PHYTOBIOMES

A Roadmap for Research and Translation

WWW.PHYTOBIOMES.ORG

PHYTOBIOMES

Networks of interactions among plants, their environment, and complex communities of organisms profoundly influence plant and agroecosystem health and productivity.

EXECUTIVE SUMMARY

The Phytobiomes Roadmap offers a new vision for agriculture in which sustainable crop productivity is achieved through a systems-level understanding of diverse interacting components.

Phytobiomes consist of plants, their environment, and their associated communities of organisms. Interactions within phytobiomes are dynamic and profoundly affect plant and agroecosystem health, which in turn impacts soil fertility, crop yields, and food quality and safety.

Global demands for food, feed, and fiber are expected to double in the next 35 years. In the same timeframe, we face a world of diminishing arable land, extreme weather events, unsustainable fertilizer inputs, uncertain water availability, and plateauing crop yields. We need new innovative approaches to sustainably increase global crop productivity.

This Roadmap describes a strategic plan for acquiring knowledge of what constitutes a healthy, productive, and sustainable agroecosystem and translating that knowledge into powerful new tools in our crop management toolbox. Integration of these tools is needed to help increase food production from existing farmland while minimizing negative impacts on the environment, increase global arable land by rehabilitating marginal and degraded lands, and ensure sustained productivity and profitability of global food, feed, and fiber.

This Roadmap aims at maximizing sustainable food production by generating, optimizing, and translating into practice new knowledge of phytobiomes. Steps to achieve this vision are to explore phytobiome components and their interactions, integrate phytobiome systems-based knowledge, resources, and tools, optimize phytobiome-based site-appropriate solutions, and apply phytobiome-based solutions in next-generation agricultural practices to sustain enhanced food production worldwide, with concurrent efforts to educate and engage scientists, public and private partners, growers, educators, and society.

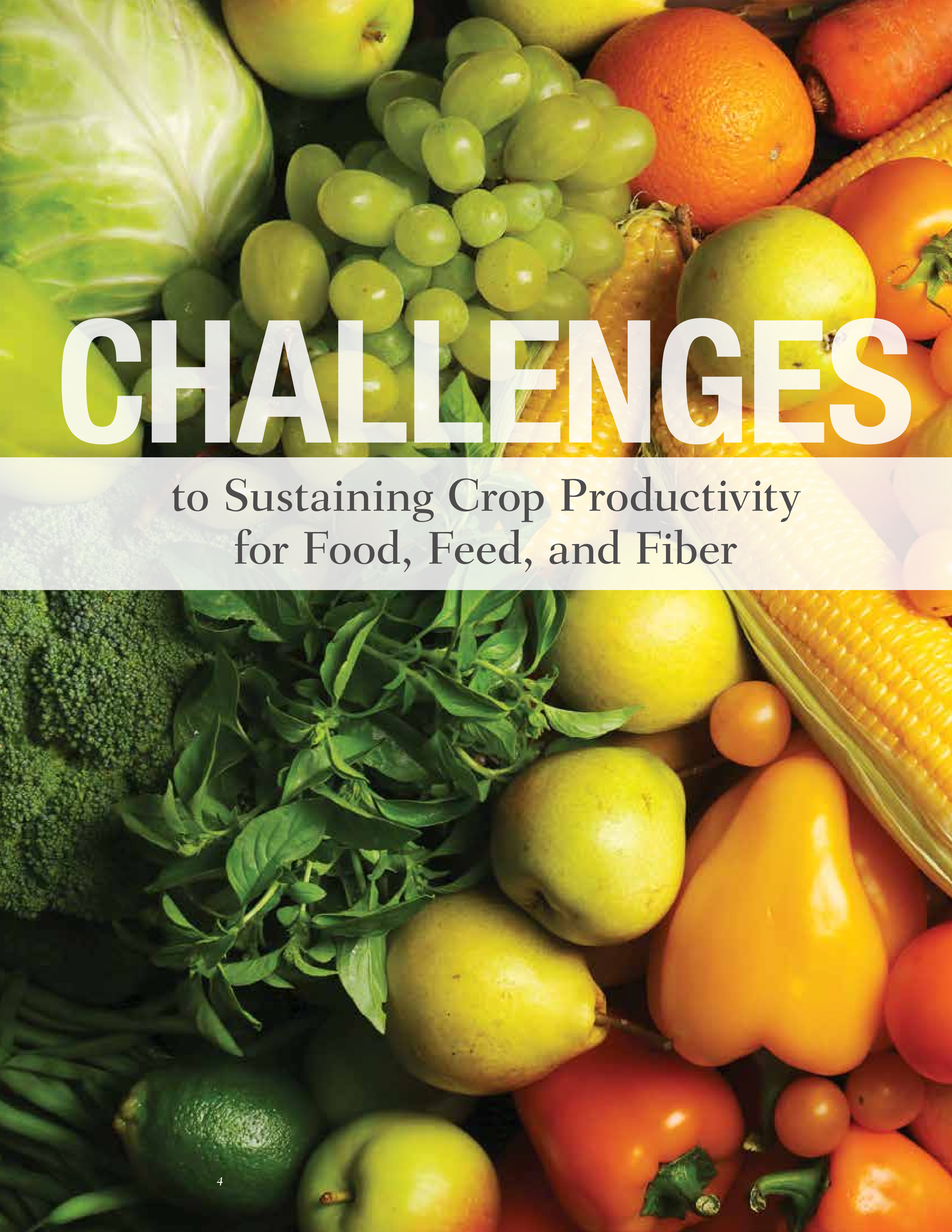
To help guide these efforts, this Phytobiomes Roadmap outlines major gaps in knowledge, technology, and infrastructure for research and translation and identifies challenges to efforts to educate and train a workforce that will carry this field into the future.

