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Plant breeding capacity in U.S. public institutions

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Abstract

Several studies in recent decades have warned that plant breeding capacity in U.S. institutions may be declining, placing our food system at risk. To further understand the status, trajectory, and needs of these programs, a national survey was conducted in 2018. Public-sector plant breeding programs (n = 278) in 44 U.S. states responded to questions about staffing levels, budgets, access to needed personnel, and access to technology for selective breeding. Almost half of program leaders were nearing retirement age. Programs reported significantly declining estimates of hours spent on program activities by program leaders and technical support staff. On average, programs reported devoting 2.78 full-time equivalent (FTE) to plant breeding research in the most recent fiscal year (including all types of personnel); for germplasm enhancement activities and variety development, mean estimated hours per program totaled 1.58 and 2.20 FTE, respectively. The median annual operating budget in the most recent fiscal year was US$150,000; the mean (average) annual operating budget was US$266,562. Budget and FTE means are somewhat skewed toward higher figures because of a few unusually large programs; almost 80% of programs reported annual budgets of US$400,000 or less. Institutional funds, federal competitive grants, and commodity check-off programs accounted for 67% of program budgets. Many programs reported that budget shortfalls or uncertainty "endangered or severely constrained" or seriously constrained their ability to support key personnel, infrastructure and operations, and access to current technology for collecting, analyzing, and applying knowledge from phenotype and genotype data on plant materials in their programs.

1 | INTRODUCTION

A series of studies conducted in recent decades have attempted to assess the status of U.S. plant breeding efforts in public-sector institutions (for example Frey, 1996; Shelton & Tracey, 2017; Traxler, Acquaye, Frey, & Thro, 2005; see also Brooks & Vest, 1985; James, 1990; Kalton & Richardson, 1983). Collectively, these articles have warned that U.S. plant breeding capacity, a critical component of our food system and national security, is at risk from factors such as shrinking budgets, declining institutional support, increased labor and land costs, and attrition and nonreplacement of senior staff members. Additional challenges include the changing landscape of intellectual

Abbreviations: FTE, full-time equivalent; NAPB, National Association of Plant Breeders; NRSP10, National Research Support Project 10; PBCC, Plant Breeding Coordinating Committee.

property rights management that can impede collaboration; a growing need for advanced technology such as DNA testing, genomics, and bioinformatics, along with expertise for applying these tools within selective breeding programs; and increased need in both public and private programs for appropriately trained staff members at the same time that necessary educational programs are dwindling.

The most recent of these articles, Shelton and Tracy (2017), asked individual breeders involved in cultivar development about their overall level of funding, how their breeding operations were affected by recent developments in intellectual property rights and germplasm exchange, and related issues; breeders who had not released finished cultivars were excluded. The authors noted that "there are not enough younger breeders working in the public sector today to maintain the current level of cultivar development as the most senior breeders retire" and concluded that "plant breeding in the public sector is in a current state of crisis as a result of a lack of sufficient funding to support this public good." Shelton and Tracy (2017) contended that public plant breeders "play a critical role in determining the future of agriculture. Their work is varied, and includes long-term research in areas such as assessing and broadening genetic diversity, introgression of traits from wild species, development of new breeding methodologies, and expanding applications for genomic tools. Public plant breeders are responsible for the education of the next generation of plant breeders (both public and private)…." We would add that some large-scale research and development efforts in crop improvement require long-term investment and collaboration across multiple geographies and institutions—challenges which may be difficult or impossible for private-sector companies to tackle—though proprietary food companies ultimately benefit from the presence, stability, and achievements of public breeding programs.

In 2017, members of the U.S. Plant Breeding Coordinating Committee (PBCC), under the objectives of the multistate research project SCC080: Sustaining the Future of Plant Breeding, began work on developing and fielding a new survey to provide a more detailed understanding of the human and financial resources available for public-sector plant breeding in the United States by drilling deeper into questions of financial stability and personnel availability. A survey design group involving representatives of the PBCC, members of the National Association of Plant Breeders (NAPB), Washington State University, and Cedar Lake Research Group, LLC, met regularly during late 2017 and early 2018 to clarify the focus of an initial survey of public institutions and develop specific survey questions and methods. Unlike previous studies that gathered responses from informants at the state or university administrative levels or that collected responses directly from individual public plant breeders about themselves and all of their plant breeding work (i.e. a single combined response potentially including multiple crops or markets targeted by the breeder), the unit of analysis chosen for this study is the plant breeding program (not the breeder, who may lead more than one breeding program as defined by the target crop and market). The sample includes not only breeding programs that release cultivars, but also programs focused on plant breeding research or germplasm enhancement since these prebreeding activities are integral to U.S. plant breeding network capacity.

The final survey instrument was designed to focus on the level of human and financial resources available for selective plant breeding programs that are located within public-sector institutions. We hope to repeat the study in future years to assess ongoing change in these programs and to field a separate survey on educational issues in plant breeding, which would require input from both public- and private-sector institutions that house plant breeding programs.

