Community Perspectives: Genome to Phenome in Agricultural Sciences

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Abstract

The Agricultural Genome to Phenome Initiative (AG2PI) project was launched in 2020 with support from the United States Department of Agriculture National Institute of Food and Agriculture. The goal of AG2PI is to engage and prepare the scientific community to develop novel and creative solutions to problems in agriculturally relevant genomics and phenomics. As part of this ongoing effort, AG2PI developed and implemented two surveys for researchers and stakeholders in genome to phenome (G2P) activities as they apply to agricultural science and practice. These surveys were conducted in Fall of 2020 and Fall of 2021. The purpose of these surveys was to gather information on existing G2P-related organized activities as well as proposed AG2PI organized activities; research gaps and opportunities; and barriers to success (e.g., availability, access, and needs for resources and expertise). In this article the results of these surveys, based on hundreds of responses from the community, are summarized and critical directions for future investment are discussed.

Introduction

In 2018, USDA NIFA was directed by Congress to create an Agricultural Genome to Phenome Initiative (AG2PI) program, charged with addressing the challenges and opportunities of achieving genetic improvement of agricultural species, enhancing sustainability and profitability of US agriculture. To date, AG2PI has been led by a single awarded team (the authors) with the primary goal of engaging a broad community of agricultural genome to phenome (AG2P) researchers, drawing from crop and livestock communities as well as integrative disciplines (e.g., engineers, data scientists, economists, social scientists), and relevant stakeholder groups (e.g., trade associations, commodity groups). The current AG2PI project has engaged and continues to grow a community prepared to develop novel and creative solutions to agricultural genome-to-phenome challenges for the benefit of US agriculture and society. Specifically, AG2PI has worked toward developing a vision for AG2P research – a vision which begins to emerge in this paper – by 1) identifying research gaps and opportunities, 2) fostering first steps towards the development of *community solutions* to these challenges and gaps, and 3) *rapidly*

disseminating findings to the broader community. To these ends, AG2PI organizes four types of activities: virtual field days, conferences, training workshops, and seed grants. In the project's first year, over 10,000 community members from every inhabited continent engaged with the AG2PI website and activities, and over 30,000 community members (Google analytics, unique users) had engaged by the end of the second year.

To achieve part of AG2PI's mission to identify research gaps and opportunities so we may define strategic needs, we created and distributed two surveys to the agricultural research and stakeholder community between November 2020 and December 2021. Each survey met a distinct goal concerning the needs and current activities of the community. We present here a summary of the results of these surveys and implications for the future of AG2P research. A selection of results of these surveys are available on the AG2PI website (https://www.ag2pi.org/community-surveys/) and are shared with USDA NIFA in annual reports.

Methods

Two surveys - the first in fall 2020 (November 23-December 21, 2020) and the second in fall 2021 (November 1-December 3, 2021)- were sent via email to the global AG2PI community and Animal Genetics community (AnGenMap member) lists (together totaling 4,582 members in 2020 and 4,836 in 2021) as well as representatives of AG2PI institutional partners for dissemination to their organizational members (for list of AG2PI's 31 original institutional partners go to https://www.ag2pi.org/institutional-involvement/). Surveys were created using Qualtrics, responses were anonymous, and respondents did not need to be a member of AG2PI to participate. Each survey asked respondents about their needs in agricultural genomics and phenomics, and what specific activities or resources would help them meet those needs. The first survey was largely aimed at describing the current AG2P community members and assessing the state of research and existing methods/tools. The second survey focused on what barriers currently exist for AG2P research – such as institutional infrastructure, human infrastructure, and access to resources – and what could be possible if all barriers were removed.

Fall 2020 survey: describing the AG2PI Community

A total of 467 people provided responses to most questions (out of the 535 people who opened the survey); however, not all questions were required and only 339 respondents completed the survey. All responses are summarized below. Respondents represented professions across academic, government, and industry settings (Figure 1) and across a diversity of species studied (multiple entries were possible in this open text question). Species were grouped by categories (Appendix 1) during survey analysis using USDA definitions of major versus specialty as guidance and using Food Insight's definition of orphan crops [1,2,3]. The majority of respondents were from the U.S. (69%), but all six inhabited continents were represented.

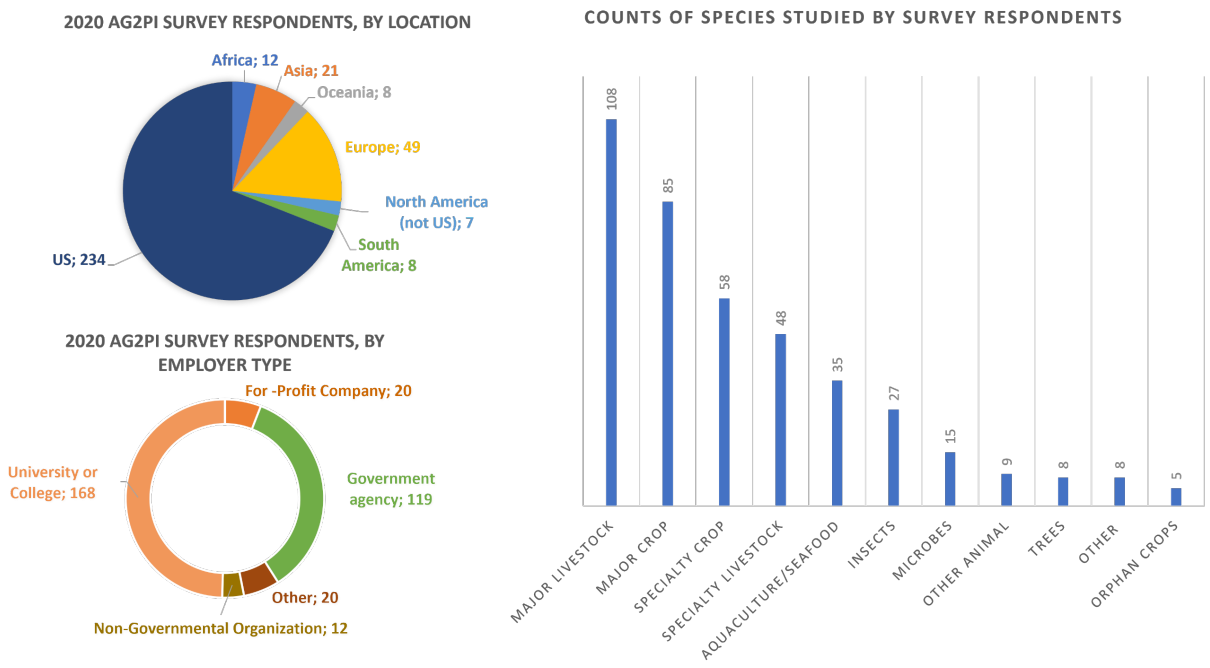

Figure 1: Demographics of respondents to AG2PI Community Survey #1, which was deployed in fall 2020. Numbers following category names of graphs represent the number of responses recorded. USDA definitions were considered in creating categories. Note: “specialty livestock” is used in place of “minor breeds” but represent the same category of species.

Fall 2021 survey: Identifying challenges and opportunities for collaboration

A total of 177 community members provided responses to our second survey. Respondents represented a similar diversity of professions and species studied as reported in the first survey (Figure 2). The question asking about “what species do you work with” was modified in this survey as a multiple selection from the categories identified in the 2020 survey. To be consistent with category names across surveys the term “specialty livestock” was used in place of “minor breeds” but represents the same category of species. A smaller percentage of respondents were from the U.S. (43%) compared to the first survey. It is not clear why fewer respondents participated in this survey compared to Fall 2020, considering a larger number of community members or community-adjacent professionals were given the opportunity. All six inhabited continents were represented.