We are currently witnessing a nexus of technologies that will enable advances in fundamental knowledge of phytobiomes and translation into sustainable crop production practices. Conceptual and technological advances in diverse fields of research, including ‘omics sciences, systems biology, microbial ecology, data science, and precision crop management systems, are positioning researchers to achieve major leaps in characterizing, analyzing, and managing phytobiomes as integrated systems.

Strategic funding and public-private partnerships are needed to support critical research and infrastructure for developing phytobiome-based management approaches. Key research areas include fundamental studies of phytobiome components, interactions, dynamics, and functions; the generation of integrated systems-based models for phytobiome analysis and prediction; the development of practical phytobiome-based crop management strategies; and the establishment of collaborative global platforms for open communication among growers, researchers, industry, extension, agricultural consultants and advisors, and consumers. Filling the knowledge gaps will require interdisciplinary cooperation.

A new journal, *Phytobiomes*, will launch this year, and an international phytobiome alliance is being established to contribute to the coordination of research and communication among diverse disciplines and disciplinary initiatives relevant to phytobiomes. Working groups will be established to help develop priorities and standards for phytobiome research. Major thrusts will focus on forging international and public-private collaborations in foundational and translational phytobiome research and on attracting and strengthening the phytobiome workforce. The goal is to generate and integrate knowledge of phytobiomes with next-generation technologies to empower both small- and large-holder farms to produce, sustainably and profitably, sufficient crops to meet the increasing global demand.

In the year **2050**,
the world population will require **70%** more food.



CHALLENGES

to Sustaining Crop Productivity for Food, Feed, and Fiber

The world's population will increase by 2.4 billion people by 2050. Meeting societal demands for food, feed, and fiber will require doubling production in less than 35 years, and doing so in the face of increasing resource constraints, extreme weather events, uncertain water availability, and increasingly limited arable land.

Major crop breeding efforts have propelled us through an era of remarkable agricultural prosperity, but annual yield growths for essential food crops are slowing. We are currently at a critical juncture in which new approaches are needed to sustainably increase global crop productivity. We outline a vision for agriculture in which crop management is founded not on managing the individual or system components but rather on exploiting systems-level knowledge of the many interacting components within phytobiomes.

VISION AND MISSION

VISION: Knowledge of phytobiomes maximizes sustainable food, feed, and fiber production.

MISSION: Enhance sustainable food, feed, and fiber production using phytobiome-based approaches:

- Explore individual phytobiome components and their interactions.
- Integrate phytobiome systems-based knowledge, resources, and tools.
- Optimize phytobiome-based site-appropriate solutions.
- Apply phytobiome-based solutions in next-generation precision agriculture to sustain enhanced food, feed, and fiber production worldwide.
- Educate and engage scientists and society.

PHYTOBIOMES FOR SMALL-HOLDER FARMS

A cellphone can link a farmer to an ocean of data. Just as personalized medicine strives to use comprehensive genomic data to optimize our individual health, comprehensive data of the phytobiome of a farm could optimize its productivity by guiding management choices. Farmers querying large databases via their phones could make local management choices. In turn, through crowdsourcing, their data could enhance the database and improve its predictive capacity for all users. The increasing global spread of cell phones and the internet and their rapid integration into people's lives has enormous potential to bring the knowledge of phytobiomes to farms of all sizes throughout the world.

