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Plant Science Decadal Vision 2020–2030: Reimagining the Potential of Plants for a Healthy and Sustainable Future

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WHITE PAPER

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Abstract

Plants, and the biological systems around them, are key to the future health of the planet and its inhabitants. The Plant Science Decadal Vision 2020–2030 frames our ability to perform vital and far-reaching research in plant systems sciences, essential to how we value participants and apply emerging technologies. We outline a comprehensive vision for addressing some of our most pressing global problems through discovery, practical applications, and education. The Decadal Vision was developed by the participants at the Plant Summit 2019, a community event organized by the Plant Science Research Network. The Decadal Vision describes a holistic vision for the next decade of plant science that blends recommendations for research, people, and technology. Going beyond discoveries and applications, we, the plant science community, must implement bold, innovative changes to research cultures and training paradigms in this era of automation, virtualization, and the looming shadow of climate change. Our vision and hopes for the next decade are encapsulated in the phrase reimagining the potential of plants for a healthy and sustainable future. The Decadal Vision recognizes the vital intersection of human and scientific elements and demands an integrated implementation of strategies for research (Goals 1–4), people (Goals 5 and 6), and technology (Goals 7 and 8). This report is intended to help inspire and guide the research community, scientific societies, federal funding agencies, private philanthropies, corporations, educators, entrepreneurs, and early career researchers over the next 10 years. The research encompass experimental and computational approaches to understanding and predicting ecosystem behavior; novel production systems for food, feed, and fiber with greater crop diversity, efficiency, productivity, and resilience that improve ecosystem health; approaches to realize the potential for advances in nutrition, discovery and engineering of plant-based medicines, and "green infrastructure." Launching the Transparent Plant will use experimental and computational approaches to break down the phytobiome into a "parts store" that supports tinkering and supports query, prediction, and rapid-response problem solving. Equity, diversity, and inclusion are indispensable cornerstones of realizing our vision. We make recommendations around funding and systems that support customized professional development. Plant systems are frequently taken for granted therefore we make recommendations to improve plant awareness and community science programs to increase understanding of scientific research. We prioritize emerging technologies, focusing on non-invasive imaging, sensors, and plug-and-play portable lab technologies, coupled with enabling computational advances. Plant systems science will benefit from data management and future advances in automation, machine learning, natural language processing, and artificial intelligence-assisted data integration, pattern identification, and decision making. Implementation of this vision will transform plant systems science and ripple outwards through society and across the globe. Beyond deepening our biological understanding, we envision entirely new applications. We further anticipate a wave of diversification of plant systems practitioners while stimulating community engagement, underpinning increasing entrepreneurship. This surge of engagement and knowledge will help satisfy and stoke people's natural curiosity about the future, and their desire to prepare for it, as they seek fuller information about food, health, climate and ecological systems.

KEYWORDS
research areas, research methods, research organisms

1 | INTRODUCTION

Humankind faces profound challenges related to food, health, energy, and the environment, amplified by the many effects of climate change. Plant systems (the microbes, fungi, insects, and other organisms that live on, in, or around plants) are integral to addressing these challenges; they are the foundation of healthy ecosystems and environments, sentinels of climate change, and the primary producers of food, feed, fiber, energy, and shelter. The intersection of biodiversity, human activity, population growth, and climate change was addressed systematically in a recent intergovernmental report (IPBES, 2019), which reached alarming conclusions for sustainability that were echoed in a report from the The Intergovernmental Panel on Climate Change (IPCC), UN, (2019).

In the United States, agricultural production accounts for about 40% of freshwater withdrawals (Ritchie and Roser, 2020, and cropland covers about 17% of the nation (Ritchie and Roser, 2020; Bigelow, 2017). he US agricultural economy is remarkably productive, worth more than $1 trillion annually (Kassel & Morrison, 2020). It plays an important role in carbon sequestration (Lal, 2004; Harnessing Plants Initiative, 2020) and can reduce environmental pollutants, but it is also responsible for most eutrophication and a quarter of greenhouse gas emissions.(Ritchie & Roser, 2020) Dramatic increases in food production are required to alleviate food insecurity and provide for anticipated population gains (WHO, 2020) However, realizing those increases in an environmentally and socially responsible manner presents a monumental challenge (Beynon et al., 2020; Hunter, Smith, Schipanski, Atwood, & Mortensen, 2017).

Plant systems science goes far beyond food- and fiber-producing crops. Plants have many other actual and potential uses, including ornamental, recreational, and medical uses. Chief among these are therapeutics derived from plant chemistry. Paclitaxel (Taxol), which is used for cancer treatment, is one recent example (McElroy & Jennewein, 2018; Rowinsky & Donehower, 1995), but there are hundreds of other herbal remedies in use, many of which have indigenous origins and whose scientific basis remains little explored.

Plants are also being adapted in new ways to substitute for meat and dairy (Simon, 2019; Wild et al., 2014) and are being reprogrammed as molecular factories. For example, plants are involved in the production of the monoclonal antibodies that compose the ZMapp Ebola vaccine (Qiu et al., 2014; Zhang, Li, Jin, & Huang, 2014) and development of a prospective vaccine for SARS-CoV-2 (Keown, 2020). Plants, particularly algae, are also seen as a scalable source for hydrocarbons and specialty chemicals (Fu, Nelson, Mystikou, Daakour, & Salehi-Ashtiani, 2019). Beneficial uses of plants are limited only by available knowledge, scientific resources, and our imaginations.

1.1 | Developing a collective vision across plant science

Plant Summits held in 2011 and 2013 began to coalesce the plant research community around a road map for the future and led to the first Decadal Vision (Plant Science Research Summit, 2013), published in 2013. At that time, it was recognized that future conversations and activities should involve a broader group of stakeholders. This conclusion led to the establishment in 2015 of the Plant Science Research Network (PSRN; Supplement 1). This network brings together representatives of 15 scientific and professional societies spanning agronomy, botany, biochemistry, cell biology, cell development, chemistry, crop science, ecology, education, evolution, genetics, genomics, horticulture, plant pathology, soil science, and taxonomy. The PSRN has facilitated workshops to imagine future scenarios around plant science (2016), recommended new paradigms for cyberinfrastructure and big data (2017), urged the reimagining of postgraduate training (2018), and discovered new approaches to broadening participation (2019; Plant Science Research Network, 2020). The 2019 Plant Summit (Supplement 2) used these earlier activities as a starting point for the development of the *Plant Science Decadal Vision 2020–2030*.

A community vision should be both informative and influential. The 2013 document was successful in highlighting the need to invest in plant phenomics, at that time still in its infancy. Today, the plant phenomics community has an annual meeting, a scientific journal, and its own community network (Carroll et al., 2019). A chapter of the 2013 Decadal Vision focused on the need to provide training in transferable skills, or T-training, called attention to the need to complement disciplinary research skills for early career scientists. Five years later, many training opportunities, including technical internships and leadership workshops, have been integrated into graduate programs and made available at scientific society annual meetings. The National Science Foundation (NSF) Research Traineeship program (2014) and the National Institutes of Health Broadening Experiences in Scientific Training program (2013) incorporate similar concepts and promote broad career exploration. In addition, the 2014–2018 National Plant Genome Initiative (NSTC, 2014) drew on the 2013 Decadal Vision as one of its sources to develop a strategic plan for facilitating and funding genomics research in plants.

1.2 | Values and language of plant systems science

We, the plant science community, believe that dissonance in values and vocabulary is an impediment to progress that must not be underestimated. Diverse perspectives give us strength, but they also highlight the need to seek common ground. Values and vocabulary discussions (Marder, 2020; Supplement 3) therefore became foundational for the development of the 2020 Decadal Vision. The values described in this report were developed by the 2019 Plant Summit participants as representatives of the larger community; plant scientists constitute a global, borderless community in which nationalities and cultures mix freely and productively, yet one in which there are differences that must be understood and accepted in order to unite. Here we state and affirm four Guiding Values (Supplement 4) for our community that both have been historically evident and are aspirational in their full expression: collaboration, diversity, integration, and equity.

1.3 | Using this report

This report is intended to help inspire and guide the research community, scientific societies, federal funding agencies, private philanthropies, corporations, educators, entrepreneurs, and early career researchers over the next 10 years. The discrete and aspirational goals we propose here are intended to ignite the next generation of participants, technologies, and discoveries in plant systems science. Many of our goals, including those relating to the bioeconomy, agriculture, big data, and workforce diversification, are shared and aligned with the White House's fiscal year 2021 research priorities and 2020–2025 priorities for the US Department of Agriculture (USDA, 2020; Vought & Droegemeier, 2019).

2 | Recommendations

Our overarching aspiration for the next decade of plant research is reimagining the potential of plants for a healthy and sustainable future, which connects transformative thinking and discoveries in plant systems to environmental and societal benefits. Our success relies on the integration of strategic priorities related to research, people, and technology, embodied in cross-cutting goals and specific recommendations. The associated action plans are intended to be implemented through academic training, activities of scientific and professional societies, research and development, and with the support of funding bodies.

2.1 | Research

Four broad goals for plant science research have the potential for significant societal impact (Figure 1), with advances in any one area stimulating progress in another. Although these goals could potentially be realized through large-scale team science, they are more likely to be met through the combined contributions of integrative hubs and constellations of smaller scale researchers in a range of institutional environments. The goals are bold and aspirational and are intended to challenge and guide our community well beyond the 10-year time frame of this Decadal Vision. Along this exciting path lie numerous near-term discoveries and impacts that promise to motivate and engage. All the goals require improved transdisciplinary collaboration and increased participation in convergence research (National Research Council, 2014) and thus are linked to the people and technology goals of our vision.