The study focused on programs and activities related to selective plant breeding, as described by the NAPB (www.plantbreeding.org): "The process involves combining parental plants to obtain the next generation with the best characteristics. Breeders improve plants by selecting those with the greatest potential based on performance data, pedigree, and more sophisticated genetic information … Breeding involves the creation of multi-generation genetically diverse populations on which human selection is practiced to create adapted plants with new combinations of specific desirable traits. The selection process is driven by biological assessment in relevant target environments and knowledge of genes and genomes." The rapidly changing applications of genetic engineering methods (alone or in combination with selective breeding) raise somewhat different questions of institutional capacity and may be best explored using a distinct research approach.

2 | MATERIALS AND METHODS

Iterative content drafts of the survey were circulated among the design team and advisors (plant breeders and researchers), resulting in a final version that included introductory material, informed consent information, definitions of key terms, and 100 questions. Major topics included respondent and organizational information; breeding program crop and market focus; personnel FTE devoted to selective breeding program activities; access to needed personnel; budget levels, funding sources, expenditure categories, and budget-related program constraints; and technology and technology-related program constraints.

Questions about FTE devoted to the program by particular types of personnel were structured to elicit the total number of individuals involved and the total amount of personnel FTE expended on three major categories of selective plant breeding activities: plant breeding research, germplasm enhancement, and variety development. Program representatives were asked to report the total FTE across these three activity types during the most recent completed fiscal year and to estimate what this figure had been during the fiscal year 5 yr prior to the most recent completed fiscal year. These three plant breeding activities were defined as follows:

- Plant breeding research: Research on the genetics and genomics of plants and on methodologies of selective plant breeding to provide fundamental information useful for making selective plant breeding programs more efficient and productive.
- Germplasm enhancement: Any activity that includes (a) the transfer of useful genes from unadapted lines of the same species or from related species and genera into plant populations that are useful for developing new crop varieties and (b) increasing the frequencies of desirable genes in crop gene pools that will be used for developing parents or varieties. For this survey, questions about germplasm enhancement refer to inclusion in breeding programs of germplasm from wild or previously excluded species that can be reproductively crossed with existing breeding material within a selective breeding program. Introduction of novel genes through genetic engineering approaches such as gene editing or transgenic applications are not the focus of this survey.
- Variety development: Parent selection, crossing, and further selection of offspring with the direct purpose of developing and releasing a new crop variety for farmers, gardeners, or land managers to directly grow.

In addition to providing specific estimates for staffing and budget levels, program representatives were asked to rate a number of factors related to their access to needed personnel, the impact of budget constraints or uncertainty on program operations, and the adequacy and availability of high-quality, reasonably priced enabling technology and related knowledge and expertise for selective breeding for each specific crop program.

An online portal for the survey was built within the National Research Support Project 10 project site (NRSP10; www.nrsp10.org) hosted by Washington State University according to the specifications of the working group, and invitations to participate were circulated beginning in March 2018. In the absence of a definitive contact list of current U.S. public-sector selective plant breeding programs, open invitations were circulated broadly in U.S. plant breeding networks by the NAPB, PBCC, and State Agricultural Experiment Station directors. Breeders of multiple crops (or crops intended for multiple distinct markets) were asked to report separately on each of their crop improvement programs based on the crop classification system used within the USDA REEport database. Breeders were asked to report which market type is the focus of each program and the geographic focus of each program for both production (growers) and markets (product sales). Data collection proceeded through June 2018.

3 | RESULTS

3.1 | Breeding program sample characteristics

Survey responses were obtained from 287 U.S. plant breeding programs operating in the public sector. Responding programs were primarily located in Land Grant University State Agricultural Experiment Stations (209 programs, 72.8% of the sample) but also included programs at USDA facilities (40 programs, 13.9% of the sample) and public universities or public–private partnerships operating primarily as public-sector organizations (38 programs, 13.2% of the sample). Almost 60% of responding programs focus on three of the crop groups designated in the USDA REEport system: vegetables, grain crops, and deciduous and small fruits (Table 1).

Most but not all programs were actively engaged in variety development; some primarily exist to conduct breeding-related research or germplasm enhancement, for example, as a service to other breeding programs. Responding programs reported releasing a total of 764 cultivars for public use in the past 5 yr. No cultivars had been released in the past 5 yr by 106 programs, 40.3% of the 263 programs that answered this question. Some were new programs, some were older programs that had not released cultivars recently, and some were focused on germplasm enhancement, development of disease-resistant parents, or other prebreeding activities rather than cultivar development. Most of the remaining programs—44.9% of the sample—reported releasing from one to five cultivars in the past 5 yr. Six or more cultivar releases in the past 5 yr were reported by 39 programs, 14.8% of the sample. A single breeding program response was contributed by 202 breeders, 25 breeders contributed responses for two programs, six breeders reported on three programs each, and three breeders reported on four to seven programs. Programs located in 44 states were represented. Eleven states accounted for 60% of responses: Texas, Washington, Florida, Wisconsin, Georgia, California, North Carolina,

TABLE 1 Crop group representation in survey sample of U.S. public-sector plant breeding programs

Crop group	No. of programs	Percentage of survey sample
Vegetables	71	24.7
Grain crops	58	20.2
Deciduous and small fruits	43	15.0
Oilseed and oil crops	27	9.4
Pasture and forage crops	20	7.0
Ornamentals and turf	19	6.6
Fiber crops	15	5.2
Sugar crops	8	2.8
Tropical and subtropical fruit	6	2.1
Rootstocks	5	1.7
Citrus	5	1.7
Miscellaneous and new crops	5	1.7
Edible tree nuts	4	1.4
Tobacco	1	0.3

Note. $N = 287$.