MICROBIALS

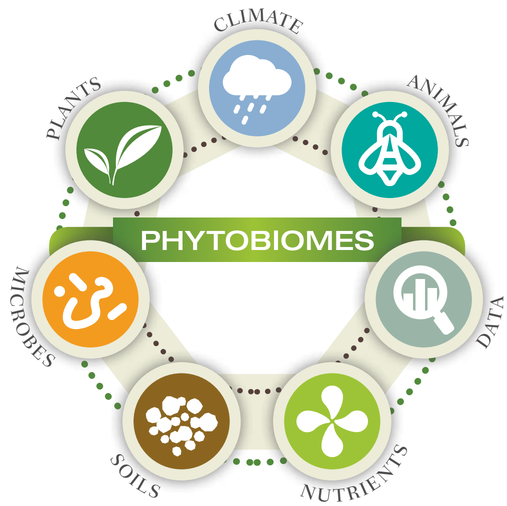
AN UNDER-EXPLOITED TOOL IN THE CROP PRODUCTION TOOLBOX

Agricultural companies are increasingly offering beneficial bacteria and fungi as products for growers. These environmentally friendly products enable growers to reduce use of limited water supplies, chemical pesticides and fertilizers and still enable high productivity of their crops. Examples include bacteria to control nematode and insect pests, fungi to increase root and shoot growth, and signal molecules to enhance plant-bacterial symbioses. These products are helping to meet growing consumer demand for healthy food with minimal residues and sustainable production practices. They also provide alternatives for chemicals discontinued due to tightening regulations. Many of these biologicals can integrate with, or complement, chemical inputs and address site-specific needs. Current products, however, represent only a fraction of the total potential benefit that could be realized with deeper knowledge of phytobiomes.

PHYTOBIOMES: A DEVELOPING FOUNDATION OF KNOWLEDGE

What are phytobiomes?

Phytobiomes consist of plants, their environment, and their associated micro- and macroorganisms. These organisms, which may be inside, on the surface, or adjacent to plants, include a wide diversity of microbes (viruses, bacteria, fungi, oomycetes, and algae), animals (arthropods, worms, nematodes, and rodents), and other plants. The environment includes the physical and chemical environment influencing plants and their associated organisms, and therefore, the soil, air, water, and climate. Interactions within phytobiomes are dynamic and have profound effects on soil, plant, and agroecosystem health. The sphere of relevance of phytobiomes is quite broad, spanning from crops (commodity crops, fruits, vegetables, forest, and specialty and bioenergy crops), rangelands, grasslands, and natural ecosystems to consumer products, including the quality, nutritional value, and safety of our foods.

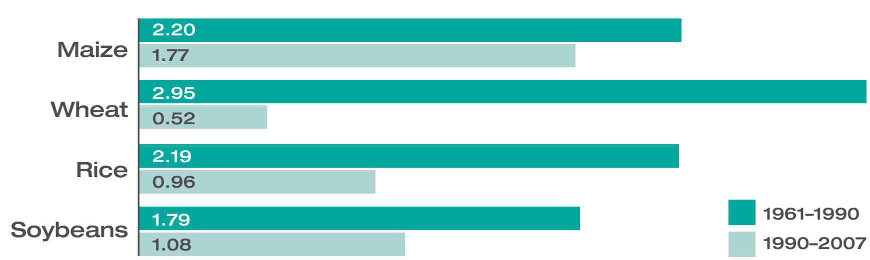


Why phytobiomes now?

Today's agricultural productivity is the result of long-term efforts of many disciplines. The majority of the yield gains worldwide in the last century have resulted from advances in plant genetics and biotechnology, which when coupled with high inputs have enabled phenomenal yield increases that have markedly affected our society. Annual yield growths, however, have slowed in recent decades, and yields will be further impacted by current and future limitations in water, fertilizer, and chemical inputs and the increasing frequency of extreme weather events.

Plants evolved in association with diverse macro- and microorganisms and depend on them, much as humans depend on their elaborate microflora for short- and long-term health. These associations, which help drive the restoration and maintenance of healthy soils, have often been ignored and

GLOBAL YIELD GROWTH RATES (%)



SOURCE: ALSTON ET AL. 2009. SCIENCE 325:1209 even inadvertently inhibited. Scientific tools are now available to probe deep into phytobiome networks and generate systems-level knowledge that can be exploited for optimizing the health and productivity of plant-based ecosystems.

What are the origins and limitations to our current knowledge of phytobiomes?

