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WHITE PAPER

Inclusive collaboration across plant physiology and genomics: Now is the time!

Interdisciplinary Plant Science Consortium

Correspondence
Ivan Baxter, Donald Danforth Plant Science Center, ASPB Needs Better Online Systems, 975 N Warson Rd, St. Louis, MO 63132, USA.
Email: ibaxter@danforthcenter.org

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Abstract

Within the broad field of plant sciences, what are the most pressing challenges and opportunities to advance? Answers to this question usually include food and nutritional security, climate change mitigation, adaptation of plants to changing climates, preservation of biodiversity and ecosystem services, production of plant-based proteins and products, and growth of the bioeconomy. Genes and the processes their products carry out create differences in how plants grow, develop, and behave, and thus, the key solutions to these challenges lie squarely in the space where plant genomics and physiology intersect. Advancements in genomics, phenomics, and analysis tools have generated massive datasets, but these data are complex and have not always generated scientific insights at the anticipated pace. Further, new tools may need to be created or adapted, and field-relevant applications tested, to advance scientific discovery derived from such datasets. Meaningful, relevant conclusions and connections from genomics and plant physiological and biochemical data require both subject matter expertise and the collaborative skills needed to work together outside of specific disciplines. Bringing the best expertise to bear on complex problems in plant sciences requires enhanced, inclusive, and sustained collaboration across disciplines. However, despite significant efforts to enable and sustain collaborative research, a variety of challenges persist. Here, we present the outcomes and conclusions of two workshops convened to address the need for collaboration between scientists engaged in plant physiology, genetics, and genomics and to discuss the approaches that will create the necessary environments to support successful collaboration. We conclude with approaches to share and reward collaboration and the need to train inclusive scientists that will have the skills to thrive in interdisciplinary contexts.

1 | BACKGROUND

Complex societal challenges typically require collaboration of experts from diverse scientific disciplines. This holds true for the most pressing challenges in the field of plant sciences. It has become increasingly

A list of participants and their affiliations is provided in Supporting Information.

clear that successful and effective collaboration requires sustained support. For this reason, colleges and universities, funding agencies, industry partners, and scientists have made concerted efforts to increase and encourage collaborations and to improve their quality and efficiency. These efforts, over decades, have reshaped the landscape of plant physiology and genomics research into one that is increasingly collaboration-centric (Figure 1). However, supporting and recognizing successful collaborations across disciplines and institutions still faces cultural (between fields and institutions), educational (how scientists are trained), and inclusivity (gender, racial, and financial) barriers (Hofstra et al., 2020; Institute of Medicine et al., 2011; National Academies of Sciences and Medicine, 2021; Nielsen et al., 2017; Shaw et al., 2021). Creating functioning collaborative teams that connect people beyond local and regional institutions and across diverse communities remains a challenge (Box 1). Here, we present the outcomes and conclusions of two workshops convened to address the need for collaboration between scientists engaged in plant physiology, genetics, and genomics and to discuss the approaches that will create the necessary environments to support successful collaboration. We conclude with approaches to share and reward collaboration and the need to train inclusive scientists that will have the skills to enable interdisciplinary science.

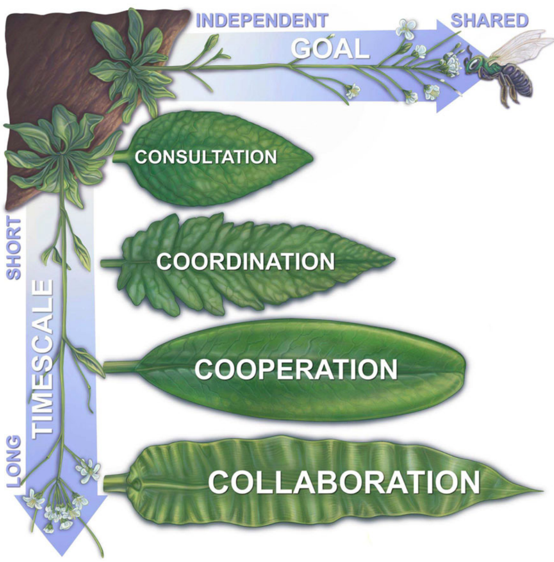
In October 2020 and March 2021, two workshops funded by the National Science Foundation (NSF) and USDA-NIFA engaged scientists from across the world. The objectives of the workshops were to (1) identify successful strategies that use physiology, genetics, and genomics to understand how plants respond to the environment; (2) identify scientific and technological gaps that could be bridged by interdisciplinary approaches; (3) identify communication and collaboration challenges to overcome; and (4) propose solutions and directions to advance the interdisciplinary plant sciences field. Although we started with a specific focus on interdisciplinarity between plant physiology and genomics, our discussions soon extended to the challenges of interdisciplinary research in general, and we discuss both in this white paper. We present here the results of our discussions, including

1. The need for interdisciplinary collaboration in plant physiology, genetics, and genomics.
2. Identifying collaboration-friendly challenges.
3. Creating inclusive collaborative environments by finding and engaging collaborators.
4. Enabling and sharing successful collaborations.
5. Training collaborative and inclusive plant scientists.

