some of the benefits derive from molecular signals rather than colonization. The nonspecific immune system-training benefits of infections (assuming survival) can be replaced by vaccines. Targeted hygiene can maintain the essential exposure while protecting from pathogens.
SOURCE: Used with permission of Springer Nature BV, from "Human Evolution, Microorganisms, Socioeconomic Status and Reconciling Necessary Microbial Exposures with Essential Hygiene," in *Evolution, Biodiversity and a Reassessment of the Hygiene Hypothesis*, Rook, 89, 2022; permission conveyed through Copyright Clearance Center, Inc.

Supporting these findings, a study of baboons collected genetic material on 14 populations in southwest Kenya and examined 13 variables in each population's environment (e.g., soil traits, vegetation) to understand the factors that supported gut microbiome membership and abundance across populations (Grieneisen et al. 2019). Neither host ancestry nor distance between populations were predictors of baboon gut microbial diversity. Instead, the effects from soil (namely geologic history and sodium content) were 15 times stronger than host population in predicting gut microbiome composition and diversity. It is possible that the baboons' gut microbiomes are being colonized through geophagy via consumption of soil microbes with their food. Regardless of the route, the study lends support to soils and their biotic content playing a structuring role in mammalian gut microbiomes. However, the exact mechanism of how soil and the environment more broadly shape the human gut microbiome, and particularly how healthy and degraded soils (and their microbiomes) could differentially affect the gut microbiome, needs further evaluation (Blum et al. 2019; Banerjee and van der Heijden 2023). While poorly resolved today, the relationship between soil health, soil microbiome, gut microbiome, and human health may have relevance for preventive medicine (Blum et al. 2019).

Gut Microbes, Nutrition, and Human Health

The largest concentration of microbes in the human body can be found in the large intestine, with roughly 10^11 microbes per gram of intestinal content (Sender et al. 2016). The gut microbiome is the most widely studied ecosystem in humans. This section focuses on diet as a major mediator of microbiome composition and human health. Primary aspects of nutrient processing by gut microbes involve extraction of calories and nutrients from ingested foods, and production of a vast array of metabolites that can be absorbed by the host with organismal wide benefits far beyond the origin of absorption in the gut. Some examples of microbial products in the gut lumen include amino acids, short-chain fatty acids (SCFA), methylamines, and cometabolites that result from metabolism of human-derived compounds such as bile acids.

Dietary intake can influence gut microbiome composition both in the short and long terms. On the one hand, individual gut microbiomes respond differently to identical meals (Zeevi et al. 2015; Korem et al. 2017; Johnson et al. 2019), while commonalities in dominant taxonomic groups appear with similar dietary patterns, such as vegetarian or omnivore (Wu et al. 2011; Gorvitovskaia et al. 2016; Figure 7-5). Certain dietary components may have a high potential to shape the gut microbiome and human health. For instance, the Fiber and Fermented Foods (FeFiFo) study demonstrated that a diet rich in fermented foods substantially increased microbial richness and decreased inflammatory markers (Wastyk et al. 2021).

Notably, in the same study, the impact of a high-fiber diet depended on individuals' baseline level of fiber consumption, suggesting that the metabolic capacity of the gut microbiota may hinge on its composition before significant dietary changes. The bacteria in fermented foods may have accounted for the benefits observed in the FeFiFo study, which exemplifies how, in addition to nutrients and other compounds, microbes in foods can influence the composition of the gut microbiota. Astonishingly, even a single apple contains approximately 100 million bacterial cells, and the apple's microbial richness can be shaped by agricultural management practices (Wassermann et al. 2019). Recent research highlighted the role of fruits and vegetables as sources of human gut microbial seeding (Wicaksono et al. 2023), revealing that foods can be a key linkage between the environmental microbiome (including the soil microbiome) and the human microbiome. This research underscores the significance of agricultural practices and plant microbial diversity for human health.

Dietary patterns may promote the expansion of taxonomic groups that have the metabolic capacity to process frequently consumed nutrients by (1) making these nutrients more bioavailable, (2) extracting calories from frequently consumed macronutrients, and (3) metabolizing nutrients into compounds with either health-promoting or disease-inducing properties. The latter pathway has been covered in previous sections of this chapter, so here the focus is on the influence of dietary patterns on microbiota composition and the role of gut microbes in human energy metabolism.