TABLE 2 Age of individual breeders who responded to a survey of U.S. public plant breeding programs

Reported age of individual breeder representing program	Frequency	Percentage of survey sample
30–34	10	3.8
35–39	27	10.3
40–44	32	12.3
45–49	30	11.5
50–54	33	12.6
55–59	41	15.7
60–64	52	19.9
65–69	24	9.2
70+	12	4.6

Note. N = 261 programs. Twenty-six programs did not answer this question. Individuals who reported for more than one program are represented in this table multiple times, once for each program report.

Michigan, Mississippi, Oregon, and Tennessee. Figure 1 displays responding programs by state-based USDA Economic Research Services farm production regions.

More than one-third of programs (33.7%) were represented by breeders age 60 or older; almost half (49.4%) were represented by breeders age 55 or older; 62% were represented by breeders age 50 or older (Table 2).

Nearly 70% of responding programs focus on food for people, including 34.9% with a focus on fresh market foods and 34.5% with a focus on ingredients for processed foods

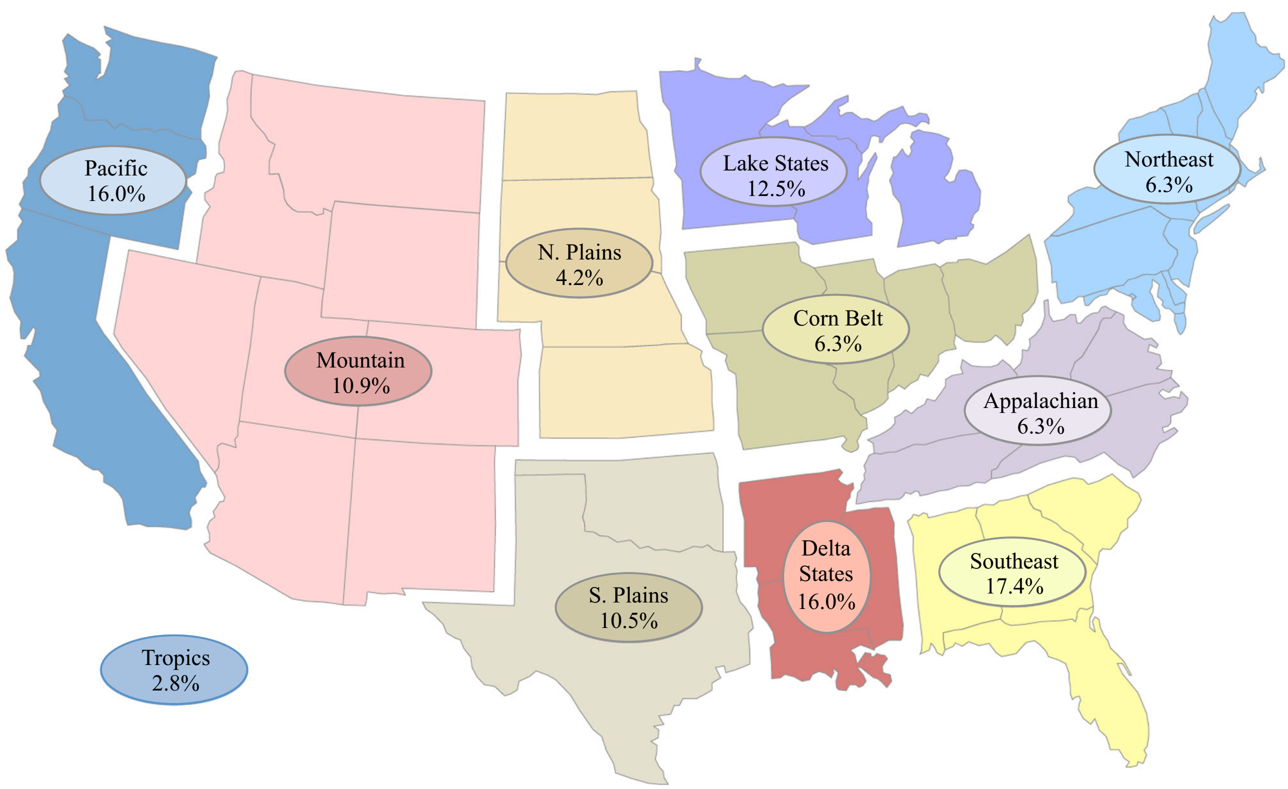

FIGURE 1 Percentage distribution of plant breeding program survey responses by state-based USDA Economic Research Services (ERS) Farm Production Regions

TABLE 3 Market type focus reported by U.S. public plant breeding programs

Market type	Frequency	Percentage of survey sample
Fresh market (food for people)	89	34.9
Processing market (food for people)	88	34.5
Animal feed	29	11.4
Industrial market	28	11.0
Ornamentals	16	6.3
Ecosystem services or cover crops	5	2.0

Note. N = 255. Twenty-two programs did not answer this question, and 10 marked a "not applicable" response choice; these 32 programs are excluded from the table. Percentage column does not sum to 100 because of rounding.