FIGURE 1 Bridging the disciplines of plant physiology and genetics/genomics will require an interdisciplinary approach and further efforts to reorganize how our science culture works. DEI, diversity, equity, and inclusion. Figure created by Lindsay Erndwein.

BOX 1 Defining collaboration

Effective scientific collaborations require moving beyond simple consultation, coordination, or cooperation and toward a goal of co-creating, co-owning, and co-solving research problems with shared vision, shared values, interdependence, and individual empowerment. The definitions of collaboration, consultation, coordination, and cooperation can be confusing; key to distinguishing these terms is an emphasis on the goals of the interaction and time needed to accomplish the goals (Castañer & Oliveira, 2020). Consultation is a starting point for collaboration as it requires a recognition of each party's expertise in solving a scientific problem.



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Box Figure: Achieving strong collaborations requires time and effort. Figure created by Lindsay Erndwein.

Coordination involves integrating or linking together different activities to accomplish a collective set of objectives. Cooperation is an additional step in which cooperators participate in project planning and mutual respect, transparency, and shared goals are developed. Fully mature collaborations require deeper relationship building, trust between the parties, and significant intellectual investment from all involved. New ideas are generated and shared as a group, and a long-term investment is made in the group's culture. Such collaborations enable interdisciplinary science with the potential to advance the most important and challenging questions in genetics, physiology, and beyond. The importance and necessity of collaboration in driving progress in many disciplines have already been described (Way et al., 2021). Singleton and Traynor (2015) pointed out that the genetics field has greatly changed over the past two decades as it evolved from a highly competitive, individual gene-hunting exercise to a collective and collaborative approach that involves sharing data to drive discovery. They were writing about advances in human disease diagnostics, but the same applies to plant sciences.

2 | THE NEED FOR COLLABORATING ACROSS DISCIPLINES IN PLANT PHYSIOLOGY, GENETICS, AND GENOMICS

Plants are complex systems governed by known and unknown rules of life. Some of these rules govern plants at their most fundamental molecular level, but phenotypes are an emergent property of a complex system. The differential expression of genes in response to environmental cues determines plant phenotypes and phenotypic plasticity. This gene-to-phenotype mapping is a main motivator for advocating improvement of our approaches to linking genetics, genomics, and physiology. We must bridge spatial and temporal scales so that molecular mechanisms can be integrated with whole-plant responses. We refer to gene-to-phenotype mapping as *upward causality* because our reference framework places genes at a lower level of organization than plants. However, plants respond to other plants and the soil, photosynthesis in the chloroplast depends on the photons reaching the leaf, and photons reaching the leaf depends on the position of the leaf in the canopy. In such circumstances, causality reverses, and the rules of life apply from top to bottom; in other words, *downward causality* determines phenotype. Improving methods to link genetics/genomics and physiology will require viewing the linkages as multidirectional, more like a roundabout than a one-way street.

Some existing tools and frameworks enable scientists to work across the physiology and genetics/genomics spectrum; they can be roughly divided into those that (1) reveal genes or alleles present in a given genome, (2) indicate how those genes/alleles may function, (3) leverage combinations of alleles of traits in prediction, and (4) elucidate how the whole system fits together in the context of the environment. Gene function involves both physiology and resulting phenotypes, and of particular interest are technologies that provide insight to both gene presence and mode of action. One good example is biomolecular profiling technologies. Genome sequencing and transcript, metabolite, and protein profiling allow the determination of presence or absence of specific biomolecules, which alleles of specific genes are functioning, whether those alleles are available, and at what scale they are available to do work for the cell. Once these data are available, understanding whether and how perturbations of the system influence physiology and phenotype is particularly instructive; this requires transformation technology to test specific hypotheses. Improved multiscale modeling and simulation tools that can incorporate field-based observations made over temporal and spatial scales would complement in vitro and in vivo studies. A lack of broadly applicable transformation technologies that work within and across species, for example, variable susceptibility of Arabidopsis ecotypes to Agrobacterium-mediated infection (Altpeter et al., 2016), is a clear limitation to linking physiology and genetics/genomics.