2.1.1 | Goal 1: Harness plants for planetary resilience

In an era of unprecedented environmental upheaval, including rapid anthropogenic climate change and its contribution to biodiversity loss (IPBES, 2019; IPCC, 2018; Nullis, 2018), the ability to predict the reaction of Earth's living systems and to mitigate, and eventually reverse, the most detrimental consequences is vital. The ultimate implications of the increasingly accurate yet dire atmospheric and oceanic predictions for the intricate webs that tie organisms and

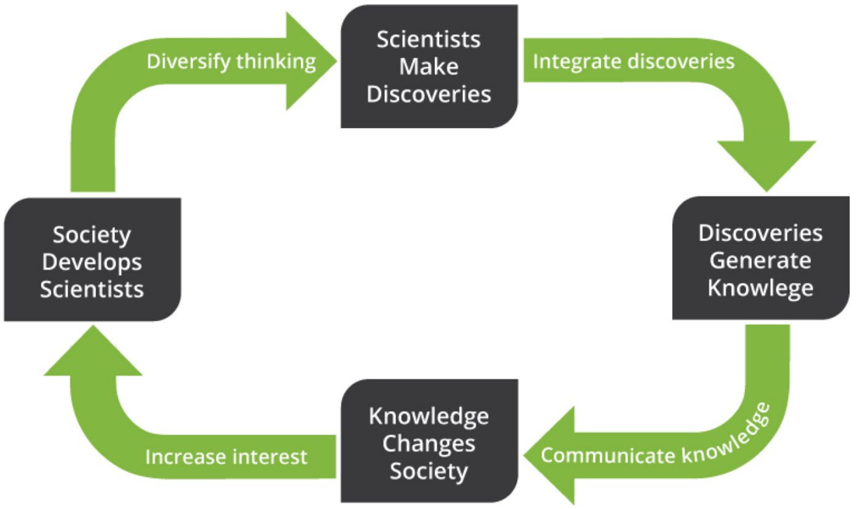

FIGURE 1 The virtuous cycle of science and society shows how each advances the other. Diverse scientific perspectives drive creativity and societal impact around the world. Diversity increases through deliberate actions and becomes self-catalyzing as diverse scientists make diverse discoveries

ecosystems together are still poorly understood, yet this insight is essential to the preservation of these webs. Removing uncertainty from these models requires precise spatiotemporal knowledge, and in particular an understanding of the patterns and processes by which biodiversity evolves and adapts.

Just by asking the deceptively simple question "How much diversity exists in plant systems?" the challenge becomes evident: Some 400,000 plant species are currently known to science, and 2,000 additional species are being discovered yearly (Kew Royal Botanic Gardens, 2016; Willis, 2017). Each plant interacts with other organisms, forming intricate relationships (e.g., herbivory, pollination, dispersal, nutrient uptake) that determine plant health, fitness, and survival. As an example, the study of plant microbiomes is in its infancy, but metagenomic data have already identified many thousands of bacterial and fungal species, not to mention a plethora of viruses (Schoelz & Stewart, 2018), that engage in an entire spectrum of interactions with their host plants from mutualistic to pathogenic.

The composition of plant–organismal interactions and their influences on plant phenotypic diversity varies by evolutionary history, environment, and other biotic and abiotic factors. Understanding the nature of biodiversity therefore requires documenting and cataloguing the extant diversity of plants and their associated organisms, along with relevant environmental data, and placing this information within the context of anatomy, physiology, phylogeny, and genetics. This effort is both a colossal challenge and a promising frontier, with far-reaching implications for the livability of our planet.

Aspirations for digital biospheres

The desired predictive ability regarding the structure, function, and dynamics of biological communities, ecosystems (ecological systems), and evosystems (evolutionary systems) will necessarily combine deep and detailed knowledge of organismal and functional diversity with an understanding of how organisms are shaped by internal and external forces. We should strive for the creation of a series of digital biospheres, at progressively improving levels of detail and accuracy, that can be used to explore and display the results of ecological and evolutionary changes—in populations, lineages, and ecosystems—from deep time to the present. These models would help us visualize current data and knowledge, but would also be predictive in service of aiding experimental design or forecasting ecosystem changes under specified conditions, for example, as the climate changes or land use is modified. The combination of fundamental understanding and predictive tools would then help us develop new approaches for conservation and restoration, carbon capture, bioremediation, agricultural resilience, and ecosystem sustainability for wild and managed landscapes.

Although fully operative digital biospheres would provide powerful new tools for exploring alternative scenarios of ecosystem and evosystem change and appropriate interventions, the likelihood of our achieving the levels of detail and accuracy that will eventually be needed is low within the time frame of the Decadal Vision for 2020–2030. Indeed, earlier efforts at comprehensive ecological modeling during the International Biological Program (1964–1974) were unsuccessful (Schleper, 2017). Although we have far more data and massively more computational capacity than we did in the 1960s and 1970s, the scope and inherent complexity of the problem remain immense (Peters, 1991). Thus, we view the concept of digital biospheres as a long-term aspirational goal that will build on the meaningful milestones found in the Action Plan for Goal 1.

Progress toward developing robust and comprehensive ecosystem and evosystem models must be achieved by building forward from a historical context, by exploring and querying fossil records, herbaria, botanical and germplasm collections, and seed banks. We recommend maintaining and mobilizing these existing biodiversity resources to amplify dramatically the content and use of the Extended Specimen Network (Lendemer et al., 2020), which enables novel discoveries arising from linking genotypic and phenotypic data on plants and their associated biota to detailed ecosystems data. This information repository needs to be supported by sustained investments in data sciences and ecosystem research such as the Critical Zone Observatories, Long-Term Ecological Network research sites, and the National Ecological Observatory Network.

Predicting near-term vulnerabilities of plant systems

Success in predicting and reacting to ecosystem change in the face of the enormous challenges of changes in climate, pollution of the environment, loss of biodiversity, and wide-scale conversion and destruction of natural habitats is the ultimate integrative challenge (Martin-Luther-Universität Halle-Wittenberg, 2019; Nogués-Bravo et al., 2018): it requires us to draw on the expertise not only of scientists in multiple biological disciplines, but also of soil scientists, biogeographers, conservation biologists, and computational modelers. One of the most daunting yet exciting challenges of cross-disciplinary research is the integration of data across temporal and spatial scales and from genes to organisms to communities to ecosystems, thereby building our ability to impute and predict future scenarios across landscapes that include inter-organismal interactions (e.g., plant–pollinator networks; plant–microbe associations, both beneficial and harmful) and interspecies competition.

In a practical sense, plant systems scientists, whether in academia, public service, or private contexts, will benefit from efforts to develop more comprehensive ecological and evolutionary models. Such models will yield mitigation strategies for specific environments, including the adaptation or incorporation of previously unknown or underutilized plants and their associated species. A digital biosphere tool to predict how plants interact with the environment will inform public policy to mitigate severe environmental degradation from physical disturbances, climate change, soil erosion, and reduced water quality.

Action plan: Goal 1

1. Develop well-resolved phylogenetic trees for all plants, including algae, and their associated biota; these phylogenies will form the basis of an online global catalogue that will be unprecedented in depth and value (NSF, 2020). One valuable outcome of this effort will be a comparative framework for detecting how genotype–phenotype associations vary across timescales, exploring how genes evolve along phylogenies and in turn affect phenotypes, and understanding the assembly of existing and novel biological communities.
2. Strategically select a broad set of phylogenetically and ecologically diverse plant lineages for in-depth analysis of their morphology, anatomy, physiology, ecology, genomics, and genetics in their natural environments. Of key consideration should be their additional feasibility as experimental systems for testing hypotheses for mechanisms of diversification and adaptation under controlled conditions.
3. Explore, identify, and characterize as-yet undiscovered plant-associated biota, from mutualistic to pathogenic, to understand through floristic and systematic studies their contributions to biological diversity. Such information is invaluable in addressing problems arising from emerging pests and diseases and unfavorable interactions caused by introduced and invasive species. Leveraging information about mutualists across scales from microbes to macrobes (e.g., herbivores, pollinators) will better support efforts to mitigate, reverse, and adapt to ecological and environmental changes.
4. Enhance global mapping of species distributions and threats to elucidate trends and enable predictions of near-term vulnerabilities. Similar efforts to classify, map, and assess vulnerabilities of both natural and cultural plant communities are also imperative. Accurate risk assessment will be critical in slowing and perhaps reversing the impacts of human-mediated loss of biodiversity.
5. Develop efficient ways to mine centuries of scientific studies, biodiversity literature, and specimens and to integrate old and new data to develop useful ecological and evolutionary models that inform our understanding of current environmental degradation and the steps needed for successful mitigation and adaptation.
6. Although the accumulation of data stemming from Actions 1 through 5 will be invaluable, we must also use and manage these data (Goal 8) to push the boundaries of our knowledge of interspecies interactions, food webs, ecosystems, and biomes to understand and mitigate the effects of changing environments at all levels of biological organization from genes to the biosphere.