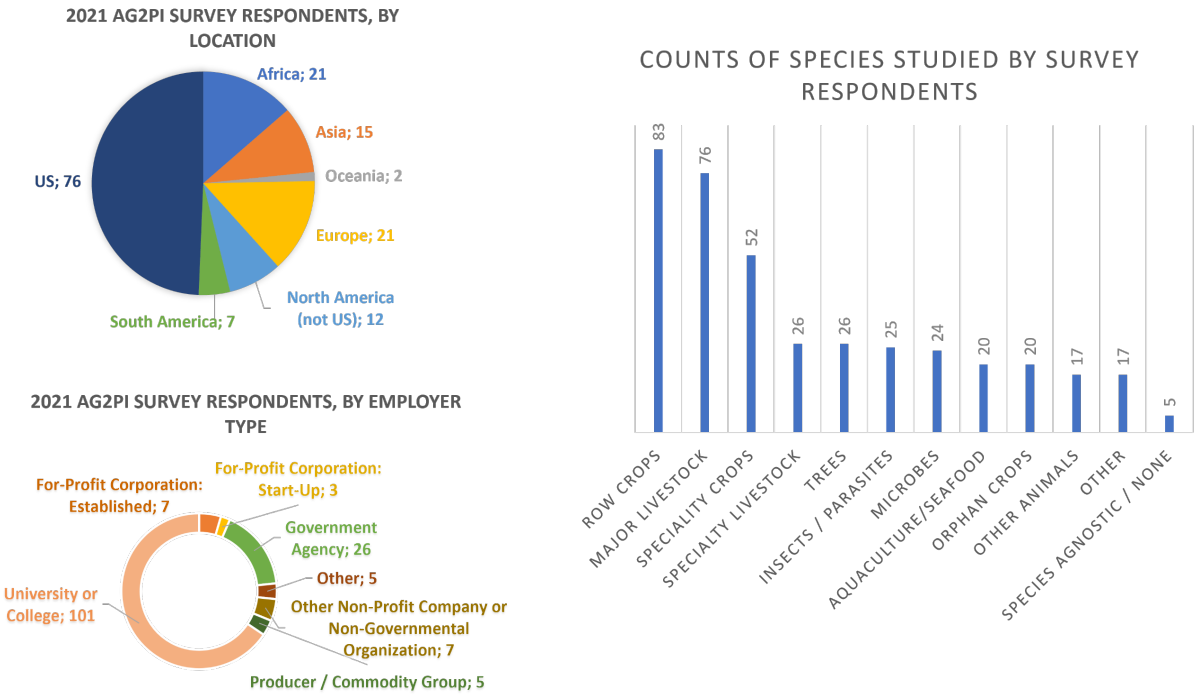

Figure 2: Demographics of respondents to AG2PI Community Survey #2, which was deployed in fall 2021. Numbers following category names of graphs represent the number of responses recorded. USDA definitions were considered in creating categories. Note: "specialty livestock" is used in place of "minor breeds" but represent the same category of species.

Results

Fall 2020 survey

Overall, the community members who participated in the 2020 survey were either "very familiar" (n = 312; 67%) or "somewhat familiar" (n = 141; 30%) with research efforts to improve the genetics of crops and/or livestock and, in a follow-up a question, 44% (n = 206) reported participating in genome to phenome (G2P) research. Although the sample was majority US-based, in general, these respondents provided answers that were similar to those provided by non-US-based respondents; therefore, that the findings are reflective of the community, as a whole, and not skewed toward one nationality. For example, the US-based sample from the above questions about familiarity with research on genetic improvements broke down as 65% (n = 151; versus 161 non-US respondents) were "very familiar", while 33% (n = 78; versus 63 non-US respondents) were "somewhat familiar". Additionally, 46% (n = 107; versus 99 non-US respondents) reported that they currently participate in G2P research. The remainder of this paper will focus on describing the responses of *all* survey takers.

We would like to note that although just 44% of all respondents (as noted above) reported being active in G2P research, 61% (n = 283) responded in a subsequent question that they are interested in "applying (their) skills and time to G2P research" and an additional 35% (n = 161) responded that they were "potentially interested in applying their skills but needed to learn

more about G2P". This illustrates the potential to expand the current work being done in agricultural G2P as a substantial community is already active in G2P research and interest is there to expand the community. A major component of the AG2PI project is to help build this community, so the tracks are being laid by AG2PI for educating and onboarding those interested with each virtual field and training workshop held.

When asked about which G2P resources are most critical for their work in three areas [genomics (Figure 3), phenomics (Figure 4), and data science (Figure 5)], some emerged as more critical than others. Generally, resources related to genomics were most often deemed as critical to respondents' work, followed by resources related to data. Since phenomics is, in many ways, the most nascent field of the three, it is not entirely surprising that resources related to it were largely identified as not applicable to a respondent's work. However, a small group of respondents identified these resources as the most critical. We believe this is an indicator of the amount of work still to be done in developing and deploying phenomics resources. When asked if they create these same resources, a similar pattern emerges (Figure 6).

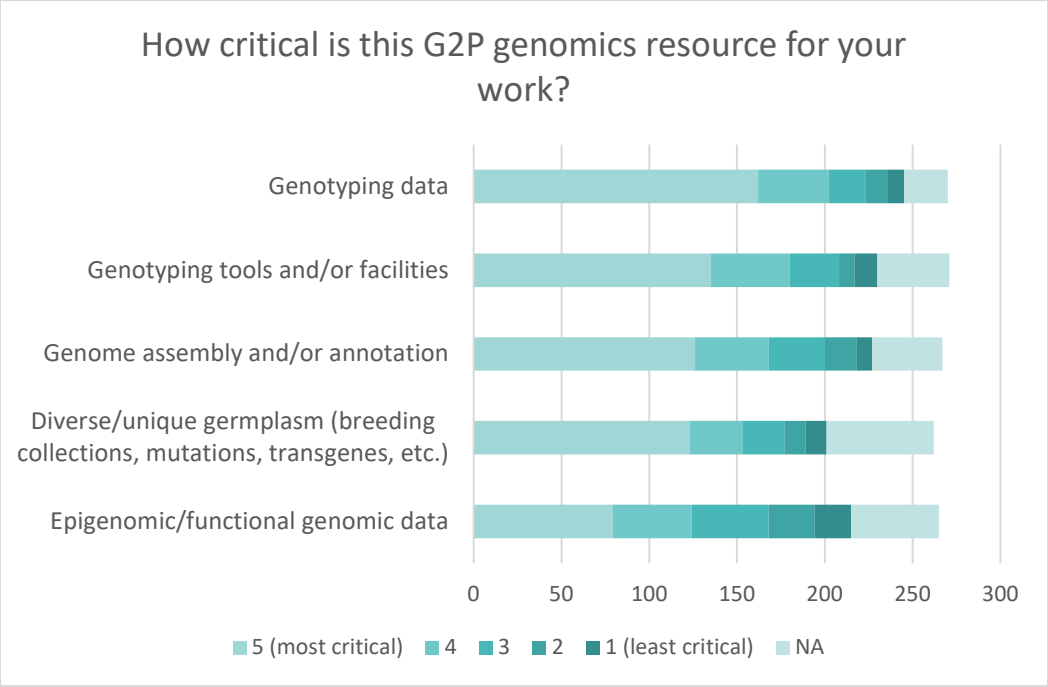

Figure 3: Number of respondents who rated each genomic resources on level of criticality for their own work, where "1" signifies "least critical" and "5" signifies "most critical". If a resource was not applicable to a respondent's work, then they could choose "NA" for "not applicable". Resources listed in order of most "5"s (most critical) at top to least "5"s at bottom.