Beyond measuring and manipulating genes and their products, automated methods for measuring the consequences of changes to genes and other system components and the response to environmental signals are needed. These include sensors and methodologies for collecting hard-to-access phenotypic data including, but not limited to, below-ground traits, proxy and component traits (traits that reflect plant functions or attributes or subprocesses underlying a complex trait of interest; Kuijken et al., 2015; Yin et al., 2004), and methodologies to collect trait data over time (especially for perennial species). To enable the connection between genetics, genomics, and physiology, we need sensors to measure aspects of plant physiology but also contextual sensors that monitor large- and small-scale environmental parameters both above and below ground. Sensors that can more accurately measure physiological processes or that can increase the density of data collection would be particularly useful to pair with high-throughput genomics technologies in populations. Although there has been widespread adoption of sensors in the private agriculture sector, the data are private, leading to a growing divide between public and private research enterprises. With widely deployed sensors, we can apply computational analytics based on the integration of statistical learning and differential analyses. Interrogating these multifaceted datasets to discern patterns will help to make sense of how genes produce the biomolecules that build phenotypes and explain the diversity of possible phenotypes. These approaches will underpin predictive modeling capabilities. In some ways, symbolic modeling encapsulates knowledge as it is created, and subsymbolic modeling (e.g., deep learning) reveals patterns to instigate scientific discovery at the interface of genomics and physiology (Diepenbrock et al., 2022). The emergence of multiscale models that integrate environmental data, growth concepts, phenotypic observations, and molecular datasets through quantitative reasoning have the potential to bridge the vast difference in scales encompassed by these disciplines (Peng et al., 2020). Modeling and simulation are becoming critical tools in the scientist's toolkit to help formulate hypotheses, generate quantitative predictions under a given hypothesis, and design experiments to exclude hypotheses (Jones et al., 2017). In this way, modeling can advance our knowledge through more rigorous use of the scientific method and more rapid iterative learning and can be a key connection point between scientists from different disciplines (Cooper et al., 2021; Hammer et al., 2006).

3 | IDENTIFYING COLLABORATION-FRIENDLY CHALLENGES

At the onset of the workshops, participants considered the qualities of collaboration-friendly challenges and developed these general categories.

1. Big challenges. These include long-standing challenges that may have different solutions in different systems and outcomes that could change the way we conceptualize the world. Examples include making annual crops take on a perennial growth habit, developing non-nitrogen-fixing crops capable of taking up nitrogen from the environment more efficiently, and increasing the efficiency of photosynthesis-based carbon fixation.
2. Questions that involve both prediction and validation. The skills to model and predict outcomes are generally analytical and computational. Testing models and hypotheses involve experimentation in the lab or field to determine mechanisms and processes. These efforts necessarily involve different skills and expertise to create understanding that spans the patterns-to-processes spectrum.
3. Complex questions. Solutions or outcomes produced in one environment, or in one species, may not be replicated in others. A key example is the determination of a biological process or mechanism by experiments carried out in controlled environments; these processes may play out differently in natural or field conditions. To determine whether and how such findings translate to diverse environments or species often involves multidisciplinary expertise. Another example is challenges that emerge as national or international needs; these often require special funding to address the particulars of coordination, teamwork, and social or political concerns, making these challenges ripe for collaborative team approaches.

4 | CREATING INCLUSIVE COLLABORATIVE ENVIRONMENTS BY FINDING AND ENGAGING COLLABORATORS

The first step toward collaboration is finding and engaging collaborators. Although there are numerous formal and informal ways to build collaborations across disciplines, they are not evenly or widely distributed and often exclude people and groups outside of the traditional power structures of large universities or those traditionally underrepresented in the plant sciences. There is a need to strengthen existing collaborative mechanisms and to create new and innovative ways to initiate the collaborative process through both top-down (institution- and organization-driven) and bottom-up (individual- and community-led) approaches.

4.1 | Top-down (institution- and organization-driven) approaches

Top-down initiatives incentivize and kickstart collaborative projects. For example, numerous university campuses fund institutes or centers that convene diverse talent from different departments and colleges to tackle key challenges in genomic biology (see https://en.wikipedia.org/wiki/List_of_genetics_research_organizations for a partial list) and biological sciences more generally (e.g., BioX at Stanford, IOB at UGA, IBB at Georgia Tech, WICMB at Cornell, the OpenPlant Synthetic Biology Research Centre, and iSTEM-Xe at Morehouse College). These provide highly collaborative multidisciplinary environments for answering questions that a single discipline could not effectively answer. Although many genomic biology institutes or centers have a biomedical focus, some include plant genomic biology (e.g., the Carl R. Woese Institute for Genomic Biology at the University of Illinois, Urbana-Champaign) and genomics, physiology, and breeding (e.g., UF/IFAS initiative on artificial intelligence at the University of Florida). Geneticists, plant physiologists, systems biologists, computational biologists, synthetic biologists, computer and data scientists, statisticians, biochemists, bioethicists, sociologists, legal scholars, and many others work side-by-side to address shared scientific challenges. Undergraduate students, graduate students, and postdoctoral associates working in these centers may view interdisciplinary collaboration as the norm, not the exception. Multidisciplinary seminar series associated with such centers provide early-career scientists exposure to different disciplines and approaches. Institutional funding for interdisciplinary research also provides an incentive for faculty to find and engage collaborators across fields.