2.1.2 | Goal 2: Advance technology for diversity-driven sustainable plant production systems

Sustainable production to feed a growing global population is increasingly challenged by the availability, unreliability, and rising costs of associated inputs (e.g., water, nutrients, arable land), as well as by geopolitical factors. There are no simple causes and solutions to these multifaceted challenges. However, today's predominance of relatively few commodity-focused high-intensity systems needs to be rethought to increase the functional diversity of cropping systems as a whole; the world's top 10 crops—barley, cassava, maize, oil palm, rapeseed, rice, sorghum, soybean, sugarcane, and wheat—supply a combined 83% of all calories produced on cropland (Ray et al., 2019; University of Minnesota, 2019).

Likewise, past improvements to production have been very successful but focused on increasing yield, mainly in a few major crops. Novel production systems are needed that combine high productivity with greater crop diversity and enhanced resilience that does not stop at reduced environmental harm but actually improves ecosystem health (Brummer et al., 2011). Key elements of plant production systems include predictive modeling and selection of traits, breeding, and scaling. Such a goal is in keeping with greater societal interest in the origin of food and the impact of agriculture. We also propose two “moonshots” to inspire far-reaching innovations in sustainable production systems (Supplement 5 and 6).

Crop system improvements

Farms collectively have an enormous physical and environmental footprint. Therefore, they must balance their replacement of natural ecosystems and need for inputs with respect for ecosystem management principles such as harboring reservoirs of certain types of biodiversity, serving as bulwarks against urbanization, and potentially acting as vastly augmented carbon capture systems in concert with other strategies such as the Trillion Trees initiative (2020). The predictive tools described in Goal 1 will enable farmers and agricultural researchers to continue working toward better environmental stewardship and to prepare for future economic opportunities. Digital agriculture tools ranging from robots and drones to Internet of Things sensors (Goal 7) are examples of emerging technologies that are already innervating the agricultural enterprise (Blue River Technology, 2020; Ekekwe, 2017; Meola, 2020; Padilla-Medina, Contreras-Medina, Gavilán, Millan-Almaraz, & Alvaro, 2019) These initiatives will ultimately revolutionize land and crop management. Historically successful crossing-based breeding methods, including genomics and artificial intelligence (AI)-driven selection strategies (Voss-Fels, Cooper, & Hayes, 2019), as well as responsible exploration and application of emerging technologies such as gene editing and phenomic selection (Rincent et al., 2018), will provide further advances. Targets will include productivity, pest and pathogen resistance, domestication of new crops with valuable traits (e.g., perenniality, extreme weather hardiness, combinations of traits), and development of high-diversity production systems that incorporate plant microbiomes tailored for sustainably improved production.

Research on and implementation of new crops and novel sustainable plant production systems will begin as trials and demonstrations, but we expect the first demonstration of economically viable and improved sustainability by 2030, with rapid uptake across the market through the following decade. The science must be responsive to the input of markets, farm providers, retailers, and exporters and, of course, the farmers themselves. That said, alternatives to current monoculture practices that enhance biological diversity across the landscape (Kremen & Merenlender, 2018) and optimize production on the basis of nutritional and environmental needs will meet less resistance if they are economically and operationally feasible and viewed as being in both producers' and the public's interest. Such a dramatic shift could become part of a revolution as transformative as the Green Revolution of the 1950s and 1960s, which incorporated a bundle of new technologies on a very broad scale (Evenson & Gollin, 2003).

Technology for crop innovation

The second focus area is more rapid development of individual crops. Breeding of new varieties is slow and has not been accelerated by genetic modification technology (Genetic Literacy Project, 2016). Rather, tools that shift research from description to prediction—for example, moving from genome-wide association studies to genomic selection (Heffner, Sorrells, & Jannink, 2009; Voss-Fels et al., 2019) or from phenotyping to phenomic selection (Rincent et al., 2018)—will be part of the innovation that drives crop improvement. Important emerging methods in this area include phenomics, crop physiological modeling, and AI and the intersection of these through genomics. These advances necessarily encompass crop plant phenotypes within diverse biotic environments. Another rapidly growing research area, on understanding phytobiomes—that is, systems encompassing plants, their environments, and the microbes and other species they interact with—and their influence on plant performance, could elucidate new biology and influence breeding and production practices.

Although much is to be gained from using species and germplasms more effectively, paradigm-shifting tools for genomics, such as precision genome editing, are arriving in waves. Genome editing has the potential to improve drought tolerance, nutritional quality, appearance, shelf life, and disease and pest resistance and to provide applications not yet imagined. Leveraging these tools effectively, however, will require major improvements in the ability to identify target genes and desired modifications, along with a culturally, ethically attuned, and internationally coherent regulatory framework for release of genome-edited products. The whole-organism extension of editing is synthetic biology, a growing toolbox for inventing and introducing new pathways and even creating new chromosomes. The social, legal, and ethical implications of such technologies must be identified and tackled, and science-based risk assessment mechanisms and safeguards must be developed for introducing these resources into our agricultural systems.

Broader implications of agroecology

Agroecology—the ecology of farming—has enormous potential related to biodiversity, renewable energy, and carbon markets. Investing in sustainable systems allows farmers to diversify economically and could stimulate rural economies given appropriate political and monetary incentives. Deployment of research advances to farmers across broad geographies will need to leverage cooperative extensions, private sector training platforms, and numerous commercial partnerships. Modeling, digital agriculture, and genome editing are already sparking entrepreneurship, and each has given rise to a burgeoning number of start-up enterprises (Graff, Silva, & Zilberman, 2020). Continuing improvement in collaboration between the private and public sectors, whether in training or sharing of data and methods, will accelerate progress dramatically. These mutual interests are well recognized and in some cases have been successful (FFAR, 2020; NSF, 2015; University of Bern, 2020) but they constantly face institutional barriers, which history shows are well worth surmounting.

Action plan: Goal 2

1. Identify and apply genetic mechanisms for crop resilience and increased productivity, without increasing the carbon footprint on the same acreage, to meet the needs of projected population growth while maintaining profitability and livelihoods for farmers and farmworkers.
2. Identify and develop alternative crops for domestication and production, including fiber-producing plants, assessing benefits and drawbacks in partnership with nutritionists, food scientists, and agricultural economists.

3. Diversify production in terms of crop rotation to increase resilience and economic return while reducing external energy inputs and securing nutritional output of farms.
4. Understand and apply phytobiome research to reduce plant disease, improve water efficiency and nutrient utilization, maintain soil health, and improve plant productivity.
5. Reduce the use of agricultural water by 20% and fertilizer by 15% through cultural and management practices outlined in a recent National Academy of Sciences report (National Academies of Sciences, E, & Medicine, 2019), as well as through genetic improvements.
6. Implement measures, including novel robotic technologies, to dramatically reduce the use of fungicides and pesticides in plant production.

2.1.3 | Goal 3: Develop 21st-century applications of plant science to improve nutrition, health, and well-being

Plants, associated microbes, and their products impact human health; provide comfort through shelter, clothing, and recreation; and bring aesthetic beauty and value to our surroundings. These benefits of plants should not be overlooked by scientists as we leverage the information, insights, and tools driven by food production or large-scale environmental research. Indeed, as a chronically under-resourced area of plant systems science, biofortification for human nutrition (Zhu et al., 2020), therapeutic applications (Chan & Daniell, 2015; Rosales-Mendoza, Angulo, & Meza, 2016), and use of plants to improve well-being (Haller, Kennedy, & Capra, 2019) offer attractive risk/reward targets and a high-potential return on investment.

Plant nutritional value

Two areas with high potential are synergistic with Goal 2: identifying new plant sources for nutritional improvement and increasing the nutritional content of current crops. The methods used to create golden rice represented a scientific tour de force at the time, (Regis, 2019) but present-day and emerging tools are far more precise (Dong et al., 2020) and can leverage much-improved knowledge and modeling of metabolic pathways. For example, biochemical engineering has been used to enrich tomatoes for improved health benefits to consumers (Butelli et al., 2008; Zhang et al., 2015). Nevertheless, a major lesson from golden rice is that outstanding plant science alone does not suffice to achieve positive societal impact: research achievements also need to be coupled with efforts to improve prospects for commercialization and consumer acceptance (Napier, Haslam, Tsalavouta, & Sayanova, 2019). These efforts begin with tailoring such research to the communities and cultures of the intended beneficiaries and working with in-country regulatory agencies to continually improve science-based risk assessment.

Another high-potential area is to deepen our understanding of what therapeutics and other useful specialized metabolites, plants, and their associated biota might provide; one example is synthetic biology production of artemisinin, an ancient Chinese herbal remedy, as a malarial therapeutic (Ikram & Simonsen, 2017; Peplow, 2016). High-throughput screening (Atanasov et al., 2015) of plant compounds produced paclitaxel (the cancer medication Taxol; McElroy et al., 2018; Rowinsky & Donehower, 1995), but development of screening tools with much higher accuracy and throughput is needed for health science and other applications. Novel developments may also be expected from investigations of how plant-associated organisms, especially microbes, contribute to and influence plant metabolic phenotypes. For example, the efficacy of some herbal remedies may depend on host plant–microbe associations (Huang, Long, & Lam, 2018).

To adopt these novel products successfully, a deeper understanding of the way in which genetic and environmental factors influence the responses of humans to plant and microbial products is needed. A further-off frontier concerns the factors affecting responses of individual humans to particular plant products. This understanding could lead to a form of precision natural medicine that improves lives across the globe—for example, by providing medications for multidrug-resistant bacteria (Dettweiler et al., 2019).