(Table 3). The remaining programs target animal feed (11.4%), industrial uses (11.0%), ornamental plants (6.3%), and ecosystem services or cover crops (2.0%).

Geographic areas targeted by programs for production (where growers are located) and for product sales (where products are sold) were also reported (Table 4). A program could focus on breeding cultivars for producers in one or more geographic areas and could focus on breeding cultivars intended for product sales in one or more geographic areas. More than three quarters of responding U.S. breeding programs focus on developing cultivars for local or regional (U.S.) producers; more than half target cultivars to larger domestic production areas, and more than one-third develop cultivars for growers outside the United States. More than three-fifths of programs target end-product markets in the United States (local, regional, or national), while more than half of programs reported producing cultivars aimed at an international product sales market.

3.2 | Personnel

The survey asked for the number of individuals employed in several job categories during the most recently completed fiscal year, the total amount of FTE devoted to specific selective plant breeding program activities and how these numbers had changed from 5 yr ago.

3.2.1 | Program leaders

Most programs (86.2%) had a single program leader—a principal investigator or scientist with responsibility for designing, planning, managing, and conducting breeding activities. Another 5.8% reported two program leaders, 7.2% reported three to five program leaders, and two programs (0.7%) reporting operating with no program leaders. The mean number of program leaders was 1.22 (SD = 0.78). On average, more program leader time was spent on plant breeding research (0.37 FTE) and variety development (0.39 FTE) than on germplasm enhancement (0.28 FTE) (Table 5).

3.2.2 | Post-Doctoral associates

Almost two-thirds of responding programs (62.7%) had no post-doctoral associates; 24.4% reported only a single post-doctoral associate. Another 28 programs (10.3%) reported having two post-doctoral associates, and seven programs (2.6%) reported having three. The mean number of post-doctoral associates was 0.52 (SD = 0.78). As shown in Table 6, more post-doctoral time was spent on plant breeding research than on germplasm enhancement or variety development. The FTE among all respondents provides an estimate of average effort across all responding programs for those interested in how much FTE plant breeding programs in the United States devote to this activity broadly. A second row for each type of personnel drills down to look at only those breeding programs that employ at least one person in that particular category of personnel for those interested in a tighter focus on how such personnel are deployed when they are available.

3.2.3 | Graduate students

More than two-thirds of responding programs (70.7%) had at least one graduate student; 18.5% reported a single graduate student, 23.7% reported having two students, 19.6% reported having three or four students, and 8.5% reported having five to eight graduate students. The mean number of graduate students was 1.84 (SD = 1.77). More graduate student time was spent on plant breeding research than on germplasm enhancement or variety development.

3.2.4 | Technical support staff members

Almost all programs (84.6%) reported at least one technical staff member (lab, greenhouse, or field technicians); 35.5% reported having one, 26.0% reported having two, and 23.1% reported having three to nine technical staff members. The mean number of technical support staff members was 1.84 (SD = 1.61), with more of their time spent on variety development than on plant breeding research or germplasm enhancement.

TABLE 4 Geographic production area focus and market area focus of U.S. public-sector breeding programs

	Production area focus		Sales market focus	
Geographic area	Frequency	Percentage of survey sample	Frequency	Percentage of survey sample
Local or regional	220	76.7	175	61.0
National	149	51.9	175	61.0
International	102	35.5	148	51.6
Not applicable	2	0.7	7	2.4

Note. $N = 287$. Programs could choose more than one response to this question, so the percentage columns are not expected to sum to 100.

TABLE 5 Annual program leader full-time equivalent (FTE) devoted to plant breeding activities reported by U.S. public plant breeding programs

Plant breeding activity	Percentage of programs reporting zero FTE	Percentage of programs reporting 1.00 or more FTE	FTE mean (SD)
Plant breeding research	27.3	20.7	0.37 (0.40)
Germplasm enhancement	37.7	14.5	0.28 (0.41)
Variety development	27.4	19.7	0.39 (0.40)

Note. $N = 274–276$.

3.2.5 | Advanced scientific personnel

Most responding programs (71.6%) reported having no advanced scientific personnel (allied scientists, physiologists, pathologists, bioinformatics specialists, etc.) employed within the program; 19.6% of programs reported having one and 8.5% reported having two to 10 advanced scientific personnel. The mean number of such staff members was 0.48 (SD = 1.09). More of their time was spent on plant breeding research than on germplasm enhancement or variety development.

3.2.6 | Other personnel

No other personnel (e.g. temporary or seasonal farm workers or others not categorized above) were reported by 31.4% of programs; 34.1% of responding programs reported one or two other staff members and 34.5% reported having three to 20. The mean number of other staff members was 2.35 (SD = 2.83). More of their time was spent on variety development than on plant breeding research or germplasm enhancement.