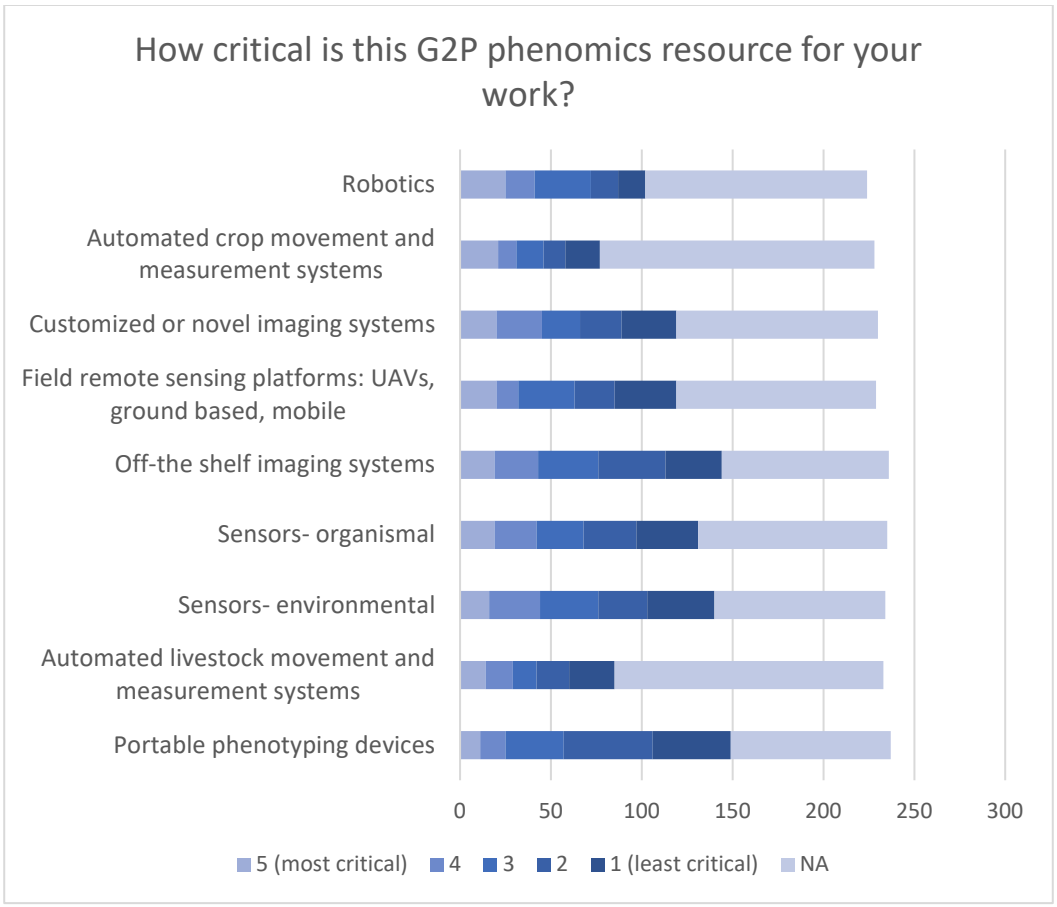

Figure 4: Number of respondents who rated each phenomic resources on level of criticality for their own work, where "1" signifies "least critical" and "5" signifies "most critical". If a resource was not applicable to a respondent's work, then they could choose "NA" for "not applicable". Resources listed in order of most "5"s (most critical) at top to least "5"s at bottom.

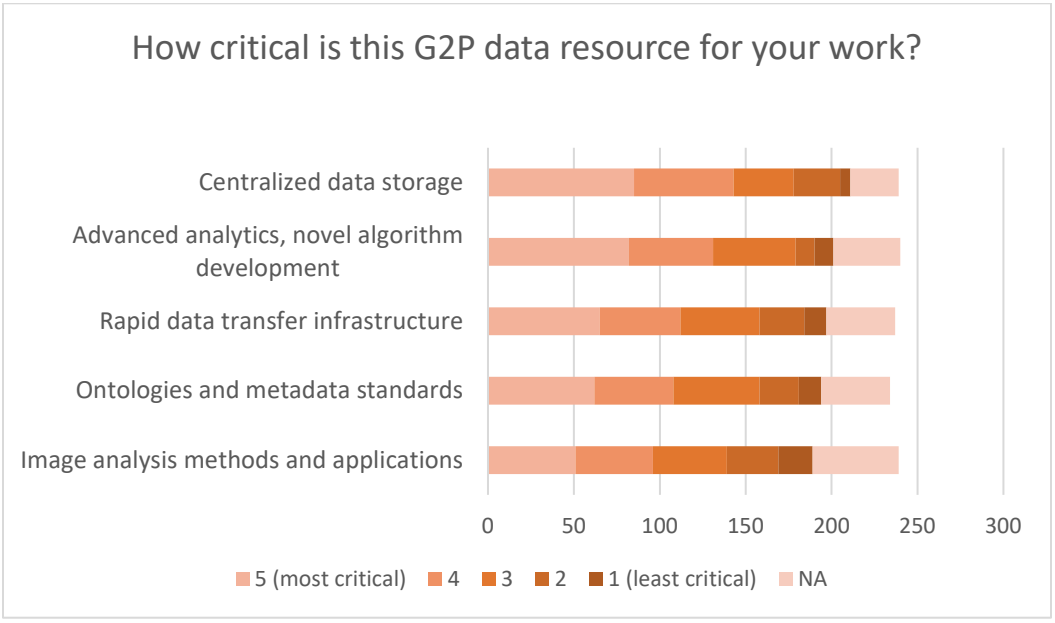

Figure 5: Number of respondents who rated each data resources on level of criticality for their own work, where “1” signifies “least critical” and “5” signifies “most critical”. If a resource was not applicable to a respondent’s work, then they could choose “NA” for “not applicable”. Resources listed in order of most “5”s (most critical) at top to least “5”s at bottom.

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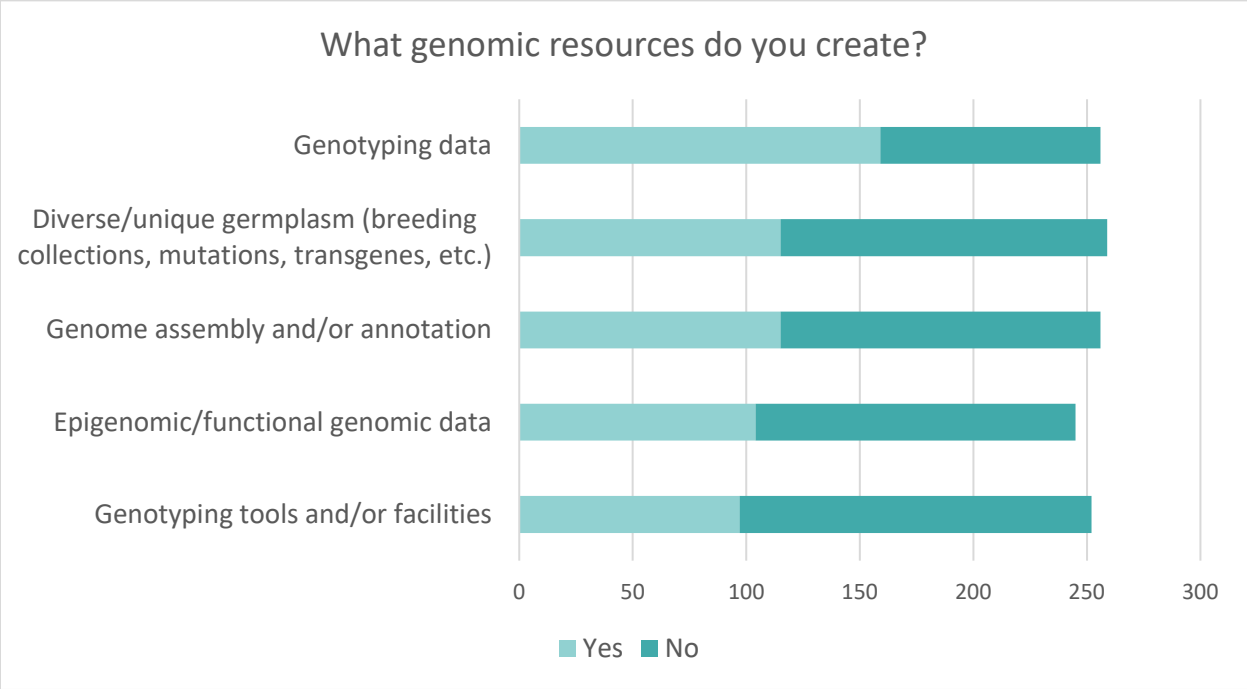