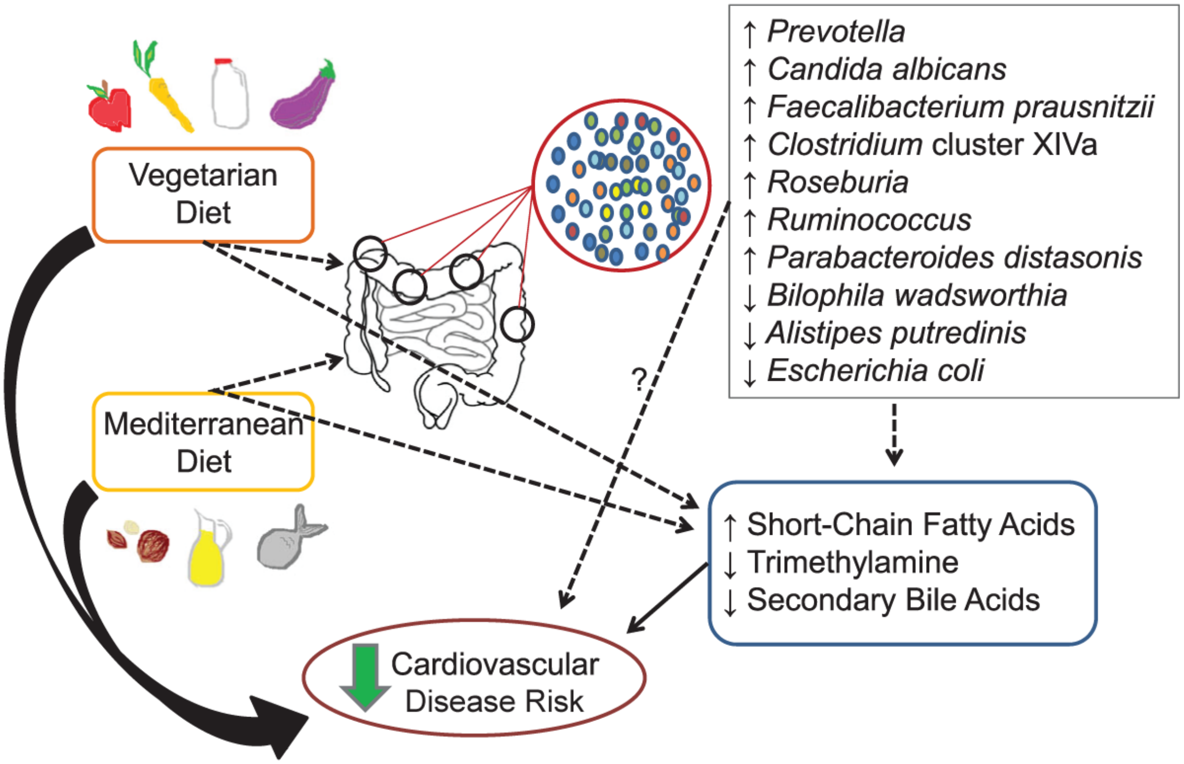

FIGURE 7-5 A schematic of known and proposed interactions between diet and cardiometabolic risk illustrates the known risk-reducing properties of vegetarian and Mediterranean diets on cardiometabolic diseases and the proposed interactions between the vegetarian and Mediterranean diets with the gut microbiome and gut-derived metabolites that can reduce cardiovascular disease risk.
NOTE: The thick, solid-black arrows represent a large pool of evidence to support a pathway; narrow, solid-black arrows represent an intermediate amount of evidence to support a pathway; narrow, dotted black lines represent emerging evidence to support a pathway; and narrow, dotted black lines with a question mark represent other possible mechanistic pathways. Vegetarian and Mediterranean diets can alter the presence or absence of various bacteria and, in turn, also alter the gut metabolome. The direct effect of the gut microbial environment on cardiovascular disease risk is unknown. Vegetarian and Mediterranean diets can also affect the production of gut metabolites by serving as substrate for the resident bacteria.
SOURCE: Tindall et al., 2018. CCBY 4.0.

The involvement of gut microbes in energy metabolism was first observed in animal studies where germ-free rodents gained less weight than their conventional counterparts when consuming the same caloric load. It was later shown that the obese phenotype could be transferred between mice through the microbiome (Turnbaugh et al. 2006; Bäckhed et al. 2007). The same phenomenon was observed when transferring fecal microbial samples from humans with obesity to germ-free mice in a diet-dependent manner (Ridaura et al. 2013). Animal studies have shown that energy metabolism, and in particular glucose and lipid homeostasis, are affected by the gut microbiome (Bäckhed et al. 2004; Caesar et al. 2015). Further, microbes and their metabolites can regulate hunger and satiety signaling as part of the gut-brain axis (Fetissov 2017).

Understanding the mechanisms underlying the regulation of energy metabolism is important in the context of both under- and over-nutrition, which are responsible for the greatest disease burdens around the world. Evidence thus far shows that the potential primary pathways for caloric extraction from macronutrients involve the production of metabolites from nutrient precursors by gut microbes. It has been suggested that the liberation of molecules such as proteins from the constant turnover of the bacterial biomass in the gut lumen contributes to energy extraction (Fetissov 2017). In rodents, modification of dietary fatty acids by gut microbes has been shown to generate lipid intermediates that may modify host lipid profiles (Kishino et al. 2013). Most notably, fiber fermentation yields SCFA such as butyrate, which serves as an energy source for colonocytes (Canfora et al. 2015; T. Chen et al. 2017). These microbially derived SCFA can modulate metabolic and anti-inflammatory pathways in the human host (Canfora et al. 2015; Nogal et al. 2021), but these mechanisms are not yet fully understood. The connections between fiber, the gut microbiome, and human health have been extensively reviewed elsewhere (Martens 2016; Holscher 2017; Sawicki et al. 2017).

Americans are far from aligning their diets with dietary guidelines and, in particular, from reaching daily dietary fiber recommendations (King et al. 2012). Intakes are especially low among low-income households and marginalized groups (McAnulty et al. 2017). Diets low in fiber, as seen, for example, in populations migrating to the United States, have been associated with low richness and diversity of gut microbiomes (Deehan and Walter 2016). Dietary patterns rich in fiber have been connected to multiple gastrointestinal and cardiometabolic health benefits (Anderson et al. 2009; Sawicki et al. 2017; McKeown et al. 2020). Strategies to promote fiber consumption are therefore urgently needed to promote human health.

CONCLUSIONS

The evidence strongly suggests that microorganisms create a link between the health of soils and the health of humans, but the processes by which microbiomes are established and influenced across these systems are still unexplored. The similarities and dissimilarities between soil and human microbiome composition and function need to be studied in detail while considering the environmental conditions and other contextual factors that may account for the lack of research reproducibility thus far. The committee proposes that attention be paid to the following areas.

Robust Sampling

Microbiome functional or compositional information could serve as early indicators of health. However, all microbiome indicators from biomass to gene expression traits lack universal standards, as these metrics are often context specific or relative to other samples and do not have universal cut-offs for what constitutes health responses. Moreover, it is uncertain how microbiome-derived indicators maintain their signals or diagnostic capabilities over time and changing external landscapes. Fortunately, microbiome sampling is becoming more cost-effective and efficiency in data processing is improving, enabling researchers to address the microbiome heterogeneity across relevant experimentally defined spatiotemporal scales, which offers a better understanding of the variation in microbiomes in both untreated and response to different treatments and health gradients. This knowledge combined with statistical approaches and a priori data exploration (both in sequencing depth and numbers of samples) can support funding for microbiome experiments designed with appropriate rigor for indicator discovery (Calgaro et al. 2020). These higher-dimensionality sampled microbiome data, combined with better reuse of existing data across studies, are needed to build more robust artificial learning models to discover microbiome indicators of health, uncovering local drivers and microbiome-enabled responsive indicators across axes of variation.

Recommendation 7-1: Researchers must incorporate sufficient rigor in the sampling design to capture the spatial and temporal heterogeneity of the microbiome to reveal responsive indicators of health.

Recommendation 7-2: Researchers should enhance universal methodologies (sampling, documentation) for microbiome analysis across different sample materials.