3.2.7 | Personnel full-time equivalent change estimates over the past five years

To get a sense of the extent to which breeding programs were increasing or decreasing in capacity over time, survey respondents were asked to estimate the total personnel FTE of each breeding program during the most recent fiscal year and also during the fiscal year that occurred 5 yr prior to the most recent completed fiscal year (Table 7).

The estimated mean FTE of current breeding program leaders (principal investigators, scientists with responsibility for designing, planning, managing, and conducting breeding activities) was significantly lower than the estimated FTE of program leaders 5 yr earlier, $t_{(253)} = -2.86$, $p = .0045$, an estimated decline of 21.4%. The estimated mean FTE of current breeding program technical support staff members (lab, greenhouse, or field technicians) was also significantly lower than the estimated FTE of technical support personnel 5 yr earlier, $t_{(233)} = -2.72$, $p = .0070$, an estimated decline of 17.7%. Differences in estimates of current and 5-yr-ago personnel FTE for other personnel categories were not statistically significant.

3.2.8 | Access to needed personnel

Respondents' ratings of 18 statements about program access to needed personnel, including overall availability of needed personnel, factors that might limit ability to hire needed staff members, and positive factors that might enhance a program's ability to attract and hire new personnel are presented in Supplemental Table S1 with some highlights noted below.

Slightly more than half of programs (53.4%) reported some level of agreement that "enough allied professionals with advanced knowledge and ability in breeding-related science and technical areas are available to this crop breeding/science program, as staff members, collaborators, consultants or vendors (e.g. pathologists, physiologists,

TABLE 6 Reported full-time equivalent (FTE) on plant breeding activities by personnel type in U.S. public plant breeding programs

			FTE		
			Plant breeding research	Germplasm enhancement	Variety development
Personnel type	Respondents	*n*	Mean (SD)	Mean (SD)	Mean (SD)
Post-Doctoral	All respondents	271	0.31 (0.60)	0.11 (0.32)	0.09 (0.28)
	Only programs with post-docs	101	0.84 (0.73)	0.30 (0.46)	0.22 (0.41)
Graduate Student	All respondents	270	0.98 (1.38)	0.37 (0.70)	0.19 (0.54)
	Only programs with graduate students	191	1.38 (1.46)	0.51 (0.79)	0.27 (0.62)
Technical support staff	All respondents	271	0.50 (0.75)	0.37 (0.63)	0.75 (1.08)
	Only programs with technical support staff	231	0.60 (0.78)	0.43 (0.66)	0.88 (1.12)
Advanced scientific personnel	All respondents	271	0.20 (0.51)	0.10 (0.39)	0.10 (0.41)
	Only programs with advanced scientific personnel	77	0.70 (0.75)	0.34 (0.66)	0.34 (0.71)
Other personnel	All respondents	261	0.42 (0.86)	0.35 (0.94)	0.68 (1.25)
	Only programs with other personnel	179	0.61 (0.99)	0.50 (1.11)	0.99 (1.40)

TABLE 7 Estimated changes in personnel full-time equivalent (FTE) over the past 5 yr reported by U.S. public plant breeding programs

	Estimated FTE, fiscal year 5 years prior to recent fiscal year	Estimated FTE, most recent fiscal year	Difference (SE)
Personnel type (no. of survey responses)	Mean (SD)	Mean (SD)	
Program leaders (254)	1.13 (1.26)	0.93 (0.59)	−0.20** (0.07)
Post-Doctoral associates (234)	0.63 (1.58)	0.49 (0.74)	−0.14 (0.09)
Graduate students (238)	2.05 (3.26)	1.73 (1.86)	−0.28 (0.18)
Technical support staff (241)	2.10 (3.26)	1.65 (1.60)	−0.45** (0.17)
Advanced scientific personnel (170)	0.73 (2.04)	0.55 (1.03)	−0.18 (0.12)
Other personnel (198)	2.38 (3.90)	2.52 (4.00)	0.14 (0.31)