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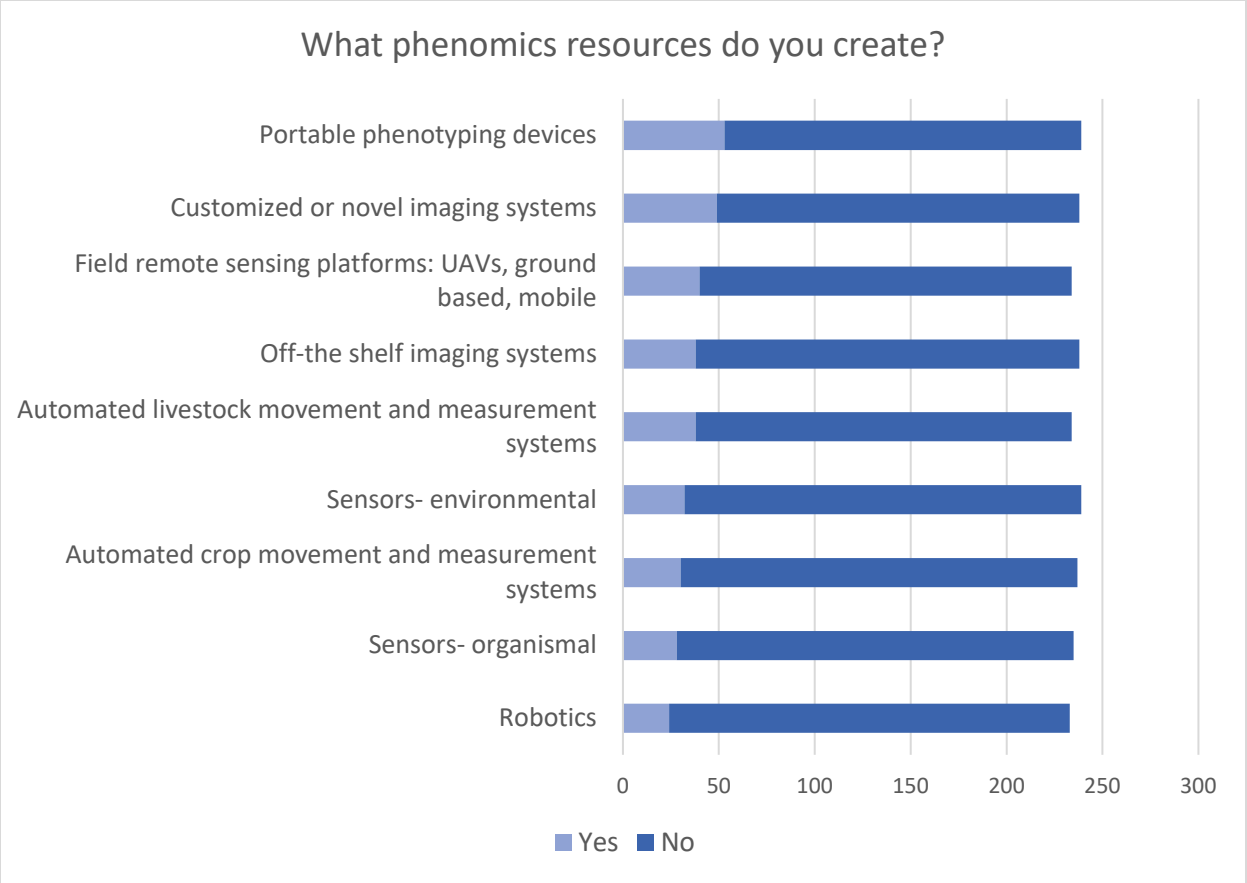

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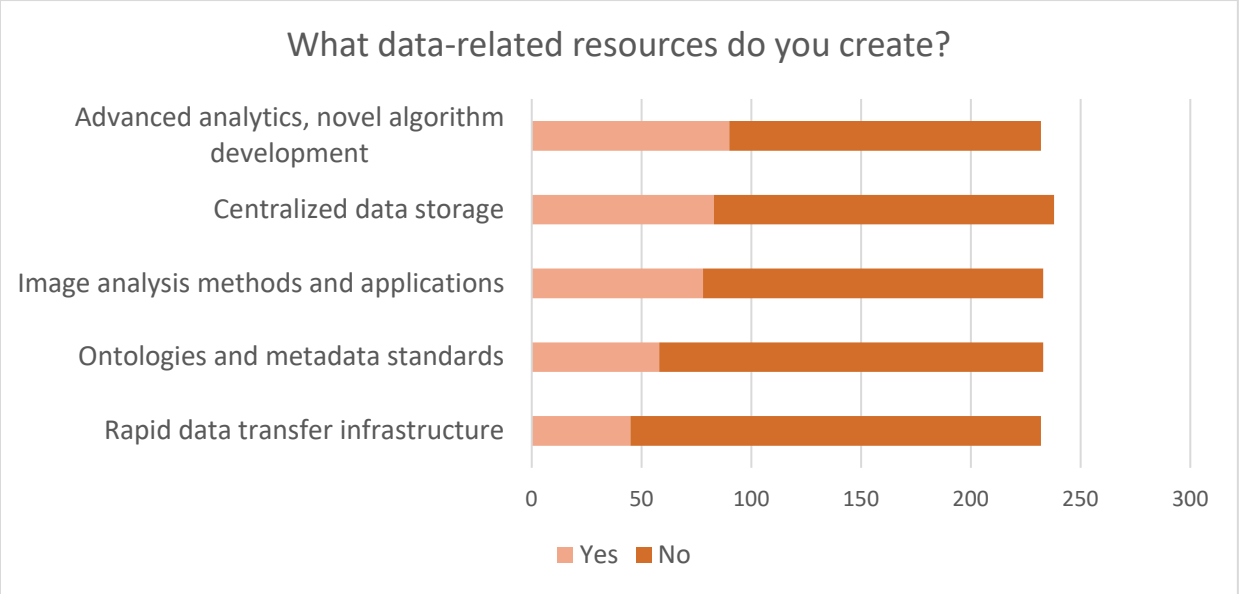


Figure 6: Number of respondents who reported whether they create each a) genomic resources, b) phenomic resource and c) data resource.

Survey respondents were also asked to “describe other important AG2P resources and their criticality to (their) work” not already mentioned in the survey. Some of the major themes that

emerged were: 1) databases and acquiring/sharing data; 2) keeping up-to-date with newest technologies; 3) high-performance computer, machine learning and artificial intelligence; 4) highly specialized resources, tools or support; 5) human infrastructure; and 6) the social and ecological impacts of G2P research. The themes that emerged are being addressed by AG2PI through future field day topics, training workshops and with the creation of working groups. Additionally, these broad categories were used to build the 2nd survey, which deployed in fall 2021.

We then asked which within a list of planned community activities are important for advancing AG2P research. While there was strong support for all proposed activities (Figure 7), the community identified coordinating the sharing of resources and information, as well as advocacy of AG2P to funding agencies, as most critical. An open text follow-up question asked, "what specific existing G2P activities…should be presented to the agricultural G2P community". The most common responses included: application of genomic selection; Genomes to Fields; data sharing; developing and sharing phenomic technologies; and developing and sharing genomic technologies. AG2PI activities, such as field days and training workshops, are designed to address these identified needs and we are committed to continuing to cater activity topics accordingly. Furthermore, two questions asked for topics deemed most desirable for field days and training workshops, as well as whether respondents were willing to attend or teach a particular topic. We used this initial list of topics and volunteers to plan the first year of these events.

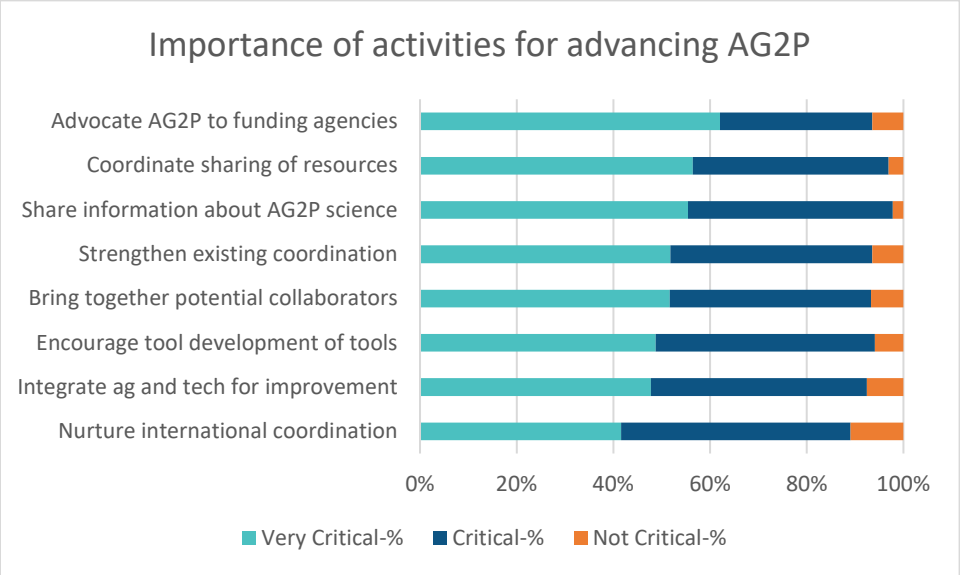


Figure 7: Percentage of responses rating the importance of each planned AG2PI activity from very critical to not critical.