Finally, the potential to impact ecosystems positively through landscaping in urban environments remains largely untapped. Investments in green infrastructure can support insect biodiversity, provide habitat for endangered species, reduce stormwater runoff, and reduce water and nutrient inputs through permaculture practices and managed landscapes (Conway, Almas, & Coore, 2019; Planchuelo, von Der Lippe, & Kowarik, 2019; Suppakittpaisarn, Larsen, & Sullivan, 2019; Zhao, Sander, & Hendrix, 2019). Plants can also be used to improve human health through creation of recreational spaces, bioremediation of urban land (Sanchez-Hernandez, 2019), and improved nutrition and reduced food deserts through urban farming (e.g., vertical plantings), which could expand with attention to improving economics and energy use. Increasing the exposure of urban dwellers to plants and their biology in homes, schools, and after-school programs and across the built environment will help improve plant awareness and stoke interest in plant science careers (Goal 6).

Intersection with other sectors

For all these objectives, close partnerships with other disciplines and end users will be integral to success. For example, food and medical scientists will need to create and implement new methods for evaluating and validating the nutritional and therapeutic benefits of plant products, including why such products might be targeted to specific demographics versus the general population. Improved methods for quantifying potential and actual environmental bioremediation are also needed. Furthermore, if society is to fully benefit from our discoveries, environmental economists, landscape architects, urban planners, and social scientists should be brought into the conversation to evaluate benefits and promote adoption by producers and consumers.

Action plan: Goal 3

1. Develop new high-throughput tools to evaluate plant products for their potential in promoting human health, nutrition, and well-being. Those tools will apply to strategic screens of plants and associated biota to identify opportunities for future investment.
2. Develop a comprehensive understanding of the genetic, evolutionary, and environmental components of how plant systems-derived molecules confer beneficial or disadvantageous traits. Partnerships with environmental economists should be formed to develop metrics for quantifying ecosystem services, recreational benefits, and other environmental benefits.
3. Engage pharmacologists, medicinal botanists, indigenous peoples, and nutrition and food scientists to understand human metabolic processes and identify targets of plant-based medical compounds (Brown, Lund, & Murch, 2017; Pan et al., 2013). Identify achievable health improvements that could come from enhanced plant systems through modification and breeding.
4. Develop technologies to improve health and well-being and reduce environmental impacts in densely populated environments through enhanced urban forestry, reforestation and greening opportunities, bioremediation, urban farming, and environmental conservation.

2.1.4 | Goal 4: Launch the transparent plant, an interactive tool to discern mechanisms and solve urgent and vexing problems

Plant systems must sense and respond to moment-to-moment internal and external stimuli, changes that can be as subtle as the sun moving behind a cloud or as dramatic as unseasonal snowfall. To survive and successfully reproduce in a given environment, plants must constantly integrate multiple inputs and produce rapid and appropriate responses that regulate water flow, defense actions, and growth. Absent or inappropriate responses can result in extinction, whereas overly successful responses can result in invasiveness. Climate volatility adds another dimension to the importance of these responses. Such dramatic outcomes underscore the importance of dissecting complex plant responses at scales from the individual to the population; Goal 4 addresses a 21st-century computational approach to accomplish exactly that.

The transparent plant tool

We envision the Transparent Plant as an interactive visualization and query tool, a digital way of describing a plant and its components, eventually underpinning the creation of designed, autonomous plants. Its abilities to model and simulate are based on two components: extensive information on plant properties (a parts list) and software that, on the basis of that information, can predict plant behavior as individual parts are exchanged or modified. Designing an airplane or car, for example, is also based on a combination of component knowledge and engineering principles. In the case of plants, the parts list encompasses genomic, transcriptomic, proteomic, biochemical, cell biological, and phenomic data sets. The engineering principles are derived from empirical experimentation, using both existing experimental systems and those established as part of Goal 1. Data generated as part of Goal 1 can, in turn, be used to validate predictions made by the Transparent Plant, allowing iterative improvements in its predictive abilities.

Why is such a tool required to predict how plants will behave? One reason is that some long-standing questions are too complex to develop machine-independent experimental approaches. For example, what are the rules underlying plant diversification? How do plants shape their phytobiomes—that is, their environment, including all microbes and macroorganisms that interact with them—and how are they shaped by the environment around them? There are also mysterious, fundamental questions about plant architectures, which are wonderfully diverse; from cacti to marine plants to domesticated species to redwood trees, these architectures presumably evolved to facilitate growth, water and nutrient transport, and reproductive success.

The Transparent Plant will help us understand these mechanisms and inform our efforts to apply that knowledge. For example, as the tool is refined, it could be used to make predictions about how plants might behave when perturbed under drought or specific nutrient stress, or how particular genetic or biochemical interventions might promote plant health. In the case of an emergent pathogen, the Transparent Plant might quickly suggest targets to mitigate the spread or severity of disease. Fully developing the Transparent Plant will be a daunting challenge, extending well beyond the 10-year time frame of this document, but will also strengthen the community by providing a platform for deep and committed collaboration and cross-fertilization among disciplines within and beyond plant science.

Transparent Plant parts lists can be built iteratively for multifaceted processes such as photosynthesis, water transport, root navigation through soil, and immunity. These modular systems and processes must one day be integrated to a whole plant, ecosystem, and global scale. For the next decade, the focus should be on integrating data from the atomic level—including the nature of receptors, catalytic sites, and nucleic acid interactions—to the molecular, metabolic, cellular, and organ level, including the microbiome. The eventual result could be engineered plant autonomy: the ability of a plant to flourish in conditions that otherwise would have led to poor performance or its demise.

Transparent plant genome

The framework of the Transparent Plant tool is an annotated catalog of the tens of thousands of plant genes diversified among all species, a modern-day expansion of the basic gene function catalog originally envisioned in the Arabidopsis 2010 initiative (Somerville & Dangl, 2000). We support the Earth BioGenome Project

(Exposito-Alonso, Drost, Burbano, & Weigel, 2019), which aims to sequence the genome of many or all extant eukaryotic species, made feasible by new technology and reduced cost. However, sequence information is only the beginning of biological insight: knowledge related to these genes, including their regulation, how they influence metabolism, and how they interact, will need to be acquired. By merging data collected through experimentation with metadata analysis using machine learning tools (Valenzuela-Escárcega et al., 2018), we will be able to develop the "brain" of the Transparent Plant, which will underlie its query and predictive functions (Goal 8). An underlying challenge is to understand the roles of genes that have subtle individual roles but collectively essential roles in creating traits (Boyle, Li, & Pritchard, 2017). Reliable approaches to study such genes are still in their infancy.

The intelligence of the Transparent Plant will rely not just on the scale of information, but also on its precision. We must improve how we measure and analyze plant responses to environmental changes at both the molecular and physiological levels (some of the required instrumentation, including sensors, are described in Goal 7). Although the term "sensors" often implies devices that measure environmental parameters, plant size and shape, or processes such as photosynthesis, genetically encoded biosensors can provide real-time tracking of molecular movement, report the concentrations of chemicals such as calcium or starch, and provide monitorable feedback on developmental events within the plant (Oren, Ceylan, Schnable, & Dong, 2017).

Transparent plant simulations

The data warehouse for the Transparent Plant will build on existing resources (such as Ensembl Plants (Bolser, Staines, Pritchard, & Kersey, 2016), CoGe (Lyons & Freeling, 2008), CyVerse (Goff et al., 2011; Merchant et al., 2016), Phytozome (Goodstein et al., 2014), and others) to facilitate interdisciplinary discoveries through its comparative powers and set the stage for the development of increasingly complex models and simulations of specific plant processes. These would be accessed via the most innovative aspect of the Transparent Plant—a scalable and interactive simulation in which a researcher could visualize and predict the consequences of a stimulus such as light, a hormone, or a pathogen through molecular, cellular, and whole-plant animations (Iwasa, 2016; Nayak & Iwasa, 2019). This interface will require advancements in virtual reality technology and graphics processing capabilities that go well beyond currently available predictive models of root biology (Hartmann, Šimůnek, Aidoo, Seidel, & Lazarovitch, 2018; Jiang et al., 2019), C_4 leaf development (Bogart & Myers, 2016), plant–insect interactions (Pearse, Harris, Karban, & Sih, 2013; Pineda, Kaplan, & Bezemer, 2017), and other processes (Bucksch et al., 2017; Fatichi, Pappas, & Ivanov, 2016; Martinez et al., 2017). Simplified versions of the interface could be developed for learning purposes (Goal 6) in the same way the high school-appropriate DNA Subway (2020) on CyVerse complements the sophisticated and data-intensive gene comparison tools used by researchers. Transparent Plant predictions would be validated using phylogenetically diverse experimental systems, allowing for iterative improvement in its predictive ability and for discernment of the fundamental mechanisms governing plant systems.