**Significant at the .01 probability level.

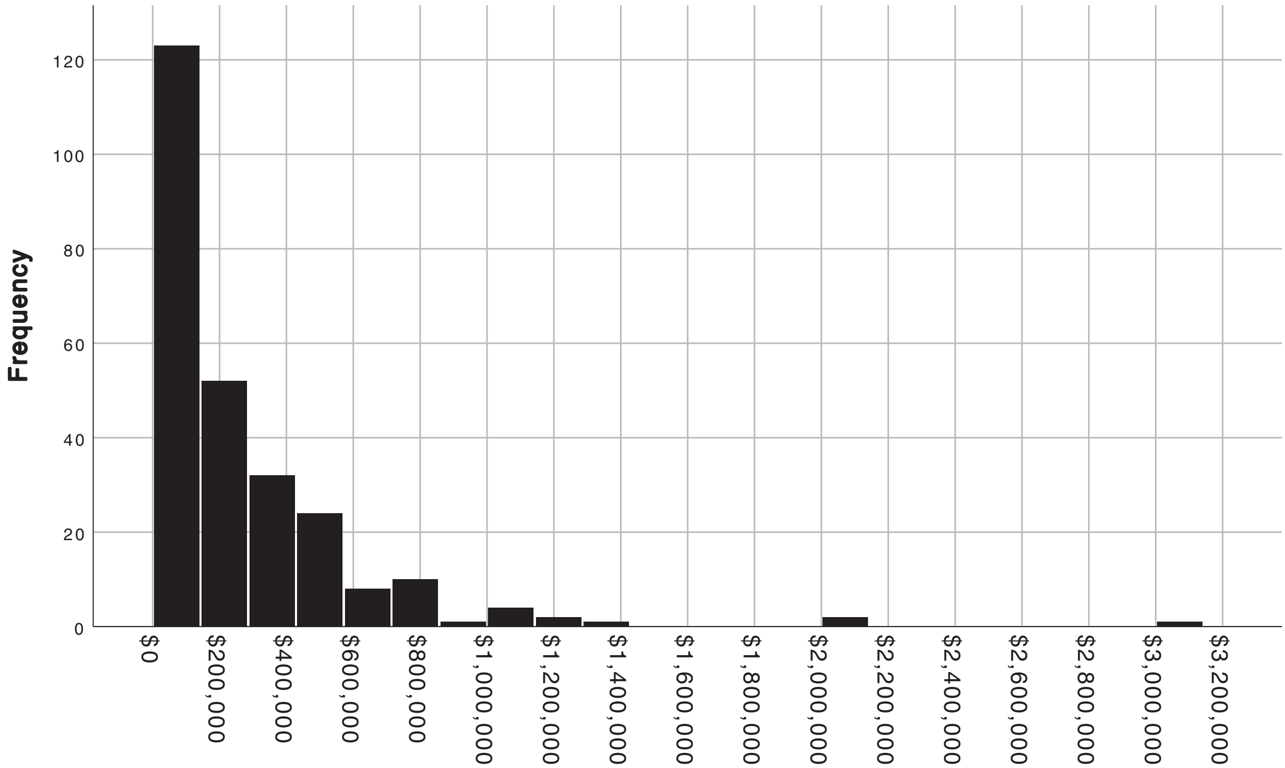

FIGURE 2 Distribution of U.S. public plant breeding program annual operating budgets

genomicists, bioinformatics specialists, etc.).” However, more than one-third (34.6%) moderately or strongly disagreed that their program has enough access to allied professionals. Fewer than half of programs reported adequate access to in-house technical support personnel, adequate capacity (salary, benefits, opportunities) to attract applicants for advanced positions, or adequate ability to readily replace departing professional staff members or collaborators.

Of the seven possible limitations on the ability to hire needed staff, two issues were rated as most problematic: lack of funding for competitive salaries and benefits and lack of stable long-term funding (causing a reliance on temporary positions, students, and post-doctoral associates). More than two-thirds of programs moderately or strongly agreed that these factors significantly limit their ability to hire needed staff.

Program characteristics that were rated as most attractive to new hires included opportunities to apply scientific knowledge in practical ways and to make new scientific discoveries; more than half of programs moderately or strongly agreed with those statements. Somewhat lower ratings were given to factors such as opportunities to contribute to public knowledge (vs. proprietary information), having an attractive setting and work environment, continuing education opportunities, and opportunities to gain professional experience (resume building). The lowest ratings for what programs offer to prospective employees were for the salary and benefits package; fewer than 20% of programs moderately or strongly agreed that such compensation is a strength of the program for attracting new staff members.

3.3 | Funding

3.3.1 | Annual operating budget

Among the 260 programs that reported a total budget amount, the median annual operating budget in the most recent fiscal year was US$150,000 (Figure 2). The distribution was skewed by a small number of programs with relatively high budgets, resulting in a mean annual operating budget of US$266,562. Ten programs reported recent annual operating budgets of US$1 million or more; 79.6% of programs reported annual budgets of US$400,000 or less.

Programs were asked to report whether they pay (from their program budgets) for six categories of expenditures that, in some cases, are provided without charge by their institutions. Programs are most likely to pay for field and greenhouse supplies followed by field and greenhouse labor; about half of the responding programs also expend program operating funds for field and greenhouse space.

TABLE 8 U.S. public plant breeding program funding sources

Funding source	Mean percentage of total budget (SD)
Institutional funds from university/employer	31.22 (32.88)
Federal competitive grants (USDA or other)	18.77 (25.72)
Commodity check-off programs	17.22 (27.28)
Private industry support (gifts, grants, contracts, excluding separate commodity check-off programs or competitive grants)	10.62 (18.34)
Federal formula funds (e.g. Hatch Act funds)	7.36 (19.03)
Royalties from previously released varieties	5.51 (13.41)
State or institutional competitive grants (not including federal formula or Hatch funds allocated competitively by institution)	5.42 (11.81)
Other	3.88 (15.33)

Note. $N = 255$.

3.3.2 | Funding sources and expenditure categories

Programs were asked to report whether federal formula funds (Hatch funds) contribute to the breeder's salary for the program. Of the 263 programs that answered this question, 41.4% answered affirmatively, while 32.7% reported that no federal formula funds supported the breeder's salary and 25.9% of respondents were not sure.

