Response from the American Phytopathological Society

Submitted online

1. Relevant Agricultural Commodity:

Our comments relate generally to all agricultural and horticultural crops and to forests

2. Challenges and opportunities to increase productivity, improve agroecosystem health and resilience, and reduce environmental footprint:

A Phytobiomes-centric approach to agriculture offers the potential to greatly increase productivity while reducing the environmental footprint of agriculture. This approach is one 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 micro- and macro-organisms. 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.

This focus on understanding the interactions among the many components of an agricultural system is a new vision for agriculture and for sustainable agroecosystem management. Knowledge of what constitutes a healthy, productive and sustainable agroecosystem can be translated 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.

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 climatic 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 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.

The development of our understanding of phytobiomes 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 knowledge 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.

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 manage crop production precisely. The optimal crop 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.

Achieving the next Green Revolution in agricultural productivity will require expertise in numerous areas using a coordinated and multi-faceted 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.

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 for 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

Outcome for the innovation solution/novel approaches and research gaps:

Genome Design.

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.

Identification of plant genes and variants that mediate plant interaction with the phytobiome in a more predictable and positive way will greatly facilitate the prescriptive use of plant genetic variation to optimize productivity and environmental resilience. Such information should enable more prescriptive gene editing schemes to be adopted in the future.. Moreover, a richer understanding of the microbial communities in phytobiomes will facilitate exploitation of the benefits of these communities for plant and agroecosystem productivity, health and resilience. f high-throughput sequencing as a powerful tool for profiling the composition of microbial communities in soils, plants and plant-associated insects and macroflora, and for characterizing the total genetic content of communities (metagenomics) and expression of genes in target organisms and communities (metatranscriptomics). Community profiling usually involves extracting the identity and abundance of organisms based on target sequences. The understanding coming from such studies might well be usefully linked to microbial or microbiome genome design in the future to better establish the most useful associations of plants and their microbial associates.

Research needs:

- We need to improve the phylogenetic resolution, sensitivity and representativeness of high-throughput sequencing techniques for viral, bacterial, fungal, nematode, and insect community profiling, including high-throughput methods that differentiate microbes at the strain level.
- We need methods for high-throughput analysis of secondary metabolites and other bioactive compounds *in situ* in phytobiome-relevant environments. These studies need to be linked to better functional annotation and comprehensive databases of the plant, microbial, and other components of the phytobiome
- We need an interdisciplinary effort to identify the metadata that should accompany microbiome studies and plant genotyping studies, including relevant plant physiology (e.g., root type and developmental stage), soil properties (e.g., soil classification), and climate data. Efforts to more fully adopt standards being proposed for microbiome analyses and published in Phytobiomes Journal in January 2020 as well as similar standards for soil chemistry should be pursued and supported.
- We need approaches to allow us to sequence and/or modify the genomes of phytobiome constituents comprehensively, including both cultivated and uncultivated microbes.
- We need approaches for modifying the genomes of phytobiome constituents (which could involve modifying individual organisms, or modification of the composition of the phytobiome) with the consequence that the collective `genome' (metagenome) is altered as a function of management.
- Investment should be made in strategies that impose selection on indigenous phytobiome community members such that an understanding of how to deliberately alter the genomic composition/phenotypic traits of the collective phytobiome is developed. The ultimate goal should be for PHENOME design, rather than genome design. Optimizing the collective phenome, or phytobiome `phenotype', will require comprehensive understanding of how the whole phytobiome and its phenotype is different from the sum of the individual components.

<u>Digital/Automation</u>

Capturing knowledge of phytobiomes using non-destructive, 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 non-destructive field-based methods for rapid phenotyping, such as imaging from drones, and sensor technologies to expand the breadth of phenotypes examined. Non-destructive, image-based phenotyping of plants would allow for high-throughput plant characterization, which is greatly enhancing the association of genes and phenotypes. Other chemistry-based methods of interrogating the plant or its system such as analysis of volatiles, measures of Carbon flux, as well as remote metrics of various soil traits could also provide the information needed for understanding and directed manipulation of the plant environment. The strong impact of the environment on plant phenotypes, including the interactions between plants and other components of phytobiomes, indicates that studies need to be performed under field conditions.