Action plan: Goal 4

1. Use community input to develop a menu of desired traits to be predicted by the Transparent Plant, and prioritize species (informed by Goal 1) and genotypes for intensive experimentation.
2. Invest in the generation of extensive transcriptomic, proteomic, biochemical, cell biological, microbiome, and phenomic data sets from priority species strategically selected to span evolutionary and ecological diversity (including both C_3 and C_4 plants), gathered at multiple scales and from multiple genotypes under an agreed set of environmental conditions.
3. Expand and standardize genomics databases to identify DNA regulatory elements found in plant genomes (Lane, Niederhuth, Ji, & Schmitz, 2014) and reference phenotyping databases for the priority species. These databases will include genomic variations, epigenomic marks and DNA modifications, gene expression patterns, small RNAs, developmental stages, environmental responses, and gene regulatory and metabolic networks.
4. Invest in experimentation, data curation, and integration to assign functions to as many protein-coding genes as possible, together with a pathway or condition of interest for all noncoding genes in prioritized species.
5. Support the development of new tools for dissecting, modeling, and simulating plant processes, informed by the collected data, that will allow multiscale analysis and prediction of plant responses. Initially, individual processes would be modeled. Then, after experimental validation, individual models would be progressively connected to create higher order models.
6. Develop a virtual reality module and visualization tools to begin testing the Transparent Plant, focusing on key aspects and capabilities such as interactions, scalability, and predictive capacity.

2.2 | People

Assembling diverse teams is a challenge to plant scientists, and teams formed in response to short-fused funding opportunities often arise within tightly knit circles. Over time, this practice can result in the unproductive and dispiriting, if unintentional, exclusion of young investigators and other talented researchers. Moving forward, we urge scientists to identify new collaborators with much more diverse research and professional backgrounds across different institutional types. The majority of new research initiatives will span disciplinary boundaries and will greatly benefit from more creative thinking and broader professional networks.

Our community must also embrace the pursuit of equity, diversity, and inclusion (EDI) to make careers in science accessible and attractive to people of all backgrounds. We need to increase the availability and rigor of sensitivity training to create more inclusive spaces. The research community must be ready to reflect on effective actions to support EDI and implement these recommendations to improve job satisfaction and reduce discrimination.[1] We must also build capacity and interest to engage with plant science throughout diverse classrooms and communities. An activist approach should be used to promote plant awareness[2] and the importance of recognizing the impacts of plant systems in all aspects of people's lives.

Over the next decade, job openings are expected to increase in the life sciences and for postsecondary teachers (Torpey, 2019).[3] New opportunities in plant science-related jobs[4] underscore the need to rethink career expectations and to retool training paradigms to prepare researchers for careers beyond academia. The PSRN previously published recommendations for postgraduate training using a subway network metaphor to illustrate three main principles: flexible pathways, multiple career destinations, and the possibility of multiple on- and off-ramps (Henkhaus, Taylor, Greenlee, Sickler, & Stern, 2018). The PSRN further emphasized the need for trainee-centric approaches that offer trainees more control over their professional development through modular customization and a new mentoring model to help them with prioritization and focus. These training recommendations were expanded on at the PSRN Inclusivity in the Plant Sciences workshop with an aim to broaden participation. Diverse workplaces are more creative and productive (Chamorro-Premuzic, 2017; Dozier & Meiksin, 2019; Phillips, 2014), and the PSRN workshops have underscored the value of embracing diversity to enrich and transform science. Faculty demographics are almost universally out of step with demographic shifts in the United States as a whole,[5] leaving the plant science community woefully short of role models.

2.2.1 | Goal 5: Reimagine the workplace to nurture adaptive and diverse scientists

The Decadal Vision research goals will not be achieved unless we engage all the talent and diverse perspectives that society offers. This engagement is absolutely dependent upon transforming workplace culture: efforts to glamorize plants through bold actions to expand plant science and involve community scientists[6] (Goal 6) as tools for recruitment and diversification will fail if we do not. In doing so, we intend not only to raise awareness of the impacts of plant research, but also to capture imaginations and excite individuals to get involved. Goal 5 includes broad recommendations to recast the research culture and environment surrounding plant science people. We believe that the prevailing culture inhibits diversity because it rewards a narrow swath of backgrounds, behaviors, and motivations. One of the main thrusts of our recommendations is to implement mechanisms and policies that diminish the prevalence of academic silos, which can be reinforced by promotion policies. In some cases, training emphasizes the need to "own" a scientific niche, but in a collaborative culture, the whole will always be greater than the sum of its parts. We believe that plant scientists can lead such a transformation but acknowledge that the issue is far broader than plant science alone.

Nurturing equity, diversity, and inclusion

Addressing the disparity between faculty composition and US demographic shifts requires a concerted effort by all faculty and administrators. Historical criteria for recruitment and promotion need to be substantially rethought. For example, diversity statements are commonly required of faculty candidates, and, when such statements are used as an important criterion for recruitment, the stage is set for long-term and substantial advancement of EDI. The plant science community must follow through on the plans embedded in those statements and reward individuals who serve as role models and develop supportive activities. In general, we recommend that contributions by all faculty in support of EDI be acknowledged and rewarded not as a bonus, but as an expectation. These expectations and contributions are most likely to be substantial among underrepresented faculty themselves, meriting commensurate recognition.

Our institutions must foster more equitable, diverse, and inclusive environments that support all individuals, especially early career researchers, through formalized policies and access to resources. For example, early career scientists should have access to mentoring systems that make available teams of mentors who reflect and support their personalized career goals and sponsorship by a relevant role model (Gottlieb & Travis, 2018). Scientists at all career stages should be encouraged to use formalized individual development plans as a tool to set goals and facilitate conversations with their mentors (Hobin, Fuhrmann, Lindstaedt, & Clifford, 2012). Implementing such support dovetails with our previously published recommendations regarding direct funding of early career scientists (Henkhaus et al., 2018). Direct funding will allow individuals to shop for institutions best suited to their intended professional pathway rather than "following the money." Although some may feel that trainees at this career stage are not sufficiently mature or responsible to make such choices wisely, we believe they are, as long as high-quality mentoring is available to support their decision-making without controlling it. Implementation of direct funding, however, might call for progressive uncoupling of research grant-funding training from various forms of fellowships.

Recalibrating how research contributions are valued

A fundamental paradox of the current work environment is that metrics based on individual achievements are still, in many cases, the primary guide for evaluation and promotion, even though collaborative achievements deliver the most important scientific insights (Little et al., 2017; Read et al., 2016). In particular, academic organizations should develop more equitable policies to recognize collaborative contributions and distribute credit for successful teams, rather than mainly rewarding the most visible participants in a project, often according to budgetary or infrastructure control. Scientists may need to further decentralize authorship models beyond multiple first authors, and alternatives to traditional peer review should continue to be tested and implemented (Carroll, 2018). As long as individual-based metrics drive career advancement, laboratory management styles and mentoring strategies tend to reinforce these goals, leading similarly abled and like-minded scientists to land the jobs and perpetuate the system (Bendick & Nunes, 2012). Understanding why academia is organized this way, and whether it should be, is beyond the scope of this report, but it is worth considering how other models have thrived (Janelia Research Campus, 2020) in national laboratories, private industry, and private research institutions (Fiske, 1999).

It is necessary but not sufficient to value research contributions equitably, because culture change also requires that contributions including writing and running training grants, performing mentoring, and undertaking community engagement also drive career advancement (Morrison et al., 2019). These activities are often undervalued (Farrell & Flowers, 2018; Meyers, 2018) and therefore become the province of the good at heart, disproportionately members of underrepresented groups (Taylor, 2020). Adequately valuing team research and community service would not only change research culture, but also attract a currently self-excluded type of scientist who does not seek individual credit but rather wishes to participate without drama in a collaborative enterprise (Leeming, 2019; Mervis, 2016; Walker, 2020). Faculty hiring across broad themes is not unusual; however, basing hiring decisions on candidates' capacity to work in teams will require alternative mechanisms.

Virtualizing the workplace

Each of our four research goals encompasses integrated, transdisciplinary research. For this purpose, science needs to move rapidly beyond a predominant dependence on physical collaborations by creating and supporting virtual workplaces that span institutions and international borders. Virtual workplaces are already used to save time and decrease carbon footprints associated with travel, for example, to participate in review panels. But as we consider the practice of science with these optics, the abilities to operate equipment remotely, to share data almost instantaneously, to video stream methods (Ather, 2019), and to incorporate virtual reality only hint at the possibilities. Indeed, the SARS-CoV-2 pandemic had accelerated adoption of many remote technologies even as this report was being finalized. At the same time, classroom instruction was moving online at warp speed, which in the long term will benefit early career researchers who wish to train remotely for both technical skills and professional development.

We encourage universities and professional societies to use their resources and networks to ensure equitable access to these tools and opportunities. Virtual workplaces will promote EDI by increasing participation of students and faculty at primarily undergraduate universities, minority serving institutions, and community colleges. In addition, virtual workplaces will support increasingly broad and sophisticated participation of community scientists. Equitable access to supporting technologies will be needed to democratize their use (Goal 7). In the case of research technologies, democratization is aided by reduced cost, ease of use, and miniaturization.

With all of its promise, the virtual environment will not erase the need for direct human interactions. Not only are humans inherently social, but spontaneous "coffee pot" interactions and nuanced conversations can never be replaced by computers, nor should they be. The SARS-CoV-2 pandemic has showcased the power, but also some limitations, of the virtual world of science. The appropriate balance of virtual and face-to-face interaction will vary enormously and evolve in concert with available technology and societal norms.