Our current body of knowledge concerning phytobiomes has been assembled from a broad community of researchers. Plant physiologists, plant pathologists, and entomologists have elucidated sophisticated plant-pathogen/pest interactions, including pathways by which pathogens and pests manipulate plant defenses. Microbiologists have detailed beneficial interactions that dramatically enhance plant access to water, usable nitrogen, and phosphorus. Moreover, they are rapidly advancing our understanding of the plant microbiome, which is one prominent component of phytobiomes, due to the rapid development of 'omics technologies and conceptual advances in other microbiome systems. Similarly, soil scientists have defined the ecosystem processes critical to soil formation, fertility, and nutrient cycling, while plant breeders, agronomists, and growers have established the production systems that have ushered us through an era of remarkable agricultural growth.

This growth resulted from efforts to optimize individual components of phytobiomes, including plant germplasm that optimally distributes photosynthetic products in the plant, nutrient inputs, and biological inputs to control pests and pathogens. This growth has been constrained by an insufficient understanding of phytobiomes, such as of comprehensive soil nutrient-cycling processes and network interactions that impact biocontrol. A key challenge is the open and dynamic nature of plants and their habitats. An understanding of how phytobiomes assemble, function, and impact the health of plants and ecosystems as a whole will greatly expand the number of tools in our crop management toolbox.

How can enhanced knowledge of phytobiomes translate to increased crop health and productivity?

The success of using beneficial microbes, biocontrol insects, and crop rotations for protecting crops against pathogens, pests, and plant-parasitic nematodes illustrates only a fraction of the potential to manage phytobiomes for crop health and productivity. A richer understanding of phytobiomes will inform practices that maximize yields and agroecosystem health. Beginning in the mid-1990s, global positioning systems laid the foundation for precision agriculture and ushered in improvements in crop, forage, and forest management. Application of advanced technologies for yield monitoring, variable rate seeding and nutrient application, active farm sensors, geographic information systems, and remote irrigation control is allowing farmers to collect, analyze, and use data from their own fields to precisely manage crop production. The optimal crop and management practices for a given field, however, will also take into consideration the interactions of all phytobiome components influencing yield, quality, safety, and sustainable production, ultimately enabling growers to manage seeds, biologicals, nutrients, soil, water, microbial communities, and other phytobiome components with next-generation precision agriculture.

WEATHER AND CLIMATE FORECASTING

MODELS FOR INTEGRATING PHYTOBIOME "BIG DATA"

Understanding phytobiomes will require a lot of data and its analysis. Integration of phenotyping, genetic data analysis, soil data, weather data and climate modeling within a changing world requires new computational methods and interlinked thinking. This is the domain of Big Data analytics. While Big Data is not new, the breadth and depth of phytobiome datasets are new. Weather and climate scientists routinely integrate enormous amounts of data using sophisticated models to generate forecasts. This integration requires coordinating complex requirements and linkages among scientists, forecasters, industry partners, and users. Phytobiome researchers can leverage advances in Big Data analysis to deliver usable knowledge to scientists, policy makers, agricultural industries, growers and consumers. An integrated Big Data-enabled approach is at the core of phytobiomes innovations—enabling us to better understand the linkages and feedbacks inherent in real-world environments where we live and make decisions.

GOALS

Achieving the next Green Revolution in agricultural productivity will require expertise in numerous areas using a coordinated and multifaceted approach to understand phytobiomes. To achieve our vision of maximizing knowledge of phytobiomes for sustainable food production, we envision an iterative, multistep process of generating, optimizing, and translating new knowledge of phytobiomes, with feedback at every step. These steps are to Explore individual phytobiome components and their interactions; Integrate phytobiome systems-based knowledge, resources, and tools; Optimize phytobiome-based site-appropriate solutions; and Apply phytobiome-based solutions in next-generation precision agriculture to Sustain enhanced food production worldwide. Concurrent efforts to ensure success are to Educate and Engage scientists, public and private partners, growers, educators, and society.

EXECUTING THE PHYTOBIOME VISION

We are poised to make rapid advances in understanding the fundamental ecological and physiological interactions within and between components of phytobiomes. This is a paradigm-shifting endeavor that will require collaboration across disciplines and national boundaries and integrating the efforts of public and private sector scientists, engineers, crop producers, extension, and agribusiness professionals. The potential to rapidly translate this knowledge into application is immense, and establishing this comprehensive knowledge base will require significant efforts. To help guide these efforts, we have identified major gaps in knowledge, technology, infrastructure, and workforce training capacity that will impact our ability to carry this field into the future.