Specifically, when asked what Training Workshops were so crucial that respondents were willing to help organize or teach, respondents rated Workshops on learning modern genetics/genomics, as well as Bioinformatics, highly. Many specific suggestions were provided

(summarized in word cloud below, Figure 8) and included phenotyping/phenomics, data collection or analysis, machine learning, and systems.

Figure 8: Word Cloud summary of open text responses to what training workshop topics AG2PI should organize.

Specific activities within the AG2PI project also had strong support. For example, holding single-subject, in-depth open house "Field Days" on G2P methods, organizing virtual community-wide G2P conferences, and surveying community opinion on G2P needs and planning garnered the highest interest (Figure 9).

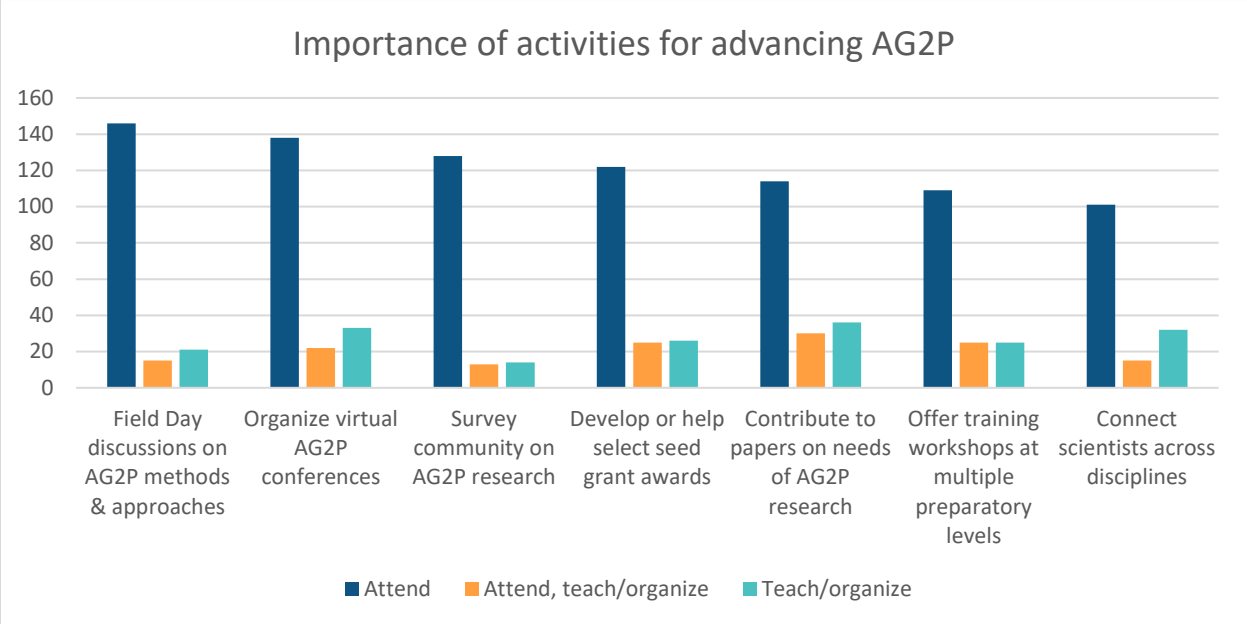


Figure 9: Count of respondents who reported interest in participating in AG2PI activities as attendees, teachers/organizes or both.

One of the most important opportunities that AG2PI provides are seed grants. These grants are intended to support activities that develop the AG2P community (e.g., broaden interactions and synergies) and relevant research infrastructure. We asked respondents about whether there "are other challenges that the AG2P community should be undertaking – especially those

potentially addressed by a seed grant" and responses generally fell within one of seven general topics. See Table 1 for the full list and some specific examples.

Table 1: Community generated topics for seed grants	
Education & Training	
engaging students in G2P	cross-disciplinary training for professionals at any level
Data Management & Integration	
preservation for meta-analysis	coordinating FAIR data
Funding Support for Research	
Funding blue skies science	Funding for research infrastructure
Increasing Collaborations, Domestic & International	
advertising available resources for new collaborations	Public-private partnerships
Developing New Technologies	
new tools for non-model, regional crops	optimization of data through better experimental design
Expand Research Areas within G2P	
Microbiome	Pest-/Pathogen-Host Interactions
Public Outreach	
Demonstrate Importance to Public	Dispelling myths

Fall 2021 Survey

This survey focused on dimensions of collaborations and barriers to research. For consistency, we are including full and partial survey responses from all respondents, which includes researchers from six continents.

In asking respondents with whom they currently collaborate, responses clearly showed that trans-disciplinary teams exist in the AG2P realm. However, the majority of collaborations appear to be within discipline and within kingdom (e.g., crop physiologist working with another plant scientist; dairy scientist working with another animal scientist). Current collaborations among geneticists/breeders were also highly reported, but, again, primarily with those who also work within the same kingdom (i.e., plant or animal). Regarding which disciplines with whom respondents would like to collaborate but currently are not, data scientists were the most desired collaborators across most disciplines. The three exceptions being 1) computer science/computer engineering who reported wanting to collaborate more with economists, social scientists and/or animal geneticists, 2) physical scientists expressing a desire to work more with animal scientists and 3) animal scientists narrowly choosing computer scientists over data scientists. Overall, our sample of respondents seem to reflect a general difference in collaborations regarding the plant and animal sciences where the plant researchers appear to have more interactions with the other sciences than animal researchers. Outside of a desire to work more with data scientists, crop and plant scientists most often reported a desire to work even more with others within the crop and plant disciplines. On the other hand, those working

in the animal sciences expressed focused future collaborations with computer scientists, data scientists and animal geneticists/breeders.

To find out why researchers collaborate in trans-disciplinary teams, we asked “How much value is added when you collaborate with others outside of your discipline?”. The majority of responses indicated strongly that there was value in trans-disciplinary collaborations with the strongest support for “Advance my work in ways I couldn't do alone” and “Uncover unique insights and approaches”. Receiving generally high but more neutral than the other statements were “access to data sources” and “grow my career”. One respondent went so far as to state, *“To me, the single PI grant approach is dead; in order to tackle the "wicked problems" facing agriculture and food production systems in the 21st Century, a trans-disciplinary approach is needed. These collaborations are required to realize that approach. As examples, true "systems biology" or predictive phenomics.”* The largest reported barrier to collaborating was difficulty in finding potential collaborators outside of their discipline, while the second most reported barrier was time (Figure 10).