Breeding program funding sources are displayed as the mean proportion of breeding program annual operating budgets that came from eight sources (Table 8). Institutional funds, federal competitive grants, and commodity check-off programs accounted for slightly more than two-thirds of program budgets. The remaining one-third of program funding came from private industry support, federal formula funds, royalties from previously released varieties, state or institutional competitive grants, and other sources (including endowments, other breeding programs, foundation funding, and unspecified sources).

3.3.3 | Adequacy of budgets for key program operations

Programs were asked to report the extent to which key breeding program operational components are constrained by budget shortfalls or uncertainty vs. being reliably supported: "To what extent is this program supported or constrained in the following areas?" Being "endangered or severely constrained" or "seriously constrained" by budget shortfalls or uncertainty was reported by almost 39% of programs when asked about graduate student or post-doctoral intern positions, by 30% of programs with regard to technical support staff positions and by almost 27% of programs with regard to having access to advanced scientific personnel (either as staff members or as consultants). Serious or severe budget constraints were reported by 18–20% of programs with regard to physical infrastructure and nontechnical labor; scientific and laboratory equipment budgets were reported as seriously or severely constrained by 13.5% of programs (Table 9).

3.4 | Technology

The last set of questions asked about technology applications used within each program and the degree to which various program activities were supported or constrained by access to technologies for selective breeding.

3.4.1 | Collection and storage methods for phenotypic data

When asked how phenotypic data is collected in the field, 118 of 251 responding programs (47.0%) reported using paper to record phenotype data in the field, while 31.5% reported using spreadsheet software on a handheld device such as a tablet or phone, and 21.5% reported using another dedicated application on a handheld device.

When asked how phenotype data is ultimately stored and managed, 84.8% of 244 responding programs reported using generic spreadsheet software (Microsoft Excel); 11.1% reported using specialized database software (AgroBase; Agronomix Software, Inc.), and 4.1% reported using generic relational database software (Microsoft Access).

3.4.2 | Adequacy of budgets for breeding program technologies

Ratings of program access to high-quality, reasonably priced enabling technology and related knowledge and expertise for selective breeding are summarized in Table 10. Technical tools for the collection, management, and analyses of phenotypic data were the most reliably accessible technologies, with fewer than 26% of programs reporting being endangered or seriously constrained by

TABLE 9 Impact of budget constraints or budget uncertainty on specific components of U.S. plant breeding program operations

Breeding program component	Endangered or severely constrained	Seriously constrained	Somewhat constrained	Reliably, adequately supported at a basic operating level	Reliably, very well supported
			%		
Building space and maintenance (greenhouse, lab and office space, not including equipment)	7.7	10.4	33.6	30.9	17.4
Scientific and laboratory equipment	2.3	11.2	36.0	32.6	17.8
Farm field space, field/greenhouse equipment, basic field/greenhouse labor/services (excluding seasonal/temporary labor)	6.6	12.8	26.0	32.9	21.7
Seasonal/temporary labor	6.8	12.4	40.0	28.4	12.4
Technical support (lab, greenhouse or field technicians)	10.8	19.2	31.5	22.7	15.8
Access to advanced scientific personnel	8.3	18.5	29.9	24.8	18.5
Positions for graduate students or post-doctoral interns	17.1	21.8	32.1	17.5	11.5

Note. $N = 250–260$. Row percentages may not sum to 100 because of rounding.

lack of access to these tools. Among tools for phenotyping work, access to technology for phenotypic measurement of market supply chain characteristics was the most constrained, with 25.7% of programs reporting their operations being severely or seriously constrained by lack of access.

Technologies for genotype testing and for managing and analyzing genotypic data were rated as being least accessible, with 23–39% of programs reporting that their operations were endangered, severely constrained, or seriously constrained by lack of access to these technologies. Technology and knowledge for integrated management and analysis of phenotypic and genotypic data were reported as being almost as constrained as technologies for genotype testing and related data management and analysis, with 24–29% of programs reporting that their operations were endangered, severely constrained, or seriously constrained by lack of access to these technologies.

When asked about other technologies for selective breeding, several were mentioned as constraining factors, including harvesting equipment, genomic selection technologies, seed storage, plant pathology, funds for genotypic data, chemical analyses, disease resistance screening, and GPS equipment.

4 | DISCUSSION

In 2015, the USDA published the *USDA Roadmap for Plant Breeding*, which described plant breeding as a "core capacity for robust response to USDA's strategic and action goals" aimed at ensuring the country's food security, natural resource resilience, and public health. The *Roadmap* specifically highlights the importance of public-sector investment in plant breeding, particularly in areas of systemic private underinvestment, while noting that in recent years "public investment in cultivar development has fallen." The report notes many examples in which public funding for plant breeding has produced beneficial scientific and economic outcomes that were highly unlikely to have been achieved by private organizations alone but noted that the repetitive, uncertain grant-driven challenge of "piecing together various short-term (1-, 2-, or sometimes 5-year) funding sources" to address projects that require "typically a 7- to 12-year process, or far longer" distracts public-sector breeding programs from their substantive work and may lead new graduates in plant breeding and plant sciences to avoid public-sector work entirely. In addition to decreased funding and structural problems with funding mechanisms, the *Roadmap* highlighted the growing challenge of breeding program access to needed personnel as a result of a high rate of plant breeder retirements as well as new discoveries and advances in the science and methodology of plant breeding "occurring just