KNOWLEDGE GAPS

PHYTOBIOME COMPOSITION AND DYNAMICS

Outside of pollinators, soils, pests, pathogens and some well-studied symbionts, the majority of the phytobiome is unexplored, and as such, its enormous potential is unrealized. Defining the full complement and dynamics of phytobiomes is challenging due to complexity in the diversity, abundance, and dynamics of the components. We are only beginning to identify the critical components and how they are impacted by variables such as climate, crop, soil type, and disease. Moreover, we know little of the general principles of microbial community assembly in plant tissues and environs, and how plant traits and environmental stresses influence community development.

PREDICTIVE MODELS AND NETWORKS THAT INTEGRATE PHYTOBIOME DATA

The development of conceptual and predictive models that can integrate the various components of phytobiomes requires data across a range of spatial and temporal scales. Fortunately, many of the tools being developed for precision agriculture should generate spatial and temporal data with an unprecedented level of resolution and accuracy and will help inform the collection of critical biological data. Key needs are modeling that integrates distinct types of data and assesses phytobiome resistance and resilience to change, particularly in the face of the increasing role of climate change in agricultural systems.

COMPREHENSIVE IMPACTS OF PHYTOBIOMES ON PLANT HEALTH AND PRODUCTIVITY

Although phytobiome members have many roles, their full potential impact on the health and development of specific plants, broader agroecosystems, and the consumers of plants and plant products is not yet known—this suite of roles is certainly much larger than is currently recognized. Similarly, we know little about ecosystem resilience and responsiveness to perturbations such as invasive plants, disruptive agronomic practices, and extreme weather events. Thus, a key outcome of network analyses characterizing multidirectional interactions will be describing phytobiome perturbation impacts and optimizing positive impacts on soil and plant health and productivity.

TRANSLATION OF PHYTOBIOME KNOWLEDGE INTO STRATEGIES TO ENHANCE SUSTAINABLE PRODUCTION OF FOOD, FEED, AND FIBER

A comprehensive knowledge base of phytobiomes will enable the identification and implementation of three types of strategies using site-specific predictive and prescriptive analytics. These strategies will identify management practices tailored to specific plant genotypes in specific environments: **(I)** Strategies that target cultural practices to foster organisms and communities that benefit crop productivity and sustained ecosystem health. Such practices may include crop and soil management approaches, specific crop varieties, regimes for incorporating water and fertilizer inputs, crop rotations, cover crops, and tillage. **(II)** Strategies that target the management of phytobiome components. These strategies may include the addition of microbial inoculants and biocontrol agents of insects, pathogens, and weed pests and the deployment of microbial products, signals, or secondary metabolites to alter the presence or behavior of target indigenous organisms. **(III)** Strategies that target plant genetics to favor or disfavor target organisms or their impacts. This approach is rooted in a long tradition of breeding for enhanced resistance to pathogens and pests and enhanced performance in nitrogen-fixing symbioses. Breeding and crop enhancement strategies can be expanded to exploit the diverse impacts of phytobiomes on plants.

BROADER IMPACTS OF PHYTOBIOME KNOWLEDGE

The complexity of soils supports their role as reservoirs of organisms, genes and products that have utility for society, a fact readily illustrated by the origin of many therapeutic antibiotics from soil microbes. Knowledge of phytobiomes may enable further mining for novel organisms, genes, and products for antimicrobials as well as digestion and fermentation of plant tissues for bioenergy. Moreover, mapping carbon and nutrient flux through phytobiomes will inform strategies to conserve and restore soil fertility and nutrient flow for sustainable ecosystem function.

MULTI-OMIC TOOLS TO EXPLORE PHYTOBIOME COMPOSITION, DYNAMICS, AND FUNCTION

Multi-omic approaches (metatranscriptomics, metaproteomics, and metabolomics) are powerful for exploring all of the biological components of phytobiomes. Specific challenges with these tools include characterizing viral communities, identifying truly robust prokaryotic gene targets, resolving fungal phylogeny using short-read data, and integrating the multi-omics of crops into robust genotype-by-environment models. Additional refinements are needed in the extraction, identification, and quantification of macromolecules, extension of read-length for metagenomic analyses, and coverage in metabolite databases.

HIGH-THROUGHPUT, COST-EFFECTIVE PLANT PHENOTYPING

Capturing knowledge of phytobiomes using nondestructive, image-based phenotyping of plants, both above- and belowground, will provide a powerful approach to connect plant traits with micro- and macroorganisms as well as soil and environmental conditions. Critical needs for advancing the agricultural relevance of plant phenotyping include nondestructive field-based methods for rapid phenotyping, such as imaging from drones, and sensor technologies to expand the breadth of phenotypes examined.