Top-down funding initiatives also motivate interdisciplinary collaborations (see Rethinking grant funding, below). For example, the NSF Plant Genome Research Program (PGRP) is a core funding program for plant genomic biology that has long encouraged interdisciplinary engagement across plant physiology, ecology, evolution, and plant development. The recently formed NSF Biology Integration Institute program has funded 10 institutes over the past 2 years to tackle major questions in biology; institutes must engage scientists traditionally allied with areas of biology that have been historically isolated from one another. The U.S. Department of Energy (DOE) Bioenergy Research Centers are examples of large interdisciplinary teams organized around common themes. The center structure fosters team science and has been a mechanism for funding to study organisms with bioenergy feedstock potential (sorghum, miscanthus, switchgrass, poplar, etc.). Programs such as the National Artificial Intelligence (AI) Research Institutes (funded by six federal agencies) require interdisciplinary collaboration to apply AI to topics that are relevant to plant scientists. Although funding initiatives provide mechanisms and strong incentives for working across disciplines, engaging faculty at smaller colleges without robust administrative support for team research and finding common languages across disciplines are barriers to establishing successful collaborations. Additionally, several early career researchers felt that these top-down initiatives can result in interactions more similar to consultation than true collaboration (Box 1), and their contributions were not being valued as much as their presence.

There are also many ways for institutions and organizations to enable interdisciplinary collaboration without creating large or expensive programs. Two essential components of such efforts are creating space for cross-disciplinary communication and creating and valuing time for people to engage in collaborations.

4.1.1 | Creating space

An initial step in building inclusive collaborations is finding people in other fields with complementary skills and shared goals from diverse types of academic/research institutions. Creating mechanisms such as seminar series or lightning talk sessions can foster interdisciplinary connections. A key component of these activities is to ensure that speakers articulate basic disciplinary assumptions and models; unstated assumptions and models are often difficult for outsiders to glean from context. For instance, plant geneticists trained in molecular biology may take for granted that variants of large effect are most interesting and useful for downstream applications, whereas plant geneticists trained in the plant breeding community may assume the opposite (Bernardo, 2008). Utilizing lists of diverse speakers such as DiversifyPlantSci (https://rdale1.shinyapps.io/diversifyplantsci/) can enable collaborations among more diverse scientists and increase inclusion for marginalized scientists. Building inclusive collaborations should also include trainees. Involvement in open, interdisciplinary discussions from early on in one's scientific career can lay the groundwork for successful future collaborations.

Scientific societies and meeting organizers play a special role in creating collaborative spaces, as their members and audiences usually include researchers from many types of institutions. Although the Covid-19 pandemic has demonstrated that science can be disseminated virtually, it has been more challenging to find effective ways to virtually interact and network (Remmel, 2021; Wu et al., 2021). Virtual conferences have expanded participation, however, and future events could increase inclusion with both in-person and virtual components. Organizers can re-envision conferences and proactively address the need for interactions by creating purpose-built sessions, both structured and unstructured, to help support collaborations. For example, organizers can make an open call to the community to nominate interdisciplinary speakers and session topics and designate at least one session to which attendees can submit abstracts on interdisciplinary research, education, or outreach. These steps have the added benefit of increasing overall diversity and inclusion by drawing on broader networks and perspectives.

4.1.2 | Creating and valuing time

Once potential collaborators have been identified, institutions and organizations help enable successful interdisciplinary collaborations by providing time to engage collaborators. Building interdisciplinary collaborations does not happen instantly; researchers need time to communicate, brainstorm, evaluate, and iterate ideas before they can begin to propose and execute the research. Rushing this process, as frequently happens under the pressure of funding initiatives, can lead to poorly designed collaborations or poor fits between researchers. However, current academic structures generally do not value or reward this vital foundation-building step; this is especially true at teaching-focused institutions. A culture change is needed whereby forming a collaboration is in and of itself considered scholarly work.

This shift will enable more researchers to take part in collaborative work. Mechanisms such as salary support for the process of building collaborations and writing grants, either within institutions or through seed grants like the Research Coordination Networks (RCNs) of the NSF in the US, which are designed to foster communication and promote new collaboration among scientists, can open up opportunities to collaborate. Examples of funding agencies that provide a small grant to establish collaborations before applying to the larger grant include National Artificial Intelligence (AI) Research Institutes, the Murdock Trusts Research Across Institutions for Scientific Empowerment, and NSF INCLUDES. Such small grants are frequently optional, and thus, there is considerable pressure, either institutionally or from scientists trying to fund their labs, to skip this step in favor of getting the larger grant sooner. Institutions and funding agencies could prioritize incentives to encourage and reward the process of building collaborations over time.