Data Tools and Data Management

It is posited that the next frontier in microbiome science lies in understanding the phenotype of a microbiome, the product of the combined genetic potential of the microbiome and available resources (Jansson and Hofmockel 2018). In microbiome science, linkages between phenotype and genotype are hindered by an inability to obtain most microorganisms in pure culture. Culture-independent multi-omic sequencing technologies, like those outlined in Figure 7-3, have the capacity to infer phenotypic features that would be otherwise difficult or time-consuming to assess experimentally. Inferring phenotype is considered one of the holy grails of biological research, as this knowledge can enhance predictive outcomes and provide targeted biotechnological applications in soil and human health realms. In fact, the integration of large-scale datasets with systematic meta-analysis has revolutionized biology, particularly in areas like translational research (Winkler et al. 2014). The ability to access and share well-annotated data collections allows for more robust genome-wide association studies and the application of machine-learning techniques. These advancements underscore the importance of open data and standardized methods. Here, the collation of dozens of studies equates to the analysis of hundreds of thousands of experimental assays without lifting a pipette. Now, microbiome research is poised to leverage data sharing and reproduction for similar translational value to phenotypic exploration (Huttenhower et al. 2023).

To this end, the genomic repertoire of soil and human communities is ever more tractable today, spurred by federally enabled efforts like the HMP and the Genomic Encyclopedia of *Bacteria* and *Archaea* project, but also by research collectives like the Earth Microbiome Project and independently generated genomic compendiums (Almeida et al. 2021) that each generated hundreds of thousands of genomes from diverse sources. With the establishment of these massive sequencing catalogs, it is evident that a large portion of the species and functional diversity within human and soil microbiomes remain uncharacterized (Almeida et al. 2021). Thus, research efforts to experimentally characterize and computationally improve annotation of genomic content are urgently needed for accurate phenotypic extrapolations. Likewise, data management practices guided by FAIR (findable, accessible, interoperable, and reusable) principles are conduits for data reuse and mining, enabling further knowledge discovery and innovation. Incentivization by funding agencies and scholarly publishers for additional data that facilitates reuse—such as on environmental or land use properties for soil sequences or population characteristics for human sequences—will extend the collective value of these data collections beyond journal pages. As was true in 2007 when the first metagenomic report from the National Academies was published (NRC 2007), funding sources that create and enable appropriate data management resources are needed.

The committee recognizes data management in microbiology presents a multifaceted challenge, particularly when it comes to the collection and maintenance of metadata. While funding for research endeavors is crucial, it is often overlooked that explicit allocation for metadata collection is essential for comprehensive data management. However, the process of gathering robust metadata is far from simple. Balancing the need for robust metadata against the practical limitations of available resources is a persistent issue. Without adequate support, the quality and depth of metadata suffer, undermining the integrity and utility of research findings. It is a dilemma that requires careful consideration and realistic solutions, as simply expecting exhaustive metadata without appropriate funding is unrealistic and unsustainable within existing grant structures. With increasing awareness in these directions, microbiome-based data sciences and applications can transition from a discipline of description to one that delivers more novel and surprising technologies.

> **Recommendation 7-3: Federal funders should require that resources to ensure metadata as well as data on environmental and ecosystem properties or population characteristics be included, properly stored, and reusable, as accessible data are necessary but not enough.**

Diagnostics

New analytical and conceptual approaches will likely be developed that capture microbiome-based systems characteristic of health in both soils and humans. These advances will operationalize both the monitoring of health but also further understanding of how microbiomes influence the stability and functioning of ecosystems and how these underlying properties scale to provide qualities of health or wellness. More efficient measurements of microbiome content with chemical constituents, which could be enhanced by precision or digital agricultural infrastructures and more thorough assessment of human ecosystems along time and special dimensions, are avenues that will be leveraged for quantifying microbiome diagnostics of health. A goal would be to move from correlation to predictive outcomes.

> **Recommendation 7-4: Funding agencies should support discovery of scalable diagnostics, with the goal that affordable, rapid assays will be developed for use on soil microbiomes in the field and with diverse human populations.**

Recommendation 7-5: Funding agencies should support research designed to investigate causal relationships in soil and human microbiomes, toward the development of microbial therapeutics.

Interdisciplinary Research

Microbial ecosystems are an important link in the continuum of soil health and human health. There are a variety of direct (e.g., exposure to dust and contaminants) and indirect (e.g., quality of crops and bioavailability of nutrients) pathways from soil to human health that are deeply affected by microbial composition and function. However, the evidence thus far is mostly correlational and needs validation and replication. With the ever-increasing challenges posed by human activities and climate change, it is imperative to further unveil the mechanistic links underlying microbiota composition and function, soil health, and human health. Furthermore, parallel processes whereby microbiome function influences soil, plant, and animal health should be leveraged in the development of strategies to mitigate emerging challenges to the health of these systems. As was noted in the 2007 National Academies report on metagenomics (NRC 2007), overcoming such challenges will require a systems approach across and within disciplines, supported by multiple funding agencies, to explore the existence of the microbiome continuum spanning soils to human health.

Recommendation 7-6: Funding agencies should support microbiome research within disciplines (e.g., community ecology, soil ecology, and soil biogeochemistry or microbiology and medicine) to integrate methodologies to bring together composition and functional assessments of microbiomes.

Recommendation 7-7: Funding agencies should support microbiome research among disciplines (e.g., agronomy, plant science, soil ecology, microbiology, immunology, human nutrition, medicine, engineering) to explore the connectivity of the microbiome across systems (e.g., soil, plants, and humans).

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8
Going Forward

Viewed simply as a medium for growing food, soil in the United States has and will continue to contribute to the production of abundant food because of the expanse of agricultural land and the availability of nutrient, pest management, and water inputs. This prediction is agnostic to the associated costs, monetary or environmental, that such a view may entail. Food prices may be higher in the future if the cost of inputs rise or if the same unit of input or unit of land is less effective or productive in the future due to soil degradation. Food may also be more expensive if the amount of agricultural land declines because of conversion to other land uses or because its productivity is lost to changes in climate. Water bodies may be further degraded from sedimentation and excess nutrients, adversely affecting aquatic life, drinking water, and recreational activities. Aquifers may be depleted, and soil biodiversity may be lost. Nevertheless, given the size of the country, the United States will continue to produce a substantial amount of food.

If soil is instead viewed as a living system that supports not only food production but also clean water and air, contaminant degradation, and climate regulation and that serves as a reservoir of genetic resources yet to be discovered, then the rationale for considering soil as simply a medium is not only weak but misguided. The concept of One Health posits that soil should be valued as an ecosystem that, when healthy, contributes to the health of other ecosystems, plants, humans, and other animals and that contains a microbiome that not only connects to plants but likely to people as well. Therefore, the way soil is tended to must be altered from that of a widget in a production system to that of a component in a holistic system that includes but extends far beyond agriculture.