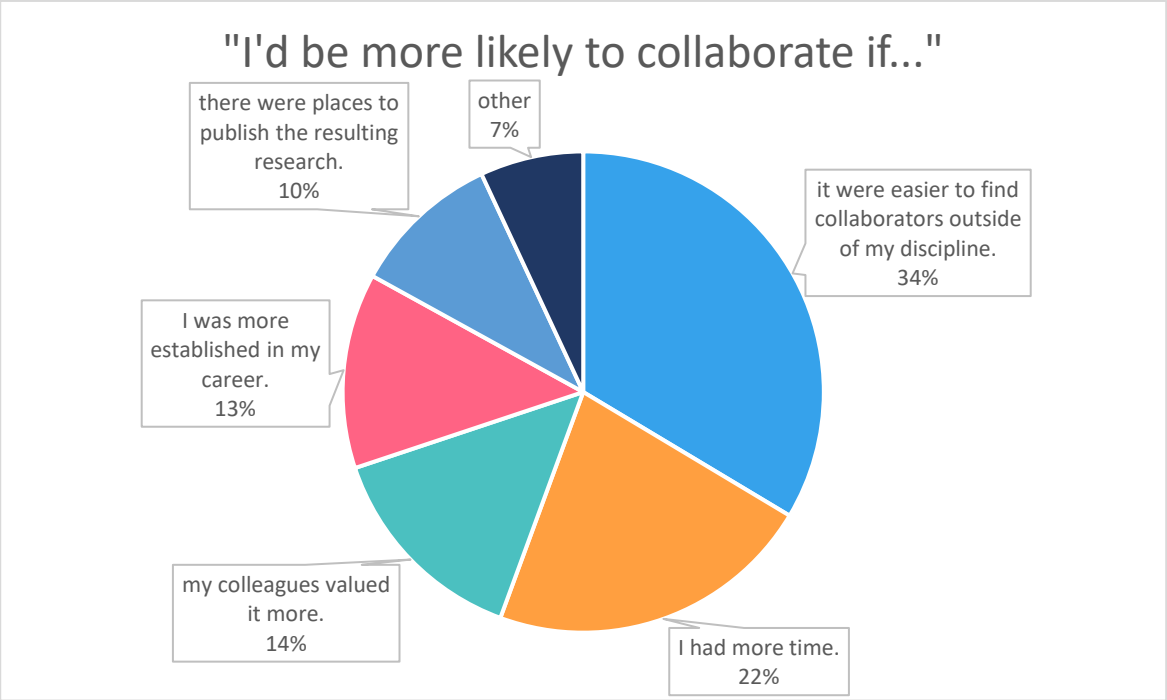
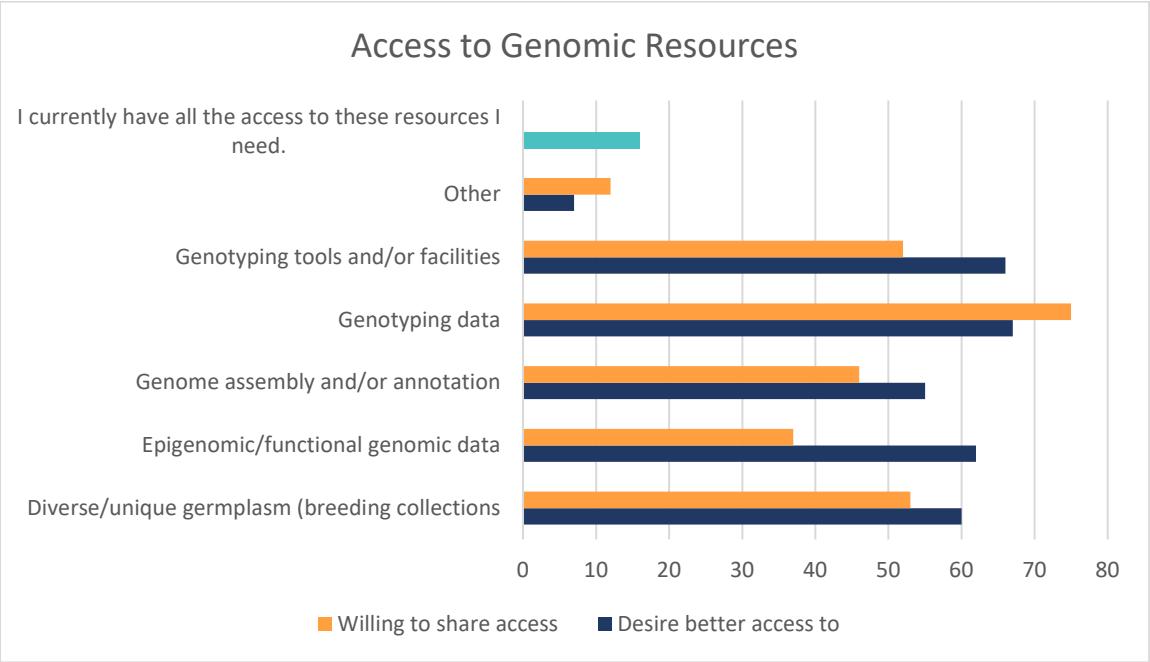


Figure 10: Responses to finish the statement, "I'd be more likely to collaborate if...", respondents were able to select all (multiple) responses that matched their experience. Total responses = 259.

Access to resources can be a major barrier to AG2P research. As such, we next asked about access to genomic, phenomic and data-related resources, and whether respondents were willing to share these resources with others outside of their institution. Overall, the resources that were most often needed were also the resources respondents were most willing to share (Figure 11). Some respondents offered additional resources they are willing to share by filling in the “other” category. However, it was noted that for the majority of resources across all three resource types, there are more researchers wanting better access to these resources than there

are researchers willing to share their resources with others. This result may be due to scientists having specific resources are usually in the minority. However, this discrepancy is most visible for phenomics resources which may indicate an issue with purchasing the equipment or acknowledgement of the difficulty in sharing phenomics equipment (as compared to shipping a sample for genetic testing or sharing a software license). This gap between availability and access should be further explored and may indicate that improving accessibility to specialized/unique resources could be a focus of the AG2PI program in future RFPs.

a)



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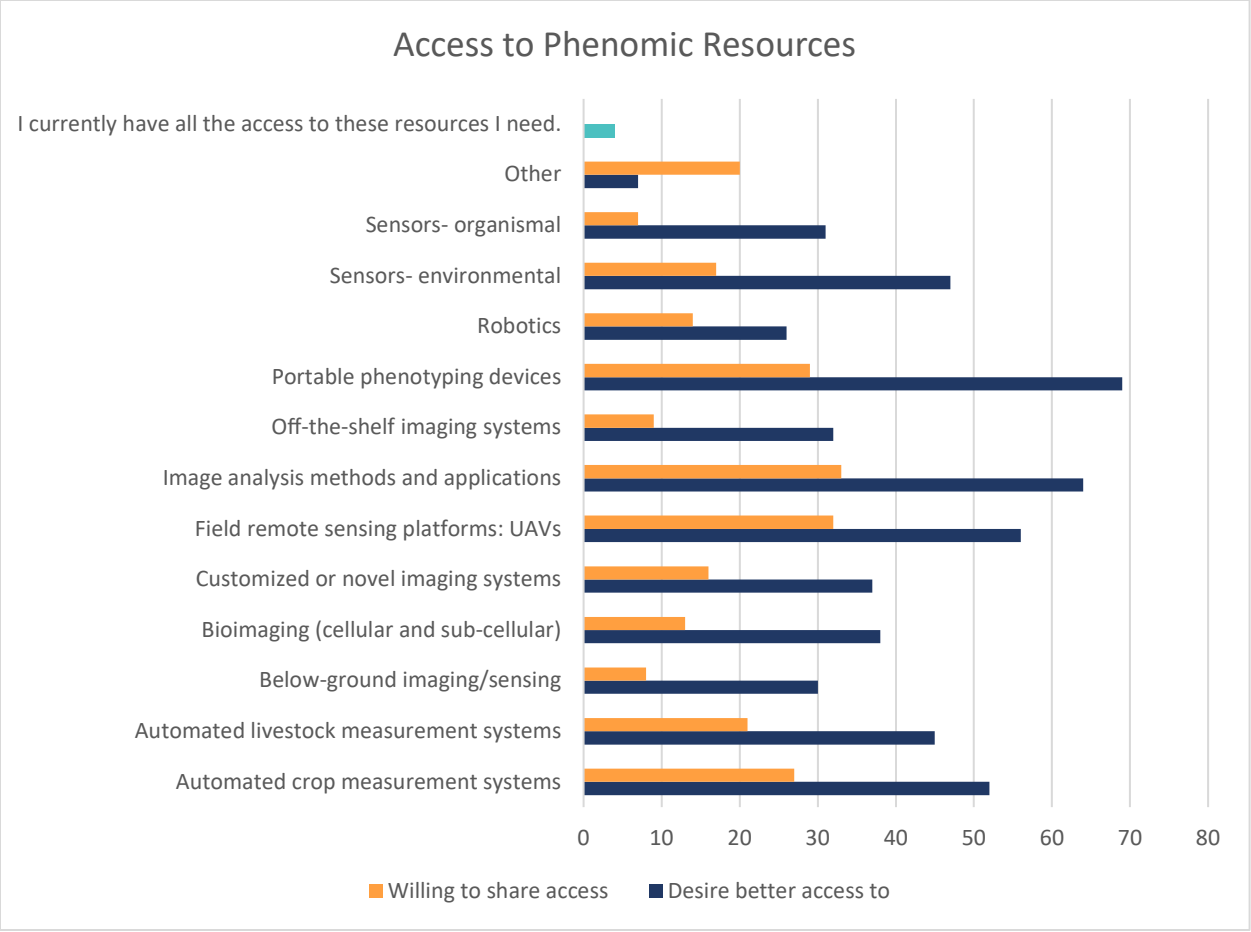
Access to Phenomic Resources
I currently have all the access to these resources I need.
Other
Sensors- organismal
Sensors- environmental
Robotics
Portable phenotyping devices
Off-the-shelf imaging systems
Image analysis methods and applications
Field remote sensing platforms: UAVs
Customized or novel imaging systems
Bioimaging (cellular and sub-cellular)
Below-ground imaging/sensing
Automated livestock measurement systems
Automated crop measurement systems
0
10
20
30
40
50
60
70
80
Willing to share access
Desire better access to

c)