Action plan: Goal 5

1. Incentivize academic institutions to rethink criteria for faculty hiring and promotion to place a premium on interdisciplinary collaboration, team science, and activities that support increased EDI.
2. Ensure that the outsized role carried by underrepresented faculty in supporting EDI is fully acknowledged and rewarded.
3. Fund postgraduates directly and provide multipoint mentoring coupled with the use of individualized development plans.
4. Provide customized T-training opportunities for diverse career pathways (Henkhaus et al., 2018), incorporating microcredentialing for graduate and postdoctoral training that emphasizes integration across disciplines.
5. Support infrastructure and computational resources that underpin workplace virtualization and use this capacity to accelerate collaborative research and community science.

2.2.2 | Goal 6: Build capacity and interest to engage with plant science

Science communication

Without effective communication, we cannot demonstrate the relevance of plant science to society, cultivate the next generation of researchers, understand the communities around us, or forge new scientific relationships across disciplinary boundaries. Blurring or even erasing boundaries will lead to longer term and more productive collaborations, more cross-training of early career researchers, better experimental design, and greater satisfaction on all sides. We must optimize communication methods for social media, a major form of engagement with the external world. Science communication also encompasses writing skills for presentations to various audiences, along with speaking and listening skills applicable to a range of situations. Although many researchers are skilled at answering technical questions, few are prepared for media interviews or public forums that challenge broad swaths of work or facts taken for granted in the scientific community. Scientists might learn to prepare and deliver a 3-minute lightning talk and an elevator pitch, draft a press release, dig deeper into communications tools for a specific purpose (Cornell Alliance for Science, 2020), or, as is increasingly common, participate in outreach to schools, science museums, and other community groups.

Practice makes perfect. To that end, communications training needs to be available outside of formal academic curricula. For example, outreach coordinators can support graduate students and postdocs who are conducting extracurricular activities, often to implement the "broader impacts" components of their research grants.

We recommend that opportunities for training in both technical and nontechnical science communication be ubiquitous for plant scientists. We encourage universities to require science communication more frequently in undergraduate curricula (Cirino et al., 2017; Hoffmann-Longtin, 2019) even when such communication might seem to be a peripheral skill at that stage. If this training is successfully implemented, budding scientists will become spokespeople calling attention to the relevance of plant science to people's lives and its nearly limitless potential to improve them.

Early development of plant awareness

Although these recommendations have focused mainly on the postgraduate and academic space, we are keenly aware that appreciation of plant biology is more likely when exposure begins early in people's lives. Many plant scientists are raising children and are therefore aware—sometimes painfully so—of how little attention plant science gets in school. These parents are prime examples of individuals who could engage with K–12 school systems to increase plant awareness (Balding & Williams, 2016). This approach does not at all exclude grassroots efforts by all parents (Rozek, Svoboda, Harackiewicz, Hulleman, & Hyde, 2017), who collectively will influence whether children will become plant aware and therefore can be bearers of our message.

"Awareness" connotes learning not only about plant science in society and daily life, but also about the esteem in which plant science, and its attendant career options, are held. We support advocacy for standards in K–12 biology to incorporate more plant science (Balas & Momsen, 2014; Uno, 2009) and to avoid plant science being subsumed into biology instruction with fleeting references to plant systems (Frisch, Unwin, & Saunders, 2010). Relevant touch points include how plant science contributes to human and ecosystem health, ecosystem services, and agriculture and its impact on sustainability and climate change. Likewise, where standardized testing is required, it should embed knowledge of plant systems and how society interacts with such systems.

Careers in plant systems science

Perception of plant science will not be improved solely by communicating knowledge: we must also promote its diverse, exciting, and satisfying career options. Hands-on training through laboratory coursework and independent research projects is highly effective in building awareness of opportunities through research experiences, and undergraduate education plays an important role in providing experiential training opportunities (González, 2001; Wilson et al., 2018). Even with research experiences, other factors such as financial potential (Melguizo & Wolniak, 2012; Xu, 2017), time to degree completion, and job prospects may impact postsecondary students' decision to pursue a plant science career. Plant science jobs pay well, and generally postgraduate training generates little debt (Bureau of Labor Statistics, 2018c). The top-paying jobs of today include several in computational science and research and development management (Connley, 2017), both of which are critical to the development and application of plant systems science. Using another lens, among employers' five most desired soft skills for 2019 were creativity, persuasion, collaboration, adaptability, and time management, according to one source (Petrone, 2019). All of these can be acquired and practiced through training and experience in plant systems science. These attributes of plant science careers must become broadly appreciated.

Career opportunities should be introduced to students as early as possible, with emphasis on the possibilities for flexibility over time, including opportunities for postbaccalaureate, masters, or doctoral training. Scientific societies must share information on the breadth and promise of plant science careers with K–12 teachers and undergraduate career counselors. A culture of active career planning for scientists at every level of training should be promoted through the development of specific lesson plans and mentoring systems.

Another mechanism is developing a centralized system to track plant science jobs in the public and private sectors, along with the associated career trajectories. An emphasis on existing job opportunities will help improve outcomes for women and other members of underrepresented groups in science, who may disproportionately encounter challenges at career or educational transition points. An assessment of current jobs is also needed to determine what training experiences are important for successful preparation and to facilitate the development of an interactive tool to guide students toward desired careers (Henkhaus et al., 2018). Critically, this assessment should go beyond traditional academic metrics to measure transferable skills and abilities imparted by experiences in public outreach, teaching, mentoring, service, project management, and advocacy.

Direct community engagement in science

The narrow perception of plant science as low-cachet (e.g., compared with biomedical fields) needs to be expanded through deliberate public engagement with farmers, teachers, families, and policy makers. The reach of plant science into space (Webb, 2017), the use of plants for medicinal purposes, and the emergence of inventions such as plantlike robots (Dudenhoeffer, Bruemmer, Anderson, & McKay, 2001; Heilweil, 2019), may have great appeal for a broader audience. The numerous recreational benefits of plants can also be emphasized; for example, urban gardens educate, provide aesthetic beauty, and literally nourish a community (Dig Art! Cultivating Creativity in the Garden, 2020; Khoury et al., 2019; Lev-Tov, 2019; Rodgers & Krcmar, 2018). Increasing public engagement through outreach by scientific societies will encourage the next generation of learners to appreciate the role of plants in their local communities.

Public engagement through community science can leverage existing resources and outreach programs to expand our understanding about the natural world. For example, citizen science projects through natural history museums and botanical gardens can supplement K–12 and undergraduate education programs (Bonney, Phillips, Ballard, & Enck, 2016). These programs allow students to actively participate in gathering valuable data about plant biodiversity (Goal 1) and play an active role in raising awareness for scientific research and impacts on society. A growing body of research suggests that formal K–12 or undergraduate education is not the primary mechanism by which the public engages with science; in fact, most science learning is free-choice (Dunlop, Clarke, & McKelvey-Martin, 2019; Falk & Dierking, 2018; Falk & Needham, 2013; NOVA Education, 2016), often through weekend family visits to a science museum or botanical garden.

Scientists can increase access to and expand the availability of free-choice informal science education by participating in volunteer outreach activities and distribution of learning resources (Holland, 2018). This outreach, in turn, may catalyze community engagement with plant science-related issues such as ameliorating environmental degradation, preserving biodiversity, or creating better jobs. The research community should establish collaborative projects to engage community scientists in these local issues as adjuncts to research projects, particularly in the context of centers or institutes that are highly multidisciplinary.

Action plan: Goal 6

1. Improve and universalize science communication training for the current and next generation of plant systems scientists.
2. Integrate modern plant science education into standardized testing and curricula for secondary and undergraduate coursework and leverage networks of scientific societies to distribute lesson plans and amplify synergistic activities among organizations.
3. Develop resources and training modules to prepare the next generation of plant scientists for diverse career pathways.
4. Increase public engagement by plant scientists, especially through support of free-choice learning.

2.3 | Technology

Advances in technology can be found intertwined with virtually every transformative discovery in the life sciences.[7] Today, miniaturization, automation, and AI are radically transforming data collection along a trajectory that, in 10 years' time, will utterly dwarf our current data sets (Kodama, Shumway, & Leinonen, 2012).[8] We can already imagine technologies for synthesizing new microorganisms or reconstructing extinct species, but it is what we cannot yet imagine that will amaze us and catalyze new breakthroughs. The plant science community must challenge itself to raise its sights, think differently, and be unafraid of audacious research investments that may become transformative.

Many of the technological challenges faced by plant systems science are common to the environmental, health, engineering, and data sciences and, most importantly, have implications for activities of everyday life. For example, the development of self-driving cars is dramatically advancing technologies for translating large-scale data streams from sensors into real-time decision-making via portable, low-power computing systems. For plants, similar technologies, as they become more affordable, can help farmers make decisions on when to plant, water, fertilize, harvest, and treat disease (Kundu, Krishnan, Kotnala, & Sumana, 2019; Zahid et al., 2019). The area of a field is often too great for a farmer to monitor without the aid of remote sensing, and advanced imaging platforms enable the identification of problems before they affect plant health, productivity, and profitability. Similarly, the possibilities for "microbiome therapy" are as alluring in agriculture (Toju et al., 2018) as they are in human health; regarding the latter, more than 2,000 clinical trials were in progress in 2018 (Fernandez, 2019).