Research needs:

- We need non-destructive, high-throughput phenotyping approaches appropriate for use in the field, including knowledge of the best traits/components to be measured, the best approaches for capturing these measures and interpreting the data.
- We need improved root phenotyping techniques, especially for the field, and tools to monitor the microbial colonization of root systems.
- We need to optimize drones and sensor technologies for real-time, high-throughput phenotyping.
- We need breakthrough approaches to connect above- and belowground plant traits identified by high-throughput phenotyping to specific phytobiome traits, including the presence and activity of microbiome members.
- Better remote detection of volatiles or other chemical signatures of plants and their local habitat are needed.
- More investment is needed in programs that actively integrate research between physical scientists and biologists to better integrate and interpret the many chemical and biological metrics associated with the phytobiome and link them to plant productivity and environmental processes.

Prescriptive Intervention

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. More extensive and complete data is needed. Without good data on the effectiveness of prescriptive interventions across management systems we lack the capacity to advance/implement large-scale innovation effectively. We need high quality data on field outcomes. 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 increasing climate change in agricultural systems. 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 US 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.

The complexity of the phytobiome components, and particularly the microbial component, present challenges to their analyses. Extensive statistical and computational tools need to be developed further to enable streamlined analytical approaches for widespread use. Regulatory needs with regard to interventions in microbial communities are substantial. The regulatory landscape is complicated for inoculation of microbes and there are different rules for different claimed effects on the plant system. A concerted effort to build scientific consensus on what constitutes risk and what information is needed to support/reject inoculation testing across diverse landscapes is needed. This currently represents a large bottleneck for microbial interventions.

Research needs:

- We need statistical tools that identify taxon differences among microbial communities in multifactorial experiments.
- We need bioinformatics and computational tools for big data processing and manipulation in preparation for data analyses.
- We need tools to better account for nonlinear interactions as well as linear interactions.
- We need to identify best practices and standardize protocols for analyzing data from phytobiomes studies.
- We need computational tools to better characterize, analyze, and model species (genomic, phenotypic) interactions within complex communities.
- We need to build predictive and prescriptive models of phytobiomes, and develop effective model validation systems.

<u>Systems-Based Farm Management</u>
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 and policies 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. To achieve optimum productivity, resilience, and sustainability we will need to characterize the emergent properties of phytobiomes. This will require systems-biology approaches for the analysis and prediction of complex community effects on individual microbial properties/phenotypes and on plant phenotypes

Needs:
- We need to promote the training of students and postdocs in disciplines that support an increased understanding of phytobiomes and their optimization in interdisciplinary research. This includes developing a workforce that nimbly integrates knowledge spanning from ‘omics tools, bioinformatics, data analysis, multi-scale modeling, and network analyses to plant breeding, plant pathology, entomology, and agronomy.
- We need to promote broad training of students and postdocs, including training in the field, to prepare them for industry jobs that will arise from sustainable exploitation of crop, forage, and forest phytobiomes.
- We need to promote community education, appreciation, and public support for generating and translating phytobiome knowledge for societal benefits. New science needs to be communicated to the public effectively, early and accurately.
- We need experiments and data collection to be made simultaneously across diverse spatial and temporal scales. Such data would better enable microbiome research that is currently performed mostly at very small scales to be better linked to that at farm management scales

- There is a need to collect sufficient data to enable tracking progress toward to the goals of phytobiome-mediated improvements in plant productivity. Such data would include, at a minimum, the use of microbials in farming systems.

There is a need to determine how individual components or consortia within complex phytobiomes mediate outcomes of the cropping system. A goal would be to identify the lynchpins for functional outcomes, and the pressure points for management. Without a complete grasp of these systems drivers it will be difficult to assemble a systems-based management scheme.