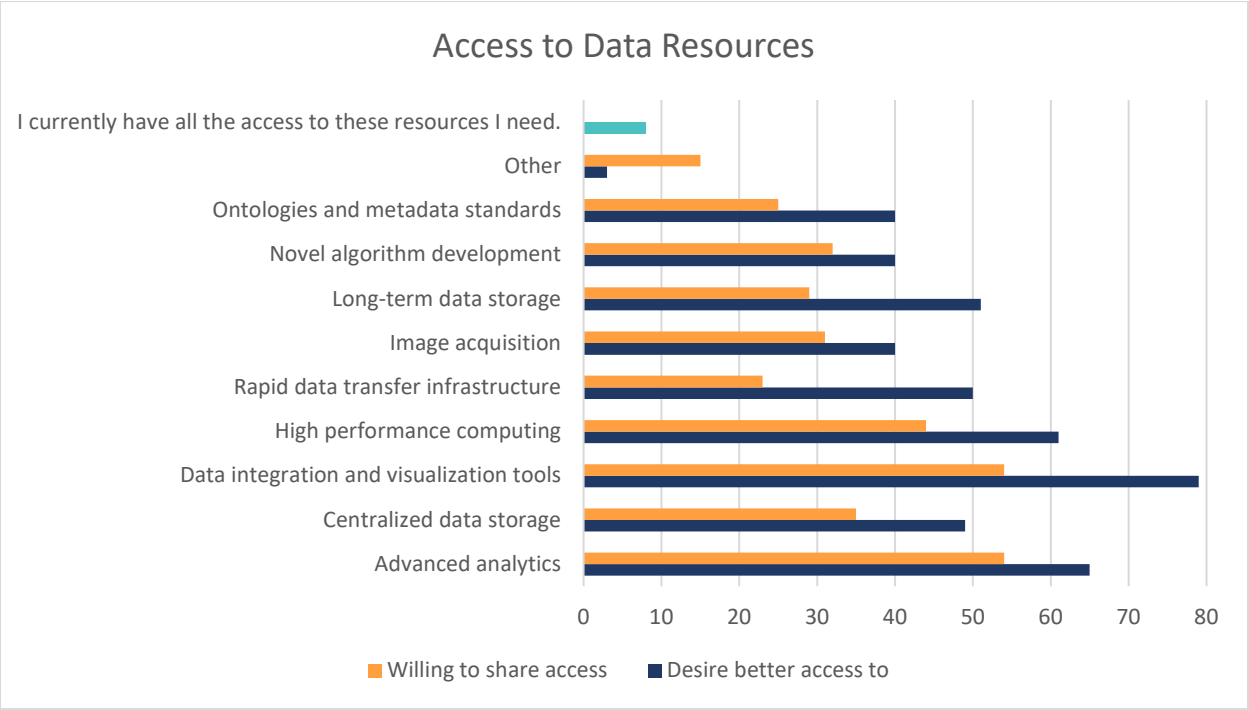
Access to Data Resources
I currently have all the access to these resources I need.
Other
Ontologies and metadata standards
Novel algorithm development
Long-term data storage
Image acquisition
Rapid data transfer infrastructure
High performance computing
Data integration and visualization tools
Centralized data storage
Advanced analytics
0
10
20
30
40
50
60
70
80
Willing to share access
Desire better access to

Figure 11: Counts of a) genomic, b) phenomic and c) data-related resources respondents needed better access to or were willing to share their current access with others.

We also asked about access to human resources and related infrastructure (Figure 12) and training (Figure 13). For different types of partners in research, we asked respondents whether they had adequate access to these people, needed better access to them, or whether they needed more funding to support them. In terms of partners within the lab (technicians, equipment managers, postdoctoral researchers, graduate students, undergraduate research assistants), the majority of respondents reported needing more funding; access was evenly split between adequate and needing improvement. In particular, postdoctoral researchers and graduate students were identified as the two areas most in need of additional funding and training [4,5]. We interpret that this reflects the reality that salaries/stipends for these individuals have not kept pace with inflation and demand for these individuals outside of academia continues to increase [6]. We also believe it may reflect the limitations in the current funding mechanisms: most often projects are funded for immediate execution which limits any funding available for those who conduct downstream, explorative analyses. The relatively short nature of focused requests for funding are not designed to support longer-term or longitudinal projects, but perhaps they could be if redesigned. The types of training most desired for students or staff in the lab were in the quantitative or computer sciences. Respondents were evenly split between having adequate access, needing better access and needing more funding for grant specialists. With respect to collaborators, better access was needed to those from outside their discipline. There was no leading result on access to collaborators within their discipline.

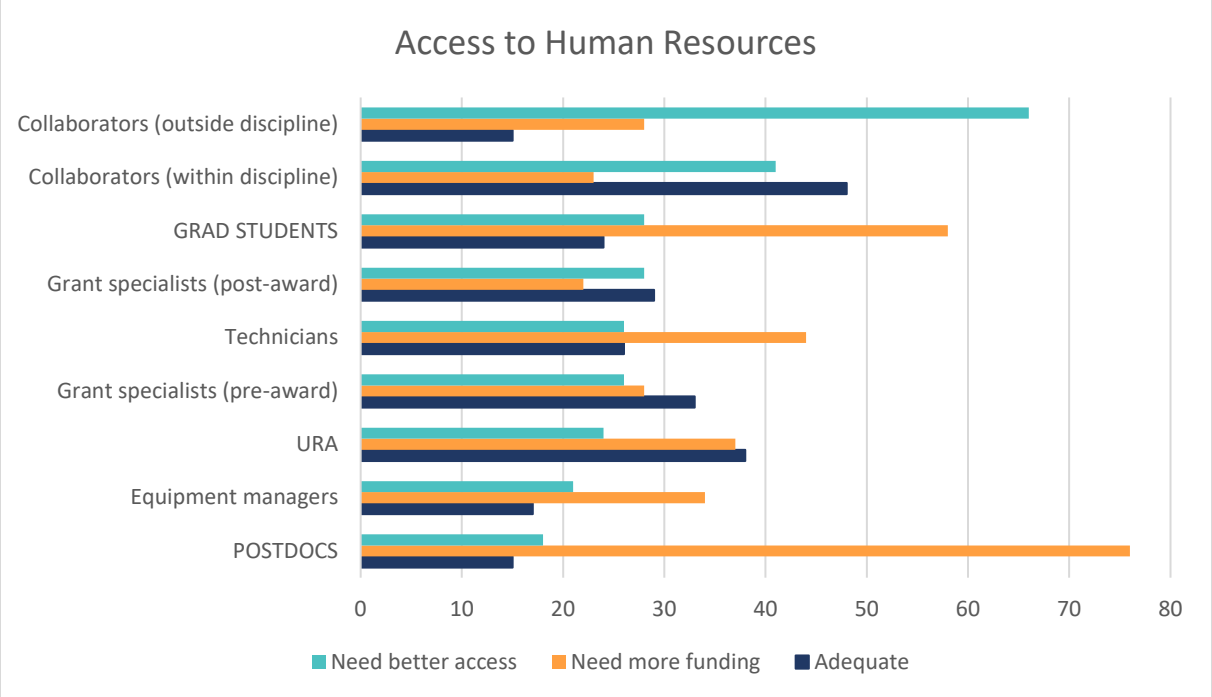

Figure 12: Counts of respondents who reported their current level of access to a list of human resources.