2.3.1 | Goal 7: Develop new technologies to revolutionize research

High-throughput technologies

Sensor technology—already billion-dollar market in agriculture alone—will see innovation in the form of both new and improved sensors. New sensors include those that can be applied directly to plants for monitoring *in planta* processes and metabolic levels, including microbial activity, and those developed to monitor belowground activities of plants and their associated biota (e.g., root response and development) and nutrient fluxes. Existing sensors will continue to improve in both sensitivity and portability while integrating data analytics and wireless networking options (described in Goal 8). Sensor costs are rapidly decreasing, which will enable extensive networks to be deployed over large areas to characterize microscale environments and support crop management strategies. Required engineering expertise will include optics, imaging, advanced electronics, and microelectronics, as well as microfluidics.

Imaging will continue to be a large component of remote sensing. Developments in imaging will include static and video imaging of biological processes at all scales combined with automated image recognition. These data will complement the genomic, chemical, physiological, and environmental data that will populate tools for the digital biosphere and its derivatives (Goal 1) and the Transparent Plant (Goal 4). Examples include deciphering changes in subcellular processes during abiotic or biotic stress, identifying crop diseases and pests, and assessing plant species mortality in forests. Similarly, drones, ground vehicles, and satellite imaging are being used to monitor ecosystems and agricultural fields, but data must be quickly interpreted and provided to growers in order to trigger necessary interventions. Current technologies remain labor-intensive and require specialized training, however. Major advances are needed in the speed, sensitivity, resolution, and portability of imaging devices from microscopes to satellite cameras. These efforts will in turn require far more economical handling of the resulting massive data streams and advances in image recognition, including edge (real-time) computing (Ghosh, 2018).

Portable laboratories

Whereas portable DNA sequencing is a reality today, increasing portability of other analytical techniques is an emerging opportunity. Mass spectrometry (chemistry) and proteomics are among the frontiers, and eventually we foresee handheld devices (e.g., "tricorders" (Warmflash, 2017; Wikipedia, 2020)) for minimally destructive and rapid analysis of specimens. Portable, lower power instruments capable of collecting and preprocessing genotypic and phenotypic information will facilitate research in remote locations with limited network connectivity. Low-cost genomics tools such as nanopore sequencing technologies (Kono & Arakawa, 2019) will continue to be crucial for field research (e.g., ecological studies) and are ideal for engaging diverse participants. As for sensors, portable laboratory data should be analyzed in the field initially (e.g., through edge analysis (O'Grady, Langton, & O'Hare, 2019)), where possible using widely available phone or tablet apps.

Action plan: Goal 7

1. Invest in high-throughput imaging technologies from the subcellular to the landscape level.
2. Improve sensor technologies to monitor *in planta* processes, metabolomics, and interactions with the environment.
3. Develop portable laboratory technologies using edge computing for real-time data capture and analysis in the field.

2.3.2 | Goal 8: Manage and realize the potential of big data

The "big" in big data keeps growing: The 30 quadrillion DNA bases in the public National Center for Biotechnology Information repository are growing nearly exponentially; image data streams, even for small experiments, are even more massive (Brouder et al., 2019). To put it another way, we are in the petabyte (10 (Qiu et al., 2014)) era for storage but the zettabyte (one million-fold higher) era for global data flow (Reinsel, Gantz, & Rydning, 2018). Thus, long-term storage and real-time data handling are significant but independent issues. Data must also be integrated when possible, whether from multiple field sites inventoried over a period of years (Maize Informatics Research Coordination Network, 2019) or from comparison of recent data sets with those created a generation ago. These data must be made readily available to researchers for analysis and discovery; realizing each of the Decadal Vision goals will require technology for data collection (hardware) and analysis (software) on scales that dwarf what we can currently achieve. Major barriers to integrating asynchronous data sets include the vast heterogeneity and poor annotation of historical data and the need to create standardized formats for newly created data types using often idiosyncratic emerging technology platforms. Finally, deriving biological meaning from data is a never-ending quest that requires attention to collection, integration, and analysis.

Cyberinfrastructure

The PSRN has made detailed recommendations on the cyberinfrastructure, big data capabilities, and training needed to advance plant systems science in the *Plant Systems Cyberinfrastructure 10 Year Strategic Plan*, which had a theme of connections—among data sets, tool sets, platforms including databases, plant and information science researchers and educators, the private sector, and the public (Plant Science Research Network, 2017; Tyler, Stern, Lyons, Henkhaus, & Taylor, 2019). Below we highlight some specific cyberinfrastructure and big data capabilities needed to advance our Decadal Vision agenda (see also Goals 1–4).

Data communication for field applications

Because single sites may deploy many hundreds or even thousands of sensors and cameras, the capacity for on-site data analysis and management will be required because it may be impossible to store data at a remote site or to transmit it to a central site for storage and processing. The sensors may be measuring very different things, such as belowground chemistry, images of flowers, internal small molecules, and pollinator visits; this is the multimodal nature of the problem. To address the challenge, sensors will need to connect to ad hoc mesh networks—a dynamic way of interconnecting devices that avoids the need for a permanently installed network (Cilfone, Davoli, Belli, & Ferrari, 2019)—to send their data and results to an on-site multiaccess edge computing (MEC) system to extract important features and signals.

Field-deployable MEC systems—called "edge" systems because they lie close to the site of data collection rather than at a distant location—can coordinate and collect data packets from multiple data streams, performing further processing that requires more computational resources than can be provided on sensors but that does not require sending all the data to the cloud or a centralized server for initial analysis. Eventually, the MEC system can coordinate the transfer of data either to an off-site centralized system or directly to a researcher. In addition to coordination of data movements and preprocessing, additional software and information technology (IT) systems need to be developed for MECs that permit researchers to easily add novel analysis tools for testing and deployment. Remote monitoring of sensors and the health of the mesh network will be needed for rapid identification of bottlenecks, faulty behavior, or other IT problems that occur at a remote site (e.g., power and hardware failure, vandalism of equipment, runaway algorithms).

Machine learning and artificial intelligence

Although a variety of approaches to improving machine learning (ML) algorithms exist, training and testing data are important in the development and validation of new ML models. Advances are needed to generate large training data sets (e.g., COCO, 2020 Dataset used to train object recognition) and ML model repositories (e.g., Model Zoo [2020] a collection of codes and trained models) that are designed around the types of data and learning desired for plant systems research. AI is a long-term goal for plant systems scientists to enable a diminishing amount of human intervention in pursuit of increasingly complex systems biology queries, especially those anticipated for Goals 1 and 4. It is expected that other disciplines will drive AI advancements that can be incorporated into plant science and opportunities far beyond ML. Deep learning, machine reading, and explainable AI will be included in plant science within 10 years; we can look to programs like the Defense Advanced Research Projects Agency's World Modelers

(Virginia Tech, 2018; World Modelers, 2020) to understand how big data can be used to identify underlying biological mechanisms. Quantum computing has the potential to accelerate many of these developments.

Action plan: Goal 8

1. Establish and expand resources that enable integration of multimodal data including ontologies, data standards, and reference data sets.
2. Expand repositories of broadly validated and well-documented tools, models, and services for analyzing multimodal data including, but not limited to, ML models and AI software.
3. Strengthen the interoperability and federation of major existing repositories and analysis centers for multimodal data about plant systems, including expansion of web services and semantic tools.
4. Improve algorithms and hardware to support on-site processing for multimodal data streams and analytical intelligence in the field, including advanced MEC systems.
5. Complete the implementation of high-speed (currently 5G) Internet connectivity for all rural communities so that data analysis centers, research scientists, extension personnel, farmers, and ecosystems managers can all be integrated into the plant systems knowledge network.

3 | IMPACTS OF THE DECADAL VISION

By investing in the bold agenda outlined in this Decadal Vision, the plant science community will realize impacts both within our community and in society at large (Figure 2). These anticipated impacts can be included in efforts to communicate our goals, seek financial support, and attract and retain participants.

The following impacts are anticipated within the plant science community:

- New discoveries and greater understanding of fundamental plant systems biology in many contexts
- Greatly improved access to new and existing data, tools, and technologies
- Breakdown of communication barriers and disciplinary silos
- Changes to academic culture that support equity, service, and teamwork
- Diversification of participants and training opportunities and a greater sense of belonging.

The following anticipated impacts will reach beyond plant science:

- Improved engagement with the public through communication and community science
- Participation from communities that have not traditionally been represented or included
- Dividends in economic growth, human health, and environmental quality
- Partnerships that accelerate the translation of discoveries to product development.

4 | INVESTMENTS

Research investments have a high return multiplier because they lead to new technologies and increase productivity. Such investments are often the most promising or only path to addressing large-scale, science-related challenges such as those described in this report. The agenda we have laid out will require several types of investments, and the impact will scale with their magnitude.