4.2 | Bottom-up (individual- and community-led) approaches

Scientists can also work within or alongside current structures to increase successful interdisciplinary collaboration. One approach is to look for collaborators for small projects as a way to build successful collaborations. Another is to strive to create welcoming communities, where communication and idea sharing are valued and all feel safe to ask questions. Journal clubs specifically designed for interdisciplinary discussion can provide opportunities to practice thinking about interdisciplinary plant science. Additionally, digital tools can help democratize community building and allow broader participation. Virtual seminars, journal clubs, and "site visits" are more accessible to researchers at smaller, more teaching-focused institutions and can effectively link researchers from geographically distinct locations (Jayabalan et al., 2021). These opportunities enable researchers to quickly expand their networks in the absence of extensive resources and open the possibility of more international collaborations. Plantae is a notable example of a cross-plant science digital community platform (https://plantae.org) that enables sharing information, resources, and meaningful opportunities for connection. Long-term funding for digital communities that support collaboration across genetics/genomics and physiology is crucial and should be prioritized. Although federal funding broadly supports research databases (NCBI, MaizeGDB, Soybase, etc.), it less commonly supports digital community collaboration platforms.

5 | ENABLING AND SHARING SUCCESSFUL COLLABORATIONS

5.1 | Rethinking how funding works

Funding for research through grants, contracts, and other sources is critical for encouraging and establishing new collaborations and traineeships associated with the integration of plant physiology and genomics. Many NSF programs were highlighted by participants as successfully accelerating the integration of plant physiology and genomics, including Rapid Response Research (RAPID), EArly-concept Grants for Exploratory Research (EAGER), and Research Advanced by Interdisciplinary Science and Engineering (RAISE). NSF programs that foster new collaborations to advance research, such as Research Coordination Networks (RCN) and the Biology Integration Institutes (BII) program, establish stronger interdisciplinary linkages between existing networks. Underscoring the long-term value of funding fundamental research and training, participants highlighted that past research funding focused on a single organism (e.g., *Arabidopsis*, maize, and sorghum) nucleated future collaborations by bringing multiple disciplines together to answer questions. These collaborations led to strong communities and multigenerational succession of research, education, and training. These positive outcomes are useful to underpin future interdisciplinary collaborations between the fields of plant genomics and plant physiology.

Beyond vital government funding, private–public partnerships show promise in funding interdisciplinary collaborations, such as the Genomes To Fields (G2F) Initiative, a U.S. research initiative to catalyze and coordinate research linking genomics and predictive phenomics (https://www.genomes2fields.org/home/), and the European Consortium for Open Field Experimentation (ECOFE), a European initiative with the objective of networking existing field stations across Europe and developing them further in a coordinated and highly standardized way (https://www.ecofe.eu).

5.2 | Expanding funding to new types of institutional collaborations

Suggestions for new funding approaches for researchers across multiple institutions are shown in Table 1. Entries are marked as UI if the suggestion is especially relevant to Underrepresented Institutes, which we define using language from the U.S. National Science Foundation as "minority-serving institutions (MSIs), predominantly undergraduate institutions (PUIs), and other universities and colleges that are not among the nation's most research-intensive institutions." R1 and R2 institutes (Table 1) refer to U.S. doctoral-granting institutions with "very high" and "high" research activity, respectively, that have a minimum level of total research expenditures as reported through the NSF's Higher Education Research and Development Survey. In general, flexibility in spending grant funds was thought to better enable new collaborations with respect to both topics (plant physiology and plant genomics) and institutions. Such flexibility may include bringing in new collaborators, and/or changing research directions partway through a funded grant. Participants from underrepresented institutes highlighted that undergraduates from their institutions greatly benefit from research experience that leads to better subject knowledge and development of career/professional skills and that this pool of trainees may constitute an important source of skilled workers and future leaders of plant science for academia,

TABLE 1 Examples of new funding opportunities for cross-institution collaboration.

1. Funds to create interdisciplinary meetings with dedicated sessions for collaboration
2. Funded fellowships at multiple career stages to incentivize new skill development and formation of interdisciplinary teams
3. Faculty seed funds toward conference/workshop participation to enhance faculty research efforts and professional development (UI)
4. Summer salary for UI faculty for their involvement in grant writing, seminar proposal development, publications, collaborative research, etc. (UI)
5. Seed funds or course release funds (to hire adjunct faculty to substitute) to create new interdisciplinary course development, in addition to providing incentives (e.g., awards) (UI)
6. Changes in current funding strategies to ensure equitable distribution of resources between R1/R2 and UI institutes and ensure collaborations through the duration of the funded projects. While this paper was being written, NSF announced a program to build research capacity at underserved institutions by supporting new faculty at those institutions (UI)

industry, nonprofit, private sector, and government jobs (Jayabalan et al., 2021). Although here we have primarily highlighted opportunities for collaborations between academic institutions, there is also potential for impact by funding collaborations between industry and academic institutions.