This latter view requires a shift in approach not only for common agricultural management practices but for land management in general. As this report recommends, a greater awareness of the importance of soil health to all citizens, not just those involved in agriculture, will be needed. Those responsible for land management will have to prioritize the preservation of soil habitat and biodiversity, the increase of organic matter content where possible, and the optimization of nutrient use, including waste products. Such priorities will likely entail an increase in the complexity of management systems, for which a diverse set of tools needs to be available. Some tools exist, such as cover or perennial crops, but have not received the research investment needed to demonstrate their effectiveness and to make their adoption attractive in all environments. Other tools, such as soil sensors and biochar, are not yet widely affordable, user-friendly options for maximizing the efficient use of resources with minimal environmental trade-offs. The benefits that may come from better evidence of microbiome connectivity between soils and humans require adequate funding, standardized approaches, and infrastructure development for researchers to collect, share, and analyze data across microbiomes. The development and deployment of all these tools would be advanced by collaboration within and across disciplines, whether in the field or in the laboratory.

MONITORING AND MANAGING DATA

Preservation of soil biodiversity would ideally be accompanied with ways not only to account for what is in the soil but also to identify function. In the case of microorganisms, function would include that of the species as well as the community. Understanding function would open possibilities for manipulating and enhancing soil health, soil-derived nature's contributions to people, and ultimately human health.

Tools for monitoring soil physical and chemical properties, soil microbial communities and their activity, and the soil processes influencing local to global scale biogeochemical cycles exist or are in development. Support from the U.S. Department of Agriculture and other funding agencies to develop and deploy these technologies at price-points that are feasible for researchers and producers to use will advance understanding of regulating ecosystem services, which can in turn inform management practices that promote such services. Similarly, efforts to map high-risk areas for chemical contamination can inform decisions about how to mitigate the bioavailability and bioaccessibility of contaminants in crops grown in those locations or whether crops should be grown at all.

Investing in data collection is not enough. To make the most use of these data, a data management system is needed that is accessible and catalogued with metadata for other researchers to query. Systematic, repeated monitoring efforts that are stored properly will eventually enable comparisons of management practices, climate conditions, and other environmental variables on soil health and ecosystem services.

Microbiome researchers have similar needs. Given the potential that microbiomes have in modulating soil, plant, and human health, adequate infrastructure is needed to store and make use of microbiome data from all these systems. Such data infrastructure would enable predictive understanding of these microbiomes and facilitate exploration of the existence of microbiome continuum spanning soils to human health. The achievement of these objectives would be greatly assisted by an improvement in the rigor of sampling designs to capture the heterogeneity of microbiomes, enhanced universal methodologies for microbiome analysis, and funding to support the metadata information and infrastructure necessary for microbiome scientists to access data, regardless of field.

FROM WASTES TO RESOURCES

Soil is a natural vehicle for recycling wastes, including animal excreta and food waste, into nutrients that support plant growth. There is no lack of underutilized material available today that can be used as soil organic amendments for agricultural soils, whether it be manure, food waste, or human excreta. The issue is that many of these waste streams may contain levels of heavy metals, plastics, PFAS, and other contaminants that adversely affect soil physical, chemical, and biological properties and can harm human health through food consumption and have detrimental effects on other soil-derived Nature's Contributions to People.

Additionally, the replacement of animal waste with excessive use of synthetic fertilizer as the primary source of nutrients—though beneficial for crop yields—has led to nitrogen pollution that harms aquatic life, contaminates drinking water, and contributes to global warming. The production and use of synthetic fertilizers are also associated with high levels of energy consumption and greenhouse gas production.

The committee is not suggesting the abandonment of synthetic fertilizer. As discussed in Chapter 4, when applied at appropriate levels, synthetic fertilizers can increase microbial biomass and soil organic matter through the promotion of plant growth and rhizodeposition. Nor is it proposing to abandon the use of waste material as organic amendments because of contamination concerns; landfilling all waste presents its own environmental problems. What is needed is investment in technologies that can facilitate the use of organic amendments to substitute for some of the use of synthetic fertilizers in crop production. Such technologies would provide producers with better information about the nutrient and carbon content of the organic amendments they are applying as well as remove contaminants in the amendments below a threshold of concern. Investment in the affordable production of biochar would be one option to pursue to help address contaminants that are particularly persistent, such as PFAS. Additionally, if safely managed and appropriately processed (e.g., through thermochemical transformation), soil organic amendments can be used to remediate soil contamination (e.g., heavy metals and perhaps PFAS) while improving soil health. Combined with precision agriculture technologies to improve the targeted use of nitrogen (whether in the form of synthetic fertilizer or organic amendments), these efforts for waste reuse would increase soil organic matter content and mitigate pressure on planetary boundaries for chemical contaminants and nitrogen flows.

COMPLEXITY AND COLLABORATION

Many benefits can be achieved by incorporating cover crops, perennial crops, or crops bred specifically for root system development or rhizosphere interactions with soil biota into planting rotations. By promoting root biomass, these approaches increase belowground biomass, which can reduce erosion, mitigate nitrogen pollution, and increase organic matter content. More research and development will be needed to make these crops viable choices in the diverse soils and climates of the United States. On-farm research that involves scientists, producers, and industry will help identify crops that work in all field conditions. Similarly, collaborative research approaches can be used to assess which biostimulants (under what conditions) promote soil health, nutrient uptake, or yield and how they interact with indigenous soil microbiomes. Practices that seek to replace tillage or herbicides as weed management strategies would also garner the best results when conducted as real-world field trials so they can be tailored to specific climate, soil, and crop parameters.

Shifting to an approach in agriculture that places a high level of emphasis on soil health, at times at the expense of yield maximization, is not a small undertaking and should not be placed solely on the backs of producers. Producers are parts of systems, too, which often involve leases, subsidies, loans, and insurance policies that constrain choices. Prioritizing soil health will require incentives for producers, and land managers more generally, to transition to more complex systems and economic structures that recognize the value of soil health in underpinning system resilience.

Translational research that identifies how different agricultural management practices, environmental conditions, and food-processing techniques influence the nutrient and bioactive density of food crops is also fraught with complexity. While it may be difficult to tease out the degree to which each variable affects nutrient and health-beneficial bioactive density, collaborative research across disciplines and with industry can support the breeding of crops and the development of food-processing technologies that enhance the profile of desirable nutrients and bioactive compounds without sacrificing consumer acceptability.