INTEGRATION AND STANDARDIZATION OF TECHNOLOGIES AND COMPUTATIONAL AND STATISTICAL TOOLS

The comparison and integration of data across studies requires standardization for data collection, processing, and analysis. Phytobiome data should be collected in a manner that enables linking with existing standardization efforts, such as those at the various standards consortia and the U.S. National Institute of Standards and Technology. Metagenomic data should be integrated into existing and new databases, such as those targeting global human, animal, and environmental microbiomes. Given the complexity of phytobiomes, and particularly the microbial component, statistical and computational tools must continue to be developed, refined, expanded, and made available to the research community. Specific needs include statistical tools that can be applied to multifactorial experiments involving complex microbial communities and tools that model species interactions within these complex communities.

RELEVANT MODEL SYSTEMS FOR PHYTOBIOME RESEARCH

Although depending on a single model plant system will not reflect the variability among agricultural plants, including a strong collaborative focus on the phytobiomes of a few selected agricultural plants would hasten advances in our understanding of phytobiomes. Selecting crops representing cereals, vegetables, and trees, including at least one relevant to bioenergy, as well as conditions that are both optimal and suboptimal for plant growth, would increase the relevance of the results to a breadth of agricultural systems.

OPTIMAL SAMPLING THEORY AND DESIGN

Given the compositional complexity of phytobiomes and the diversity of plant species, habitats, management systems, seasons, and climates of interest to phytobiome studies, sampling should be optimized to maximize the information obtained. Thus, a critical need is to develop optimized sampling theory and design to maximize the usefulness and cost-effectiveness of data collection. To further leverage the data that are obtained, methodologies are needed to optimize sample archiving, thus enabling changes over time to be quantified, to ensure access to data in useful metadata archival systems.

INFRASTRUCTURE GAPS

DATABASES

Databases that provide access to high-quality, comprehensive, curated datasets are critical for sharing data, integrating data across studies, mining data to enable multiple perspectives on interpretation, and generating predictive and network models. Databases are currently available for genomic sequence data for individual members of phytobiomes, and others are available with the capacity to support metadata content that is a critical component of community sequence data. However, critical needs remain, and these include the need for continued maintenance, curation and increased capacity of existing databases relevant to phytobiomes, possible integration of phytobiome data into a single database, and tools and software for analyzing and integrating phytobiome data that are in the public domain.

EDUCATION AND TRAINING GAPS

Advancing knowledge and the translation of knowledge of phytobiomes will require a workforce that can communicate effectively and integrate information across disciplinary boundaries. This will require greater focus on educating students and post-doctoral fellows in topics spanning from ‘omics tools and bioinformatics to plant breeding and agronomy, as well as exposing them to field- and laboratory-based research. It will also require more opportunities for training, particularly in industry and extension, and communicating technical information to the public.

SOCIETAL ENGAGEMENT

The adoption of new technologies requires significant communication and engagement with the public, often over a long period. Dialogue on phytobiome-associated technologies should begin early and broadly. A cultural shift in the community of public and private sector scientists developing such technologies is needed to recognize the need for consistent engagement with a broad community and develop strategies for effective, sustained dialogue. This dialogue should aim at technological refinements to address societal concerns as well as timely and responsible technology adoption to maximize societal benefit.

PHYTOBIOME RESEARCH

DEVELOPING A GLOBAL WORKFORCE

Advances in understanding phytobiomes may result from diverse but unpredictable sources—such as students exploring single nucleotide changes in a gene, microbes that enhance soil fertility, or global climate shifts affecting agricultural land uses. Future training programs must ensure a diverse workforce, but one that can communicate across the sciences. Activities that will help include industrial internships, interdisciplinary programs, and cross-training during a disciplinary degree. Students that are familiar with both basic and applied research approaches will be in a particularly strong position to help translate fundamental knowledge of phytobiomes into agricultural applications. Courses that span the full basic-to-applied spectrum, such as one that extends from the genomics and breeding of a crop to the fundamentals of its production in the field would enhance communication. Alternatively, students focused on a basic science could be paired to work throughout their program with those addressing applied agriculture, and global perspectives could be enhanced by pairing students from different countries.