5.3 | Developing frameworks for successful inclusive collaboration

At a systemic level, it is clear that skills in teamwork and leadership are critical for successful collaboration across disciplines. Excellent communication, patience, and empathy are needed, which are honed through professional development. This requires balancing disciplinary training and depth of knowledge with interdisciplinary training to traverse schools of thought; incorporate inclusion, equity, and diversity in both people and processes at all stages of project planning and execution; and include facilitation experts at critical stages of team development. Guides and resources to set up specific training opportunities are emerging (e.g., www.inscits.org; https://www.cscce.org/; National Research Council (U.S.). Committee on the Science of Team Science and National Research Council (U.S.). Division of Behavioral and Social Sciences and Education, 2015). For greater individual and institutional engagement, training and development opportunities should highlight why and how collaborative science advances specific research goals.

As collaborative work begins, group structure and composition should be assessed and the diversity of the team should be evaluated in the building stage, not as an add-on. Normalizing group structure assessment can have personal and professional benefits, not least of which is more creative approaches and impact (Sahneh et al., 2021). Greater collective intelligence and creativity emerge from diverse groups that operate in a nonhierarchical manner (Reche & Perfectti, 2020). To effectively harness diversity and creativity, training and support to help manage relationships are required (Jang, 2018). Looking around and asking who is not in the group can be a useful exercise to motivate researchers to expand their networks. One source for diverse potential collaborators across plant science is the DiversifyPlantSci database, where participants indicate their interests and identities; the data can be sorted by category or keyword to produce a subset of respondents based on given criteria (https://rdale1.shinyapps.io/diversifyplantsci/).

5.4 | Supporting and rewarding inclusive, interdisciplinary project leaders underpins collaborative research

Although the guidance provided thus far focuses on training individuals in interdisciplinary efforts involving teamwork, efforts to support and retain those who excel at inclusive team science are also needed. The requisite for universities to have policies and procedures that recognize and support interdisciplinary and collaborative science in promotion and tenure (P&T) has been discussed for decades (Klein & Falk-Krzesinski, 2017; National Research Council et al., 2004; Way et al., 2021). Many institutions have revised P&T documents to include specific instructions for considering interdisciplinary scholarship and team science, and those institutions often provide that guidance to external letter writers. However, challenges still exist, especially for early career scientists who are mentored to prioritize setting up an independent research program over participating in collaborative science. Additionally, the reward systems in plant genetics and physiology largely recognize an individual's contribution. Although industry and some universities specifically award team scholarship and science, most professional scientific associations give awards to individuals. This emphasis of the importance of individual over team achievement could be changed with efforts to establish awards for collaborative, inclusive team science.

Another, complementary approach to supporting effective interdisciplinary project leadership is to engage experts in team science and collaboration to work with research groups directly. This is illustrated by the Association of Public and Land-grant Universities (APLU) in their "Challenge of Change" report (https://www.aplu.org/wp-content/uploads/the-challenge-of-change.pdf), in which the research goals include increasing yields, developing varieties for sustainable production, and decreasing food waste. Two of the APLU's eight specific recommendations for advancing these goals are to align university resources and structures for interdisciplinary approaches and to educate a new generation of students to be interdisciplinary problem solvers. A report by the National Academies of Science, Engineering, and Medicine reached similar conclusions (National Academies of Sciences, Engineering, and Medicine et al., 2019). These solutions require team science approaches; why and how these goals and team science solutions align are described in detail in the report. The report outlines how university resources and structures can be aligned for interdisciplinary approaches through the hiring of experts in team science and collaboration to work with research groups (e.g., as members of the institutional office of research), with some focus on how to create and maintain collaborations, how to keep teams motivated and working well together, and how to nurture relationships as shared projects advance and mature.

5.5 | Disseminating results of successful collaborations

There are several reasons to disseminate the results of research collaborations: to share and permanently record knowledge, to gain recognition and professional advancement, to encourage others to reproduce the work, to fulfill requirements of funders, to increase participation in a program (i.e., to recruit more participants or funders), and to change perceptions of science. Common academic dissemination approaches are publishing in journals and presenting at conferences; however, these venues are often structured for single fields of research and may be less adept at featuring interdisciplinary work. Below, we make several recommendations for strengthening existing approaches of disseminating scientific results to enable more effective dissemination of interdisciplinary collaborations.