Support for collaboration is also needed to advance microbiome science. Within disciplines, research funding across different areas of soil science, for example, would help to integrate methodologies for composition and functional assessments of soil microbiomes. Across disciplines, supporting collaboration among researchers from different fields would advance what is known about the connectivity of soil, plant, and human microbiomes.

Bringing together the report's recommendations in order to leverage data, reduce and reuse waste streams, increase complexity in agricultural systems, and promote collaboration across disciplines will improve soil health and advance microbiome science, both of which will contribute positively to human health. These pursuits will also help address additional grand and interwoven challenges, namely, climate change, food security, and environmental contamination. Although investment in research and practices that improve soil health and advance microbiome science will not solve these grand challenges singlehandedly, it will expand options to reduce agricultural contributions to global warming, sequester carbon, and degrade contaminants while producing food more sustainably. Furthermore, pursuing the recommendations in this report will fill many knowledge gaps in the soil and microbiome sciences, such as the mechanistic links underlying microbiota composition and function, soil health, and human health and how to interrogate data across microbiomes. It will identify means by which trade-offs between food production and other benefits that people derive from soils can be quantified and minimized and answer questions about the effects of agricultural management practices on the nutrient and phytochemical density of crops. Finally, it will bolster what should be evident: that through myriad direct and indirect linkages, healthier soil contributes to healthier people.

Appendix A
Committee Member Biographical Sketches

Diana H. Wall *(Chair)* was the inaugural director of the School of Global Environmental Sustainability at Colorado State University. To understand the importance of soil biodiversity, she worked at the physical limits to life in the Antarctic dry valleys where climate change effects are amplified and species diversity is much reduced compared to other soil ecosystems. Her interdisciplinary research uncovered dramatic impacts to invertebrate communities in response to climate change, the key role nematode species play in soil carbon turnover, and how they survive such extreme environments. Wall was the science chair of the Global Soil Biodiversity Initiative and had previously served as president of the Ecological Society of America (ESA), the American Institute of Biological Sciences, and the Society of Nematologists (SON). She received the 2017 Eminent Ecologist award from the ESA, the 2016 Honorary Member award from the British Ecological Society, the 2015 Ulysses medal from University College Dublin, the 2012 Scientific Committee on Antarctic Research President’s Medal for Excellence in Antarctic Research, and the 2013 Soil Science Society of America Presidential award. Wall Valley, Antarctica, was named in 2004 to recognize her research. She was a fellow of the ESA and the SON and held an honorary doctorate from Utrecht University, The Netherlands. She was an elected member of the National Academy of Sciences and the American Academy of Arts and Sciences and the 2013 Laureate of the Tyler Prize for Environmental Achievement. Wall received a B.A. in biology and a Ph.D. in plant pathology from the University of Kentucky, Lexington.

Katrina Abuabara is a physician and epidemiologist at the University of California (UC), where she holds a joint appointment at UC San Francisco, UC Berkeley’s School of Public Health, and the joint program in Computational Precision Health. She has expertise in studying environmental influences on allergic and inflammatory conditions, including the role of soil microbes on human health. Abuabara is a member of the American Academy of Dermatology, the American Medical Association, the Society for Investigative Dermatology, and the International Eczema Council. She was a Fulbright scholar, was named the 2019 American Academy of Dermatology Young Investigator of the year, and is a recipient of the National Academy of Medicine’s Healthy Longevity Global Grand Challenge. Abuabara received a B.A. in human biology and an M.A. in sociology from Stanford University, an M.D. from Harvard Medical School, and received an M.S. in clinical epidemiology and completed her residency at the University of Pennsylvania.

Joseph Awika is a professor and head of the Food Science & Technology Department at Texas A&M University. Prior to joining Texas A&M in 2008, he worked on faculty at the University of Missouri, Colombia, and Arkansas State University. Awika’s research focuses on examining how the chemical structure and properties of plant-derived bioactive food constituents affect food attributes relevant to human health, with the goal of maximizing the ability of foods to prevent chronic disease. Specific areas of interest include structure-function properties of flavonoids; interactions of polyphenols with carbohydrates and proteins and consequences on polymer function and food quality; factors affecting bioavailability and metabolism of polyphenols from a complex food matrix; and technologies to harness polyphenols to improve sensory, nutritional, and health quality of foods. His international program focuses on technological innovations to address food insecurity globally. Awika is a 2018−2019 Fulbright Faculty Fellow and the recipient of the 2021 Institute of Food Technologists International Food Security Award. Awika received a B.S. in dairy science and technology from Egerton University, Kenya, and a Ph.D. in food science and technology from Texas A&M University.

Samiran Banerjee is an assistant professor in the Department of Microbiological Sciences at North Dakota State University. Previously, he held research positions at the Commonwealth Scientific and Industrial Research Organization in Australia and Agroscope in Switzerland. He is a soil microbiologist with expertise in -omics and machine-learning approaches, and experience in ecology and soil-plant-microbe interactions. His research utilizes a combination of high-throughput sequencing, synthetic biology, and advanced statistical approaches to understand the rules that govern the microbiome assembly and microbe-microbe interactions. He also examines microbiome recruitment into the rhizosphere and roots, and how various abiotic and biotic factors alter the structure and functions of plant and soil microbiomes. He serves as a reviewer for several federal and international funding agencies, including the U.S. Department of Agriculture, National Science Foundation, and Genome Canada. He is an editorial board member of Journal of Agriculture and Environment, and a member of Soil Science Society of America, American Society for Microbiology, and Ecological Society of America. Banerjee received a bachelor's degree and master's degree in botany from University of Calcuttta, India, an M.Sc. degree in plant and soil sciences from the University of Aberdeen, United Kingdom, and a Ph.D. in soil science from the University of Saskatchewan, Canada.

Nicholas T. Basta is a professor of soil and environmental chemistry in the School of Environment and Natural Resources and co-director of the Environmental Science Graduate Program at Ohio State University. His research program is focused on environmental chemistry, bioavailability, soil health, and environmental fate and remediation of contaminants in soil, with emphasis on human, agronomic, and ecosystem contaminant pathways. Basta is an active member of several international scientific organizations, including the U.S. National Committee for the International Union of Soil Science, the International Conference for Trace Element Biogeochemistry, the International Society for Trace Element Biogeochemistry, and the Society of Environmental Toxicology and Chemistry Global Contaminated Soil Advisory Group. He has served on several editorial boards including *Soil and Environmental Health* and *Soil Systems*. He is a fellow of the Soil Science Society of America and the American Society of Agronomy. Basta received a B.S. in chemistry from Pennsylvania State University and an M.S. in soil science and a Ph.D. in soil chemistry from Iowa State University.