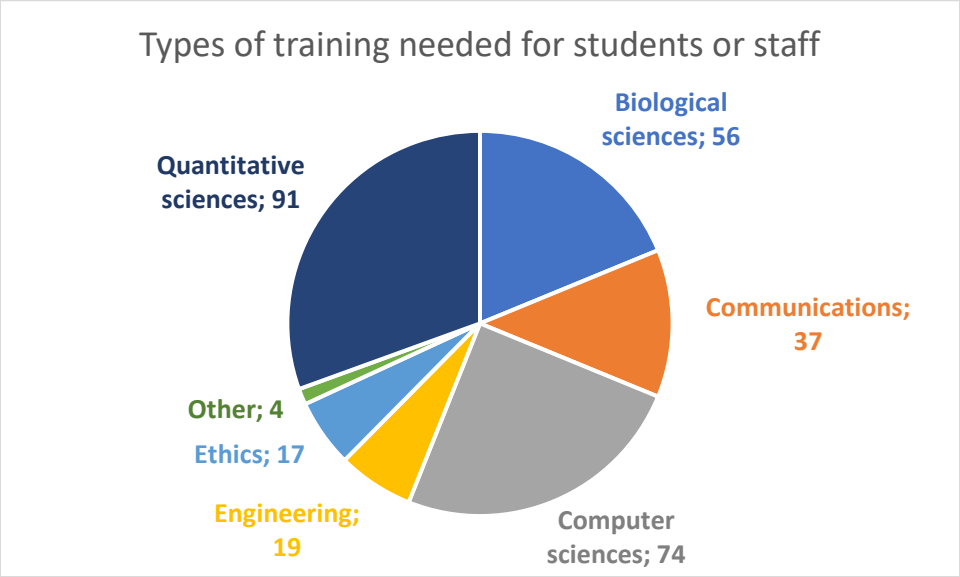

Figure 13: Share of respondents who reported needing training for their students or staff in one or more G2P-related disciplines. Numbers represent the count for each discipline; total responses = 298.

When asked, "if you had access to substantial funding, what G2P-related project would you pursue or would you like to see accomplished? In what ways would this project benefit the agricultural G2P field (e.g., what knowledge would it add; what technique/tool would it create or improve; etc.)" respondents gave answers that fell into 7 general categories, many of which overlapped with the 2020 survey question about AG2P challenges (Table 2): education and training; managing the data pipeline; managing two-way environmental effects (plant/animal to environment and vice versa); increasing collaborations (e.g., public-private, across kingdom, etc.); developing new technologies; expanding research on crops and livestock; and developing new data and data types. When respondents were asked what was preventing them from pursuing these strategies, two responses were generally provided: 1) lack of funding, and/or 2) access to technical expertise. The third most common response - that should not be dismissed - was "access to resources". AG2PI has addressed this last response to some extent by collecting information from volunteers in this survey who are willing to share their resources with others; this contact list is available on the AG2PI website at (https://www.ag2pi.org/resources/community-resources-sharing/).

Table 2: Community "dream" projects to address strategic needs if funding was available	
Education & Training	
G2P research projects for high school teachers for secondary teaching	farmer training on improved crop and animal production technologies
Data Management, Integration & Pipeline	

enable a common reference set of whole genome sequences for imputation	develop G2P prediction pipeline that includes management & environment
Environmental Impact, Sustainability, or Climate Change	
climate smart livestock improvement	enhance crops to sequester more carbon
Increasing Collaborations, Domestic, International & Private	
beyond the farm phenotyping and supply chain integration	internationally collaborative phenotype / genotype datasets
Developing New Technologies	
robotics-based phenotyping of plant and plant-parts	new technology systems for long-term selection efforts & improving welfare
Expanding Research on Crops and Livestock	
molecular breeding for biotic and abiotic stress tolerance	genomic evaluation of livestock breeds
Developing New Data or Data Types	
more UAV data & flights	single-cell-based atlas of livestock

Conclusion

The surveys conducted by AG2PI in 2020 and 2021 provided essential information about the current state of the G2P community, critical needs and challenges, and avenues for further development that AG2PI is well placed to follow. Below are some of the key findings:

- There is a notable percentage of community members who either express interest in conducting G2P research or report a desire to learn more about G2P research yet are not currently participating in G2P research. We think this represents a potential for AG2PI to further build this scientific community through education and outreach.
- Phenomics is a relatively nascent field with untapped potential to contribute to G2P research. This potential can be addressed through development and deployment of tools, data, and training resources.
- One of the greatest barriers to building multidisciplinary teams – those teams most needed to address AG2P research challenges – is finding collaborators from other disciplines. One of way to create cross-disciplinary collaborations is through funding for postdocs and graduate students who often bridge disciplinary groups. However, such funding was identified as an area most in need of additional resources. This outlines one avenue for growth of AG2P research – connecting researchers from different disciplines and supporting these connections through funding and education in phenomics (including the quantitative and computational sciences) for trainees.
- Respondents identified two activities as most critical for AG2PI: coordinating the sharing of resources and information, and advocacy on establishing research priorities to funding agencies. AG2PI has engaged in both activities since its inception. This has led to improved sharing and increased visibility, as well as the launch of new seed funding opportunities for collaborative research through AG2PI.

Elucidating the mechanisms that underlie the relationships between genomics and phenomics in agricultural species is a scientific grand challenge, particularly in the context of climate change and societal demands for sustainable food and feed systems. As demonstrated by these surveys, the community has defined strategic needs that must be met to address this challenge: education and training; tools and resources for managing data and computational analyses; understanding two-way effects between organisms and their environment; increasing collaborations (e.g., public-private, across kingdom, etc.); developing new technologies; expanding research on crops and livestock; and developing new data and data types. AG2PI welcomes additional input from the community (https://www.ag2pi.org/contact-us/) and will continue to allocate its resources on behalf of USDA in ways that are aligned with these community-defined priorities.

ACKNOWLEDGEMENTS

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Appendix 1

major crop	*count*
corn	*21*
cotton	*5*
sorghum	*5*
wheat	*14*
soybean	*13*
barley	*3*
rice	*5*
Nicotiana	*1*
oat	*2*
triticale	*1*
sugarcane	*3*
sugar beets	*3*
canola	*2*
sunflower	*2*
peanut	*4*
alfalfa	*1*

orphan crops	
cassava	*3*
cowpea	*1*
pearl-millet	*1*

specialty crop	*count*
tomato	*8*
Pisum sativum	*4*
Cicer arietinum	*2*
Lens culinaris	*2*
potato	*4*
artichoke	*1*
asparagus	*1*
Vicia faba	*1*
Brassica	*1*
horticultural crops	*1*
lettuce	*1*
Phaseolus vulgaris	*2*
Pulse crops	*2*
vegetables	*1*
citrus	*3*
grapevine	*3*
apples	*2*
apricot	*1*
blueberry	*1*
Carica papaya	*1*
muscadine grape	*1*
Pyrus communis	*1*
Fragaria x ananassa	*3*
peach	*1*
Agave tequilana	*1*
sesame.	*1*
linseed	*1*
cluster bean (guar)	*1*
hemp	*1*
ornamentals	*3*
Coffee	*1*

major livestock	*count*
cattle	*57*
swine	*33*
poultry	*16*
ruminants	*2*

specialty livestock	
sheep	*22*
goat	*12*
horse	*5*
rabbit	*3*
bison	*2*
alpaca	*1*
small ruminants	*1*
water buffalo	*1*
mink	*1*

other animal	
deer	*2*
quail	*1*
wildlife	*1*
dogs	*2*
raptors	*1*
human	*2*

aquaculture/seafood	*count*
fish	9
rainbow trout	5
atlantic salmon	3
bay scallop	2
clam	2
aquaculture species	1
shrimp	1
steelhead trout	1
sugar kelp	2
tautog	1
aquaculture molluscan bivalves	1
aquatic animals	5
catfish	1
Clarias gariepinus	1

microbes	
soil microbiomes	2
algae	1
Bacteria gut fauna	1
phytoplasmas	1
E. coli	1
Spiroplasma citri	1
X. taiwanensis	1
bacteria	1
Fusarium circinatum	1
microbial species	1
Xylella fastidiosa	1
Salmonella	1
viral pathogens	1
Candidatus Liberibacter asiaticus	1

Appendix 1

Vanilla planifolia	*1*

trees	
ash	*1*
Cedrela odorata	*1*
chestnut	*1*
pinus radiata	*1*
Pseudostrobus	*1*
redbud	*1*
white oak	*1*
Prunus	*1*

other	1
milkweed	1
duckweed	1
other Rosaceae	1
switchgrass	1
zebrafish as model organism	1
Arabidopsis	1
Cenchrus sp.	1
herbal plants.	1

insects	***count***
arthropods	2
bee	5
Chrysodeixis includens	1
circulifer tenellus	1
flies	1
fruitflies	3
Grapholitha	1
Helicoverpa armigera	1
Heliothis virescens.	1
internal / external parasites	1
invertebrates	1
Lygus lineolaris	1
mites	1
Piezodorus guildinii	1
ticks	1
Tribollium	1
beet leafhopper	1
Helicoverpa zea	1
Mosquitoes	1
Rhagoletis	1