5.5.1 | Open science

Conducting research under the principles of open science can have major benefits within interdisciplinary collaborations and for attracting scientists from other fields to your project or questions. Open science is defined as "the movement to make scientific research and data accessible to all. It includes practices such as publishing open scientific research, campaigning for open access, and generally making it easier to publish and communicate scientific knowledge. Additionally, it includes ways to make science more transparent and accessible during the research process. This includes open notebook science, community science, and aspects of open source software and crowdfunded research projects" ("Open Science Movement", n.d.). Open science approaches may be especially beneficial for interdisciplinary collaborative work as they lower barriers between disciplines and practitioners by enabling a freer flow of communication and resources. Open data practices within projects help improve reproducibility by enabling multiple participants to run analyses ("Six Factors Affecting Reproducibility in Life Science Research and How to Handle Them", n.d.). However, the implementation of open science faces significant challenges. For example, many data and resource repositories lack interoperability between platforms and are inaccessible to nonspecialists and diverse users, including the public. Existing disciplinary repositories can lack consistency and sustained funding to improve availability and accessibility. Another barrier is the culture of academia itself, which primarily rewards individual achievement and not collaboration, although team awards for science are recognized in some institutions.

Recommendations for enabling the dissemination of interdisciplinary plant genomics and plant physiology collaborations via open science approaches include

1. Greater community adoption of interactive web applications and open-source software development that allows associating metadata standards.
2. Publishing usable data and metadata in journals and data storage platforms that adhere to standards developed by the plant science community, such as MIAPPE.
3. Journal-like review mechanisms for publishing datasets. Some dataset-publishing journals/mechanisms exist, but several participants felt that their institutions would not credit them in professional development (tenure, promotion, etc.). Journals could adopt a scoring framework for how well a manuscript follows FAIR principles.

5.5.2 | Journals

1. Diversify editorial boards across fields, providing an opportunity to rethink board composition in terms of various characteristics, including familiarity with interdisciplinary work. A challenge is that a typical reviewer experienced with a single discipline may expect methods and depth of experiments typical of a single-discipline submission. In interdisciplinary collaborative work, it is not always possible to fulfill the expectations of two single-discipline reviewers. Beyond the simple additive demands is the need for editorial boards to include reviewers knowledgeable in the intersections of physiology and genomics so that interdisciplinary submissions are fully and fairly understood and assessed.
2. Publish special issues or collections that focus on interdisciplinary plant physiology and plant genomics research to provide opportunities to report collaborative science. Investing in interdisciplinary special issues may also mean that such publications would become part of the normal journal portfolio.
3. Develop a journal submission designation or type for interdisciplinary manuscripts to ensure they enter a dedicated review pipeline. Provide training on how to review interdisciplinary papers. Establish a set of common standards (best practices), and develop a checklist for proper review, such as assign a managing editor familiar with work in both disciplines; recruit multiple reviewers (also see next recommendation); and institute a collaborative decision-making process to ensure fair evaluation.
4. Use community review, such as is common in the grant review process (e.g., NSF), where different reviewers focus on a particular part of the manuscript to encompass the areas of collaborative work. Ensure there is at least one reviewer for each theme; ideally, each would be experienced with interdisciplinary assessments, but if not, recruit one who can assess physiology and genomics holistically.
5. Implement more explicit definitions of the roles of authors, such as the CRediT system (Brand et al., 2015), so that all interdisciplinary contributions to a manuscript are properly and transparently recognized.

5.5.3 | Outreach to the public

Interdisciplinary researchers are well-positioned to communicate with the public because of the inherent need to articulate connections between disciplines, approaches, and results. Across the wide variety of available outreach avenues (Friesner et al., 2021), leveraging interdisciplinary teams and researchers can have tangible benefits. As outreach opportunities reach different communities by design, they can also serve as a venue for attracting collaborators from other fields across larger institutions and regions.

6 | TRAINING COLLABORATIVE AND INCLUSIVE PLANT SCIENTISTS

Although strong collaborative research is vital to the scientific endeavor, traditional scientific training focuses on deep understanding within a single discipline with less interdisciplinary exposure and almost no training in collaborative skills. Today, significant collaborative work is well under way in the plant sciences; however, more emphasis on the value and implementation of inclusive collaborative work is needed, particularly during training and education. Novel approaches, with associated incentive structures to support them, are needed to train scientists at all career stages with deep disciplinary knowledge, interdisciplinary fluency, and the networking, communication, and management skills required to work successfully in collaborative groups that can address society's most pressing challenges.

We need to focus on developing the skills that will enable interdisciplinary science, not the specific disciplinary linkages. Successful interdisciplinary programs, such as the NSF's Research Traineeships, exist (Table 2); they share multiple key features: bridging across biological scales, using computational approaches, aligning people around grand challenges, spanning multiple departments/colleges, and flexibility in curriculum. For greatest success, programs need to value characteristics and roles defined as critical for interdisciplinary teams and scientists such as boundary crossers, process innovators, and team players (Cross et al., n.d.; Gilliland et al., 2019). Cultural training identifying specific challenges and opportunities of interdisciplinary research is arguably as important to successful collaborative work as disciplinary breadth and depth. Interdisciplinary training should perhaps start before Ph.D. programs, as traditional bachelors to Ph.D. tracks may lack flexibility for students. Development of interdisciplinary internships and post-baccalaureate and masters programs could also provide additional paths for students to become collaborative and inclusive scientists.