Sarah M. Collier is an assistant professor in the Food Systems, Nutrition, and Health Program and the Department of Environmental and Occupational Health Sciences at the University of Washington's School of Public Health. She previously served as the director of programs at Tilth Alliance, a non-profit food and agricultural organization serving the Pacific Northwest. Collier's work focuses on the intersection of agriculture and society, applying a systems approach to examining the complexities, interrelationships, co-benefits, and trade-offs that make balancing human and environmental health in the context of food systems both challenging and essential. Her areas of expertise include soil health and management, climate-smart agriculture, food system sustainability and resilience, and plant-microbe interactions. Collier received a B.Sc. in botany from the University of Washington, a Ph.D. in plant breeding from Cornell University and completed postdoctoral training on agricultural system sustainability at the University of Wisconsin, Madison.

Maria Carlota Dao is an assistant professor of human nutrition in the Department of Agriculture, Nutrition, and Food Systems at the University of New Hampshire. Previously, she was a Scientist III at the U.S. Department of Agriculture Jean Mayer Human Nutrition Research Center on Aging at Tufts University. As an interdisciplinary scientist, Dao studies the crosstalk between nutrition, the gut microbiome, and human health, focusing on populations at risk for food insecurity, obesity, and chronic disease. She also considers social and environmental barriers to nutrition and opportunities for the promotion of a nutritious food supply. She is a scholar of the National Heart, Lung, and Blood Institute Programs to Increase Diversity Among Individuals Engaged in Health-Related Research in Obesity Health Disparities, and the National Institute on Minority Health and Health Disparities Health Disparities Research Institute. She has received research support from the National Institute of Food and Agriculture through the New Hampshire Agricultural Experiment Station. Dao received a B.A. in biochemistry and molecular biology from Boston University and an M.S. and Ph.D. in biochemical and molecular nutrition from Tufts University. She also completed a Postdoctoral Fellowship at the Sorbonne University/National Institute of Health and Medical Research (INSERM) in France.

Michael A. Grusak is a U.S. Department of Agriculture (USDA) Agricultural Research Service scientist, the center director of the Edward T. Schafer Agricultural Research Center in Fargo, North Dakota, and an emeritus professor of pediatrics at Baylor College of Medicine. He currently leads a program consisting of five research units whose scientists conduct research focused on crop plants, insects, food safety, and food quality. The center's broad mission is to solve problems that will help farmers produce a safe, nutritious, and sustainable food supply. Grusak's personal research involves understanding ways to enhance the nutritional quality of plant foods for human or animal consumption; he studies how mineral nutrients are acquired from soil and transported throughout plants to edible tissues and works with breeders to translate this fundamental knowledge into strategies for developing nutritionally enhanced food crops. His group also has contributed to clinical investigations to study nutrient bioavailability from plant foods in humans. In 2016, he served as president of the Crop Science Society of America and was the 2022–2023 chair of the Council of Scientific Society Presidents. Grusak received a Ph.D. in botany from the University of California, Davis.

Kalmia (Kali) E. Kniel is a professor in the Department of Animal and Food Sciences at the University of Delaware (UD). Her research includes understanding mechanisms of environmental persistence by bacteria, protozoa, and viruses in pre-harvest agricultural environments. Kniel serves as the co-chair of the One Health Unique Strength Program and directs the Center for Environmental and Wastewater Epidemiological Research. In 2015, she was awarded the UD Outstanding Teaching and Advising Award and the Elmer Marth Outstanding Educator award by the International Association for Food Protection (IAFP). In 2020, she was awarded the UD Outstanding Researcher Award and in 2022, she was awarded the IAFP Maurice Weber Laboratorian Award for distinguished laboratory contributions. Kniel is active with Institute of Food Technologists, American Society for Microbiology, and IAFP, where she was elected to the board in 2015 and served as IAFP president in 2020. Kniel received a B.S. in biology, an M.S. in molecular cell biology, and a Ph.D. in food science and technology from Virginia Polytechnic Institute and State University.

Ylva Lekberg is an adjunct research professor in the Department of Ecosystem and Conservation Sciences at the University of Montana. She also works at a privately funded research and conservation organization located in the Bitterroot Valley in Montana. Lekberg is a soil ecologist, and most of her research has focused on how plant-microbial interactions and soil ecosystem processes are impacted by agricultural management practices, change along natural environmental gradients, and are affected by plant invasions. She received the PennState Alumni Dissertation Award for her research on subsistence agriculture in Sub-Saharan Africa, and a Marie Curie Fellowship to explore mycorrhizal associations in coastal grasslands in Denmark. She is a member of the Ecological Society of America and the International Mycorrhiza Society. Lekberg received an M.S. in ecology and horticulture from the Swedish Agricultural University and a Ph.D. in ecology from the Pennsylvania State University.

Rebecca J. Nelson is a professor in the School of Integrative Plant Science (SIPS) and the Department of Global Development at Cornell University. She currently serves as SIPS' associate director for research; from 2000 to 2021, she served as scientific director for The McKnight Foundation's Collaborative Crop Research Program. Prior to joining the Cornell faculty, Rebecca spent five years at the International Potato Center in Peru (1996 to 2001) and eight years at the International Rice Research Institute in the Philippines (1988 to 1996). Nelson's research group works on bionutrient circularity, with a focus on resource recovery from sanitation to agriculture, as well as and on plant disease resistance and mycotoxin management in the United States, Africa, and India. At Cornell, Nelson co-leads the CE@CU initiative (circular economy at Cornell University). She is a founding member of the Soil Factory Network, an international collaborative that advances the circular bionutrient economy through art, science, prototyping, and community engagement. Nelson received a B.A. in biology from Swarthmore College and a Ph.D. in zoology from the University of Washington.

Kate Scow is a distinguished professor emerita of soil science and microbial ecology in the Department of Land, Air and Water Resources at the University of California (UC), Davis. She was director of the UC Kearney Foundation of Soil Science (2001–2006) and a visiting professor at the State University of Maringa, Parana, Brazil (2015–2018). Scow's research investigates soil microbial biodiversity and processes in agroecosystems, particularly with respect to biogeochemical cycling, carbon sequestration, and disease suppression. Her team's research into the effects of contaminants on indigenous microbial communities and their roles in bioremediation of polluted ecosystems led to development of cost-effective treatment systems for petroleum-contaminated groundwater. Scow collaborated with eastern African partners, conducting research on soil health, horticulture, and small-scale irrigation systems. She is a member of the National Academy of Sciences and the National Academy of Engineering and a Fellow of the Soil Science Society of America. Scow received a B.S. in biology from Antioch College and an M.S. and Ph.D. in soil science (agronomy) from Cornell University.