LOOKING TO THE FUTURE: THE ACTION PLAN

Current initiatives are focused on many areas that are components of phytobiomes. We propose here an Action Plan that provides critical leveraging and coordinating of activities to ensure that a systems-level understanding of all of these phytobiome components is generated, harnessed, and translated to improve sustainable global production of food, feed, and fiber. Towards this end, we propose the following actions and goals.

ACTIONS AND GOALS

Short-term

- Establish an international phytobiomes alliance
- Launch a new journal, *Phytobiomes*
- Advocate for support for phytobiome research and engage in active outreach to the public and other disciplines highlighting the importance of phytobiome research and resources to advance a systems-level understanding of phytobiomes
- Broaden recognition of phytobiomes using popular media coverage and perspectives and commentary articles in high-profile and popular-press science journals and in industry publications
- Coordinate with and leverage existing studies of diverse hosts and ecosystems, including soil health studies and microbiome studies in animal- and plant-based agricultural systems
- Coordinate with existing disciplinary initiatives to promote integrated, cross-disciplinary efforts to enhance phytobiome knowledge and translation
- Enhance funding dedicated to increasing phytobiome knowledge and applications
- Develop phytobiome working groups to help establish standards and protocols for techniques, analyses, field studies, and reporting in phytobiome research

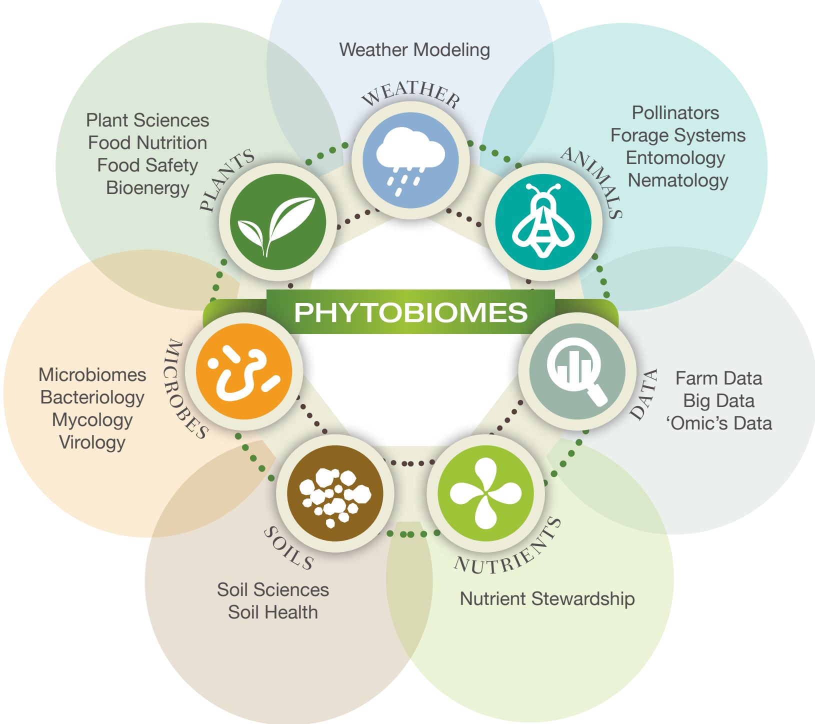
Mid-term

- Forge international and public-private collaborations in foundational and translational phytobiome research (e.g., Research Coordination Networks, European Cooperation in Science and Technology [COST] Actions, and focused industry-academic partnerships)
- Establish a collaborative platform for open global communication among growers, researchers, industry, extension, agricultural consultants and advisors, and consumers
- Coordinate conversations to identify and address regulatory and intellectual property challenges to support efforts for translating phytobiome knowledge to practical management systems
- Attract and strengthen the phytobiome workforce
- Develop and share curriculum resources for use in outreach, education, and training programs

Long-term

- Create a publicly available, comprehensive, integrated database of spatially and temporally explicit phytobiome-relevant data that maximally leverages existing databases while addressing the critical needs of agricultural production systems in developed and developing countries
- Create a publicly available computational infrastructure for big data processing and analysis that includes human resources with a knowledge base to conduct such analyses
- Develop a diverse collection of phytobiome-based analytical tools to empower growers to sustainably and profitably produce crops
- Increase resilience of plants and crop yields to diseases, pests, environmental and nutrient stress, and changing climates
- Integrate phytobiome knowledge with next-generation technologies for plant and microbial breeding and crop production
- Support routine integration of biologicals into food, feed, and fiber production systems
- Develop mechanisms for small-holder farms to collect and analyze data necessary to implement phytobiome-based management approaches
- Provide an industry-ready workforce trained across disciplines and capable of addressing real-world agricultural production challenges based on an integrated understanding of phytobiomes
- Establish sustained communication globally among growers, researchers, extension, and agriculture industry representatives to support continuing advances in phytobiome research and applications