4.1 | Foundation and agency-defined research grants

Investigator-initiated, federally funded awards will develop many of the individual pieces of the large puzzles we describe. Their often low, and sometimes abysmal, funding rates leave many ideas

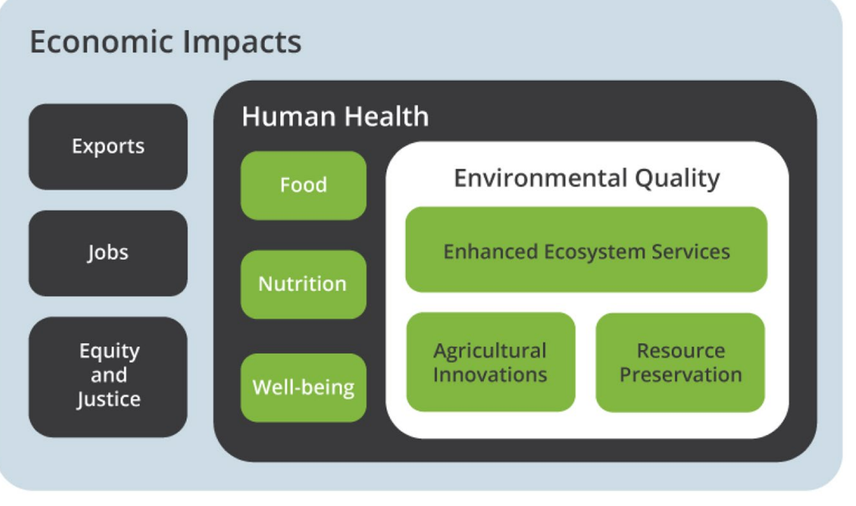

FIGURE 2 Realizing the Decadal Vision will have societal impacts. The activities described in this document will have many layers of impact, both directly and indirectly related to the research agenda

on the table and result in great inefficiencies in terms of agency, peer reviewer, and applicant time. We advocate a doubling of the funds available to such programs, leading to award rates of 15% to 30%.

Some problems are best tackled with a team approach that can be supported through targeted or thematic large investments. Examples of successful federal initiatives in plant systems science include the NSF Plant Genome Research Program, Arabidopsis 2010, and DOE Energy Research Centers. Newer, cross-cutting examples include Rules of Life, Dimensions of Biodiversity, and Biology Integration Institutes. Among private organizations, the Bill and Melinda Gates Foundation and the Foundation for Food and Agriculture Research, among others, have made their mark through targeted investments in plant science linked to society. The groundbreaking Basic Research to Enable Agricultural Development (BREAD) partnership (NSF, 2015) between the Gates Foundation and NSF could be emulated in other forms to leverage resources and meld interests of public and private funders.

There are great opportunities for increased engagement by some funding agencies in plant systems science. Some examples are the Defense Advanced Research Projects Agency for biosecurity, the United States Agency for International Development for food security, the United States Environmental Protection Agency for environmental sustainability, the National Institutes of Health for discovery and applications of plant chemistry, and the National Aeronautics and Space Administration for adaptation of plant function to space flight. All of these funders currently support plant science but have both the need and the capacity for much-increased investment. A healthy balance must be maintained between “big” and “small” science because “big” science is not always more efficient, and it also has a higher bar to entry for investigators who cannot easily identify and join relevant consortia or whose position or institution is more amenable to individual grants.

4.2 | Private sector investments

Industry is a great beneficiary of scientific training and discovery, and we strongly encourage augmented support for collaborative research, technology sharing (e.g., private sector investments in plant transformation (Bayer; Lowe et al., 2016; Masters et al., 2020; Mookkan, Nelson-Vasilchik, Hague, Zhang, & Kausch, 2017)), and direct support of trainees as interns and in graduate programs. Industry is part of our plant science community, but its incentives, vision, and mission are distinct from those of academia. Industry offers product development mechanisms, advanced technologies, and a team mentality from which academia can benefit and learn, whereas industry relies on the academic sector for staffing and discoveries that arise from the exploratory bent of institutional science. Partnerships between these two community sectors must build on and benefit from the unique talents and attributes of the other.

4.3 | Investments in people

We advocate direct funding of trainees, requiring the availability of suitable competitive mechanisms. Training grants such as NSF Research Traineeships are visionary but have a very narrow reach because of their cost and complexity. NSF’s Graduate Research Fellowships Program, by contrast, provides awards to individuals and can be an excellent launch point for early career researchers, particularly for those pursuing academic positions. We advocate additional mechanisms designed to support individuals at any career stage who are seeking modular scientific training but not necessarily positions in academia. Such individuals may be transitioning from undergraduate to graduate education, returning to science after a hiatus, or switching to plant science from another field. Such programs should be linked to mentoring capacity that can help trainees with application preparation, which most existing programs lack. This approach will help immensely in creating equity in the applicant pool without reliance on overstretched counselors or family members who may not be familiar with the institutional training environment. Equity-linked fellowships of this nature would be a major step toward diversifying plant science and the life sciences more broadly.

4.4 | Specific investment priorities

Whereas our goals describe end points of the Decadal Vision efforts, it is important to outline specific resources or investments that will lead to success. The Action Plans under each goal are rich sources of concepts to develop funding opportunities that may be suitable for federal, foundation, or industry support or support by hybrids of these entities.

5 | RISKS AND BARRIERS TO SUCCESS

This Decadal Vision promotes a departure from the status quo, not for the sake of change alone, but for the benefit of our science and community. Here we consider the risks and barriers to implementing such changes and the cost of inaction.

We have identified four primary risks to the success of the Decadal Vision. The success of our initiatives will ultimately reflect our mitigation of these risks.

5.1.1 | Suboptimal group balance

The plant science community is an interdependent network of stakeholder institutions that include universities and scientific societies, individual researchers, federal funding and regulatory agencies, industry, and farmers. All of these stakeholders have developed norms within this larger network, and any major changes can disrupt them all. In populating the workshop's participants, we attempted to hit a sweet spot between a big tent approach and a more focused group.

We may have excluded certain stakeholders unintentionally; if so, we hope to remediate this through later engagement.

5.1.2 | Disruption of the status quo

We may experience pushback from community members who prosper under the status quo. Even researchers who do not substantially benefit from the status quo may be resistant to changing the system and may fear unknown side effects of such a change or loss of resources as priorities are realigned.

5.1.3 | Perception of noninclusion

Some community members may perceive that their active research area is absent from this report. This perception is prone to arise more often in broad brush visions like this one that describe large and multidisciplinary areas of emphasis. We emphasize that this 2020 Decadal Vision is not exclusive and points toward new opportunities; our vision is not meant to exclude or devalue existing avenues of inquiry.

5.1.4 | Lack of resources and engagement

The Decadal Vision articulated in this report is audacious. It will require an extensive commitment of resources and full engagement of all stakeholders using sector-specific strategies. This vision will fail if we do not believe in our ability to work together and overcome intimidating challenges.

5.2 | Risks of inaction

The potential costs to society of inaction or insufficient action (e.g., investment to support the Decadal Vision goals by universities, government, and private sector) are myriad. Food, water, and medicine may become more expensive and harder to find and the scientific workforce will be less equipped to address future needs. Costs will potentially scale to climate change-driven starvation and global political instability.

On the other hand, the return on investment for federal funding of agricultural research is $20 for every $1 in support (Bartuska, 2017). Anticipated economic losses to agriculture because of climate change (Martinich & Crimmins, 2019) could potentially be mitigated by new research. The costs of inaction to our individual research areas are less definitive, but a major one is irrelevance. If we do not adjust our research to meet stakeholder needs by addressing new themes and problems, there is less reason to continue to hire researchers or for federal agencies or philanthropists to provide funding. As discussed in Goal 6, education of policy makers and the general public is critical to ensure long-term support for plant science research.

6 | HOW TO GET INVOLVED

We hope the Decadal Vision will inspire you to act. The plant science research community is encouraged to share this report. Feedback and documented outcomes can be shared with the PSRN on the Plantae Community page (Plant Science Research Network, 2020). Plant scientists can make use of available resources to support their communication efforts and to promote the messages of the Decadal Vision to policy makers and their communities (e.g., students, university administration, scientific society leadership). The PSRN community page makes available practical communication resources (e.g., presentation slides, images, flyers) to aid in these conversations. The PSRN member societies support the Decadal Vision by providing a variety of ways for their membership to get involved and contribute broadly.

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ENDNOTES

[1] For example, in a survey on job satisfaction in science, although some 68% of academic scientists were satisfied in their job (compared with 79% in industry), 47% of respondents had experienced gender discrimination, and only half felt that their university was doing enough to promote diversity and inclusion (Woolston, 2018).

[2] As a matter of inclusion and sensitivity, the use of “plant blindness” as an ableist metaphor will be discontinued in favor of a focus on increasing “plant awareness ” (Allen, 2003).

[3] The number of postsecondary teachers is expected to increase by 11% over the next decade (Bureau of Labor Statistics, 2018b) whereas tenure track positions will likely remain flat (Flaherty, 2003).

[4] Plant science-related jobs, including research technicians, food scientists, conservationists, microbiologists, biochemists, and environmental scientists, among others, are expected to grow (Bureau of Labor Statistics, 2018b).

[5] For example, a detailed 2017 survey of 40 public institutions found biology faculty to be 83% White, 13% Asian, 3% Hispanic, and 0.7% Black and 69% male (Li and Koedel, 2017). The Census Bureau has predicted that by 2035, the US population will be 54% White (non-Hispanic), 7% Asian, 22% Hispanic, and 14% Black (U.S. Census Bureau, 2017).

[6] *Community scientists* are students, citizen scientists, and lifelong learners who support efforts to catalog living collections, identify and characterize species in natural environments, reinforce outreach activities, and participate remotely in monitoring or data analysis for urban gardens and digital agriculture (Johnson, 2019; Tachibana, 2019).

[7] Examples include X-ray crystallography, mass spectrometry, the Internet, confocal and cryo-electron microscopy, DNA and genome sequencing, polymerase chain reaction, CRISPR, LiDAR, and many others.

[8] The federally supported Sequence Read Archive currently houses more than 30 quadrillion bases of information, a number that is growing by some 2 trillion per day (SRA Database Growth, 2020).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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