Ann C. Skulas-Ray is an assistant professor in the School of Nutritional Sciences and Wellness at the University of Arizona. Her research focuses on identifying and refining nutritional strategies for reducing chronic inflammation and cardiovascular disease risk. She specializes in human subjects intervention studies that investigate effects of omega-3 fatty acids and plant bioactives on lipids/lipoproteins, inflammation, insulin resistance, oxidative stress, brachial and central blood pressure, indices of arterial stiffness, and other cardiovascular disease risk factors. Skulas-Ray received a Ph.D. in nutrition from the Pennsylvania State University.

Lindsey C. Slaughter is an associate professor of soil microbial ecology and biochemistry in the Department of Plant and Soil Science at Texas Tech University. Her lab conducts research that investigates fundamental relationships between plants and soil microbes and how these contribute to ecosystem functioning and response to land management. Her research ultimately seeks to help reverse soil degradation and create resilient, climate-smart agricultural systems through enhanced biological networks and plant-soil interactions, particularly in semi-arid environments. Slaughter currently serves as an associate editor for the Soil Biology and Biochemistry division of the *Soil Science Society of America* Journal and was recently selected as a 2022 Outstanding Associate Editor for the journal. Slaughter received a B.S. in natural resource management from the University of Tennessee at Martin, an M.S. in plant and soil science and a Ph.D. in soil science from the University of Kentucky. Slaughter currently serves as a technical specialist for soil health in the U.S. High Plains Region with the Soil Health Institute.

Kelly Wrighton is a professor at Colorado State University, where her laboratory uses genomic technologies to uncover how microorganisms control the chemical world in, on, and around us. Her laboratory research is ecosystem agnostic, as every environment offers new perspectives on the factors that control the chemical transformations microorganisms catalyze. Current focus areas include soil microbiomes in agriculture and wetland soils and modulating greenhouse gasses from these systems. Broadly the Wrighton laboratory is interested in using microorganisms to sustain human, livestock, and soil health, while controlling carbon and nitrogen loss from these systems. Beyond these areas, Wrighton has a research history that includes harnessing microbial metabolism for biodegradation, biofuels, and in the energy sector. Wrighton was awarded the Presidential Early Career Award for Scientist and Engineers in 2020 , is a named Fellow of the American Geophysical Union, and has earned awards from the International Society of Microbial Ecology and International Geobiology Society for her team’s scientific contributions. She was recently awarded the Bishop Endowed Chair at Colorado State University. Wrighton received a B.S. and an M.S. in microbiology from California Polytechnic State University, San Luis Obispo, and a Ph.D. in plant and microbiology from the University of California, Berkeley. She serves on the science advisory boards of the Department of Energy Systems Biology Knowledgebase and Pluton Biosciences and previously served on the User Executive Committee for the Department of Energy’s Joint Genome Institute.

Appendix B
Public Meeting Agendas

Information-gathering sessions include in-person public meetings and webinars held by the committee from April 2023 to October 2023. They are listed in chronological order. The locations of the in-person meetings are provided. Presentations that were made via the Internet at the in-person public meetings are noted.

APRIL 12, 2023

The first public meeting of the Committee on Exploring Linkages Between Soil Health and Human Health was held virtually.

Open Session Agenda
April 12, 2023
2:30 p.m. – 4:30 p.m.

2:30 **Welcome and Introductions**
Diana H. Wall, *Committee Chair, National Academies of Sciences, Engineering, and Medicine*
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

2:50 **Sponsor Perspectives on Study Statement of Task**
Kevin Kephart, *Deputy Director, Institute of Bioenergy, Climate, and Environment, USDA National Institute of Food and Agriculture*
Sandeep Kumar, *National Program Leader, USDA National Institute of Food and Agriculture*
Suzanne Stluka, *Deputy Director, Institute of Food Safety and Nutrition, USDA National Institute of Food and Agriculture*

3:00 **Discussion with Committee**

4:30 **Adjourn Open Session**

APRIL 20, 2023

The second public meeting of the Committee on Exploring Linkages Between Soil Health and Human Health was held in-person.

The Keck Center, 500 Fifth Street, NW
Washington, DC 20001

Open Session Agenda
April 20, 2023
1:00 p.m. – 3:30 p.m.

1:00 **Welcome and Introductions**

Diana H. Wall, *Committee Chair, National Academies of Sciences, Engineering, and Medicine*
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

1:30 **Invited presentations**
Megan O'Rouke, *Brookings Congressional Fellow, Office of Representative Chellie Pingree*
Charles W. Rice, *University Distinguished Professor, Kansas State University*
C. Wayne Honeycutt, *President and CEO, Soil Health Institute (remote)*
Moul Dey, Professor, *South Dakota State University (remote)*

3:00 **Speaker discussion with the committee**

3:30 **Adjourn Open Session**

MAY 16, 2023

The third public meeting of the Committee on Exploring Linkages Between Soil Health and Human Health was held virtually.

Open Session Agenda
May 16, 2023
3:00 p.m. – 5:00 p.m.

3:00 **Welcome and Introductions**
Diana H. Wall, *Committee Chair, National Academies of Sciences, Engineering, and Medicine*
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

3:20 **Invited Presentations**
Jamie DeWitt, *East Carolina University: Human health effects of PFAS exposure*
Linda Lee, *Purdue University: Fate of biosolids borne-PFAS after land application*
Jonathan O. (Josh) Sharp, *Colorado School of Mines: Insights from trace organic attenuation toward forever chemicals*

4:35 **Speaker discussion with the committee**

5:00 **Adjourn Open Session**

JUNE 13, 2023

The fourth public meeting of the Committee on Exploring Linkages Between Soil Health and Human Health was held virtually.

Open Session Agenda
June 13, 2023
3:00 p.m. – 4:45 p.m.