PHYTOBIOMES—Integrating efforts spanning diverse components of agricultural systems



OUTCOMES

Our vision is that agricultural producers will manage phytobiomes rather than individual phytobiome components. This paradigm shift in agriculture will result in:

- increased resilience of our cropping systems to water and nutrient limitation and heat stress
- increased resilience to the ongoing emergence of new pests and pathogens
- reduced crop losses due to pathogens and pests with management practices other than pesticides as the primary means of protection
- full integration of biologicals into site-specific crop management (precision agriculture)
- effective rehabilitation of marginal, degraded, and depleted lands worldwide
- enhanced capacities to identify biome-appropriate crops, including the relocation of cropping systems due to climate change and data-driven selection of crop species for a site
- reduced negative impacts of crop production on the environment
- enhanced safety, quality, and nutrition of our food supply
- reduced reliance on external inputs to sustain crop productivity
- increased capacities for effective crop management to support long-term soil and ecosystem health
- adaptive, data-driven, on-farm systems for managing phytobiomes for optimal productivity
- increased profitability of sustainable food, feed, and fiber production to enable growers to meet demand

INNOVATION

TRANSLATING PHYTOBIOME DISCOVERIES INTO PRODUCTS

We all benefit when publicly-funded discoveries are translated into broad impacts for society. But how do we balance open access to intellectual property (IP) with the need for IP protection for profitable commercial development? Non-profit organizations like the Public Intellectual Property Resource for Agriculture (PIPRA) can help by providing education and guidance in policy development, IP management and technology transfer. Such organizations can help solve IP issues and facilitate commercialization of innovations from the public sector by supporting the development of technologies or tools free of restrictions for widespread distribution. Public and private interests benefit from IP rights in the public domain during the pre-commercial stages of research, and from ensuring that the climate is favorable for IP rights at the later stages of commercial dissemination and technology adoption.

APPENDICES

(available at www.phytobiomes.org/roadmap)

The following supporting materials are provided online for reference.

Appendix A. Linkages between technical needs and translational outcomes.
Appendix B. Knowledge gaps.
Appendix C. Technology gaps.
Appendix D. Infrastructure gaps.
Appendix E. Education and training gaps.

THE PHYTOBIOMES ROADMAP IS ENDORSED BY:

APS Healthy Plants • Healthy World

American Society for Microbiology

evogene Plant Innovation

Monsanto imagine

Soil Health Institute

American Society of Agronomy

Bayer Science For A Better Life

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National C-FAR

Soil Science Society of America

American Society of Animal Science

Crop Science Society of America

indigo

novozymes Rethink Tomorrow

syngenta

Dow AgroSciences

IS-MPMI International Society for Molecular Plant-Microbe Interactions

Plant Science Research Network

Forest Service U.S. Department of Agriculture

American Society of Plant Biologists

DuPont Pioneer

JGI Joint Genome Institute A DOE Office of Science User Facility

The Samuel Roberts Noble Foundation

United States Culture Collection Network

A Roadmap for Phytobiomes Research and Translation

www.phytobiomes.org

This Roadmap stems from the efforts of a large number of individuals. The conceptual seed for phytobiomes was first planted at the American Phytopathological Society (APS) Thought Leaders Workshop held in May 2012. The name "Phytobiomes" was created by the APS Public Policy Board in October 2013, and efforts to fully define the research needs and potential applications of Phytobiomes grew through the strong support of APS, the premier scientific society dedicated to high-quality, innovative plant pathology research. In 2015, the constituency of support broadened due, in part, to the participation of interdisciplinary public and private sector scientists in "Phytobiomes 2015: Designing a New Paradigm for Crop Improvement," a workshop held in Washington, DC, in July 2015.

This Roadmap is based on discussions and input contributed by attendees at the APS annual meetings in 2014 and 2015, participants at the Phytobiomes 2015 workshop, and public comments on a draft of the Roadmap posted online. Finalization and revisions of the Roadmap were performed by a writing team following discussions at a "Phytobiomes Roadmap Writing Workshop" held at The Noble Foundation in the fall of 2015. The Roadmap has been reviewed by individuals with a breadth of expertise and has been revised with every effort to accurately represent the diversity shown below.

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Phytobiomes Roadmap
a New Vision for Agriculture

maximizing sustainable food, feed, and fiber production through the knowledge of phytobiomes

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