Summer research opportunities such as NSF Research Experiences for Undergraduates (REU) and USDA-NIFA Research and Extension Experiences for Undergraduates (REEU) programs can

TABLE 2 NSF-funded interdisciplinary programs in plants.

NSF Research Traineeship (NRT) Award	Trains doctoral students in …	Awardee institution	URL
Integrated training Model in Plant And Compu-Tational Sciences (IMPACTS)	…plant science and computational/data science, and to integrate knowledge at multiple levels of biological organization to address grand challenges in plant biology	Michigan State University	impacts.natsci.msu.edu
Predictive Plant Phenomics (P3)	…plant sciences, computational sciences, statistics, and engineering to design and construct crops with desired traits that can thrive in a changing environment	Iowa State University	www.predictivephenomicsinplants.iastate.edu/about-us
Plants3D (Discover, Design, and Deploy)	…plant science and environmental and chemical engineering to address plant science challenges related to food security and human health and to foster entrepreneurial skills	University of California, Riverside	plants3d.ucr.edu
TDigital Plant Science	…plant science, bioengineering, and computational biology to acquire the foundational skills to sense, capture, and measure information about plant processes in real time and at multiple scales, from microscopic single cells to entire ecosystems	Cornell University	cals.cornell.edu/school-integrative-plant-science/degrees-programs/msphd-graduate-fields/sips-msphd-financial-support/nsf-research-traineeship
Building Resources for InterDisciplinary training in Genomic and Ecosystem Sciences (BRIDGES)	…ecosystem and genomic sciences to understand how processes encoded for in genes scale to the ecosystem scale	University of Arizona	https://bridges.arizona.edu

achieve some of these goals, but there are limitations. These programs do not support many students (e.g., 5%–10% of total applicant pool) and are short experiences, which makes it difficult for the student to gain competency in a single discipline, let alone multiple disciplines. The majority of these programs are provided to R1 institutes that are already fairly well-resourced, and there are several structural limitations that make it difficult for underrepresented and less-resourced institutes (e.g., Primarily Undergraduate Institutions [PUIs], Minority Serving Institutions [MSIs], and community colleges) to participate, including the requirement that most students come from outside the institution, lack of budgetary support for the primary research activities, and the fact that students at non-R1 institutions are given less instruction and support in writing proposals. Participants recommended extending summer research programs to underrepresented and less-resourced institutes and/or finding ways to integrate non-R1 faculty and their research into the programs to give these opportunities to more students, thereby enhancing the student experience and developing a more diverse workforce. Another recommendation was the development of undergraduate research fellowships with required interdisciplinary research collaborations for a longer time period than just a summer research experience. Any such programs should incorporate training toward professional development. For example, ASPB's Scholars program is a year-long mentoring and professional development program that does not specifically address interdisciplinary research but is notable for its longer-term activities (https://aspb.org/awards-funding/aspb-awards/aspb-conviron-scholars-program/). Workshop participants from underrepresented institutes and PUIs noted that researchers and students at these institutions would like to engage in research activities (potentially with R1/R2 institutes), not just during summers, but over the long term. Some experimental work can be expensive and thus may be prohibitive at less-resourced institutions operating alone. However, there are aspects of collaborative research that participants from underrepresented institutes can be involved in. For example, they could be involved in data mining and analytics of genomics data provided by R1/R2 institutes that have greater resources for data generation.

7 | CONCLUSIONS

The fields of study relevant to understanding how plants grow and adapt to their environments have become increasingly interconnected as the demands for understanding larger and more complex questions have grown. These workshops challenged participants to consider how plant physiologists, geneticists, and genomicists could more successfully collaborate. Through our discussions and writing sessions, several ideas emerged. The participants agreed that collaboration-friendly projects often investigate grand challenges that require multiple lines of inquiry using interdisciplinary approaches and subsequent validation. Such complex questions create and hold space for scientists to apply disciplinary knowledge and provide the interfaces for interdisciplinary creativity due to a shared goal. Yet even when scientific questions encourage team science, creating inclusive collaborative environments can be challenging in academia, where historical silos have been built that encourage individual disciplinary achievement. To their credit, many institutions and organizations have introduced initiatives that create space for interdisciplinary team science and are changing promotion documents to recognize and value collaborative projects. However, institutional changes can be slow and driven in part by science funding. Team science is being promoted by various funding agencies, and these can be expanded to further broaden participation (Table 1). Finally, we emphasized the importance of training future collaborative and inclusive plant scientists, offering programs to underrepresented and less-resourced institutions, and promoting greater cooperation between R1/R2 institutions and PUIs/MSIs.

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CONFLICT OF INTEREST STATEMENT

The Authors did not report any conflict of interest.

PEER REVIEW

The peer review history for this article is available in the Supporting Information for this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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