3:00 **Welcome and Introductions**
Diana H. Wall, *Committee Chair, National Academies of Sciences, Engineering, and Medicine*

Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

3:20 **Invited Presentations**
Harsh Bais, *Professor of Plant Biology, University of Delaware*
Jude Maul, *Research Ecologist, Sustainable Agricultural Systems Lab, USDA Agricultural Research Service*

4:10 **Speaker discussion with the committee**

4:45 **Adjourn Open Session**

JUNE 22, 2023

The fifth public meeting of the Committee on Exploring Linkages Between Soil Health and Human Health was held in-person.

The Keck Center, 500 Fifth Street, NW
Washington, DC 20001

Open Session Agenda
June 22, 2023
1:00 p.m. – 4:30 p.m.

1:00 **Welcome and Introductions**
Diana H. Wall, *Committee Chair, National Academies of Sciences, Engineering, and Medicine*
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

1:30 **Invited presentations**
Tim Griffin, *Professor in Nutrition, Agriculture, and Sustainable Food Systems, Friedman School of Nutrition Science and Policy, Tufts University*
Kelly Wrighton, *Associate Professor, Colorado State University*

2:30 **Break**

2:45 **Invited Presentations**
Nhu Nguyen, *Associate Professor, University of Hawai'i at Mānoa*
Amanda Ashworth, *Research Soil Scientist, USDA Agricultural Research Service (remote)*

3:45 **Speaker discussion with the committee**

4:30 **Adjourn Open Session**

JUNE 29, 2023

The sixth public meeting of the Committee on Exploring Linkages Between Soil Health and Human Health was held virtually.

Open Session Agenda
June 29, 2023
11:00 a.m. – 1:00 p.m.

11:00 **Welcome and Introductions**
Diana H. Wall, *Committee Chair, National Academies of Sciences, Engineering, and Medicine*
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

11:20 **Invited Presentations**
Matthias Rillig, *Director, Berlin-Brandenburg Institute of Advanced Biodiversity Research, and Professor of Plant Ecology, Freie Universität Berlin: The effects of microplastics on agricultural soils*
Erlend Sørmo, *Senior Advisor, Norwegian Geotechnical Institute: Forever no more? The role of pyrolysis in combatting PFAS*
Marcel van der Heijden, *Professor, Department of Plant and Microbial Biology, University of Zürich: Impact of pesticides on soil microbial communities and soil functioning*

12:35 **Speaker discussion with the committee**

1:00 **Adjourn Open Session**

JULY 10, 2023

The seventh public meeting of the Committee on Exploring Linkages Between Soil Health and Human Health was held virtually.

Open Session Agenda
July 10, 2023
1:30 p.m. – 2:30 p.m.

1:30 **Welcome and Introductions**
Diana H. Wall, *Committee Chair, National Academies of Sciences, Engineering, and Medicine*
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

1:50 **Invited Presentation**
Martin J. Blaser, *Henry Rutgers Chair of the Human Microbiome, Rutgers University*

2:10 **Speaker discussion with the committee**

2:30 **Adjourn Open Session**

JULY 17-18, 2023

The eighth public meeting of the Committee on Exploring Linkages Between Soil Health and Human Health was held virtually.

Open Session Agenda
July 17, 2023
2:00 p.m. – 3:00 p.m.

2:00 **Welcome and Introductions**
Diana H. Wall, *Committee Chair, National Academies of Sciences, Engineering, and Medicine*
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

2:20 **Invited Presentation**
Bruce Hamaker, *Professor of Food Science and Director of the Whistler Center for Carbohydrate Research, Purdue University: Dietary fiber and food processing links to the gut microbiome and human health*
2:40 **Speaker discussion with the committee**
3:00 **Adjourn Open Session**

July 18, 2023
1:30 p.m. – 2:30 p.m.

1:30 **Welcome and Introductions**
Diana H. Wall, *Committee Chair, National Academies of Sciences, Engineering, and Medicine*
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

1:50 **Invited Presentation**
Justin and Erica Sonnenburg, *Department of Microbiology and Immunology, Stanford University, School of Medicine: The impact of industrialization and diet on the gut microbiome*

2:10 **Speaker discussion with the committee**

2:30 **Adjourn Open Session**

JULY 26, 2023

The ninth public meeting of the Committee on Exploring Linkages Between Soil Health and Human Health was held in-person.

The National Academy of Sciences, 2101 Constitution Avenue, NW
Washington, DC 20418

Open Session Agenda
July 26, 2023
1:30 p.m. – 5:00 p.m.

1:30 **Welcome and Introductions**
Diana H. Wall, *Committee Chair, National Academies of Sciences, Engineering, and Medicine*
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

2:00 **Invited presentations**

Jo Handelsman, *Director, Wisconsin Institute for Discovery and Professor, Department of Plant Pathology, University of Wisconsin-Madison (remote)*
Katherine Karberg, *Medical Affairs Manager, Bayer Crop Science*

3:00 **Break**

3:15 **Invited Presentations**
Bhimu Patil, *Regents Professor and Director of the Vegetable and Fruit Improvement Center, Texas A&M University*
Mario Ferruzzi, *Professor of Pediatrics and Chief of Developmental Nutrition, University of Arkansas for Medical Sciences (remote)*

4:15 **Speaker discussion with the committee**

5:00 **Adjourn Open Session**

SEPTEMBER 18, 2023

The tenth public meeting of the Committee on Exploring Linkages Between Soil Health and Human Health was held virtually.

Open Session Agenda

September 18, 2023
12:00 p.m. – 2:00 p.m.

12:00 **Welcome and Introductions**
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

12:20 **Invited Presentations**
Virginia Moore, *Cornell University: Plant Breeding for Complex Systems*
Jean-Michel Ané, *University of Wisconsin-Madison: Engineering Plant-Microbe Symbioses for Enhanced Plant, Soil, and Human Health*
Lee DeHaan*, The Land Institute: Breeding Perennial Crops*

1:30 **Speaker discussion with the committee**

2:00 **Adjourn Open Session**

OCTOBER 23, 2023

The eleventh public meeting of the Committee on Exploring Linkages Between Soil Health and Human Health was held virtually.

Open Session Agenda

October 23, 2023
2:00 p.m. – 4:00 p.m.

2:00 **Welcome and Introductions**
Diana H. Wall, *Committee Chair, National Academies of Sciences, Engineering, and Medicine*
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

2:20	**Invited Presentations** Donna McCallister, *Texas Tech University* Margaret Lloyd*, University of California Cooperative Extension* Eugene Kelly*, Colorado Agricultural Experiment Station and Colorado State University*
3:40	**Speaker discussion with the committee**
4:00	**Adjourn Open Session**