TABLE 10 U.S. public-sector plant breeding program access to key technology

Technology application	Endangered or severely constrained	Seriously constrained	Somewhat constrained	Reliably, adequately supported	Reliably, very well supported
	%				
Phenotypic measurement of key characteristics for producers (e.g. plant growth, productivity, ease of harvesting, resilience/resistance/tolerance of disease and climate hazards) (251)	5.2	10.8	35.9	34.7	13.5
Phenotypic measurement of quality characteristics for consumers (taste, texture, nutrition, etc.) (225)	4.9	14.2	36.4	33.3	11.1
Phenotypic measurement of market supply chain characteristics (e.g. ability to store and ship, ease of packing and processing, shelf life) (179)	6.7	19.0	40.2	25.1	8.9
Phenotypic data management and analysis (249)	1.6	8.8	32.9	40.6	16.1
Genotype testing for fingerprinting, identity verification, pedigree verification, intellectual property protection (245)	6.5	16.7	33.5	25.7	17.6
Genotype testing for key traits for use in parent selection and cross planning (240)	9.6	20.0	29.6	24.6	16.3
Genotype testing for key traits for mass screening of seedlings (239)	10.0	29.3	30.1	18.0	12.6
Genotypic data management and analysis (239)	10.9	22.2	30.5	21.3	15.1
Software for integrated management and analysis of phenotypic and genotypic data (240)	8.3	20.4	35.8	27.5	7.9
Documentation, training, ease of use, learning curve for use of relevant software (234)	7.3	18.4	40.2	27.8	6.4
Knowledge for integrated management and analysis of phenotypic and genotypic data (242)	5.8	18.2	36.0	26.0	14.0
Adequate computational resources (hardware) for storage, analysis, and transfer of large data sets (243)	4.1	11.1	24.7	39.1	21.0

Note. $N = 179–251$. Number of responses in parentheses after each question; Not-applicable responses are not included. Row percentages may not sum to 100 because of rounding.

as agriculture globally is challenged by emerging threats of diseases, pests, and environmental extremes; changing consumer needs and preferences; expanding demand for biomaterials of all kinds; and the need and opportunity for crop products of higher quality than ever before" (USDA Plant Breeding Working Group, 2015).

This study was undertaken to generate a more detailed understanding of funding and personnel issues in public-sector plant breeding programs. Among the programs sampled, the distribution of operating budgets is highly skewed, containing many small programs and a few large programs; the median total operating budget in the most recent fiscal year was US$150,000, while about 20% of programs reported annual operating budgets greater than US$400,000. About half of programs reported being at least somewhat constrained by budget shortfalls or uncertainty with regard to core facilities, such as buildings and equipment, with many rating their operations as being "seriously constrained" or "endangered or severely constrained" by budget shortfalls in these areas.

More than 85% of programs reported having a single program leader; more than one-third of programs were represented by breeders age 60 or older, while almost half were represented by breeders age 55 or older, and 62% were represented by breeders age 50 or older, confirming widely reported concerns about the high rate of impending plant breeder retirements. Programs estimated that the mean overall FTE of program leaders and technical support personnel had fallen significantly over the past 5 yr. Both public- and private-sector breeding programs require an ongoing supply of new personnel and thus depend upon the education and mentoring provided to students and post-doctoral interns in academic programs. Declines in opportunities for education, experience, and mentoring within academic breeding programs therefore have serious consequences for the pipeline of new breeding program personnel needed to support the U.S. agriculture and food systems. On top of the impending retirement of many experienced breeders who can serve as instructors and mentors for the next generation, funding for graduate student or post-doctoral intern positions was the most likely program component to be rated as being endangered, severely constrained, or seriously constrained by budget shortfalls or uncertainty.

With regard to technical support staff and allied professionals other than the program leaders, more than one-third of programs moderately or strongly disagreed when asked if they had adequate access to enough allied professionals as staff members, consultants, or vendors; more than one-third moderately or strongly disagreed when asked if they had enough technical support personnel on staff to maintain operations, and more than one-third moderately or strongly disagreed that they are able to attract applicants for advanced breeding, scientific, and technical positions by offering excellent professional opportunities and competitive salaries and benefits. Almost 44% of programs moderately or strongly disagreed that they are "readily able to replace advanced staff members, collaborators, or service providers as they retire or move to new jobs." When asked about strengths or limitations on their ability to hire needed personnel, although public plant breeding programs were seen as being attractive for plant breeding and plant science graduates interested in making new discoveries and developing practical applications of scientific knowledge for the public good, lack of funding for competitive salaries and benefits and lack of stable, long-term funding for public breeding programs were rated as being highly problematic for attracting new hires with the required knowledge and expertise.

Funding and personnel concerns intersect when we consider the ongoing rapid development of expensive but potentially game-changing high-tech approaches to measuring and analyzing the associations between plant genotypes and phenotypes. Programs face budgetary and personnel challenges applying these new approaches to inform breeding program decisions such as parent selection and cross planning, choices of which offspring to invest with further resources and attention, how to track identity, lineage, and intellectual property, and how to weigh the risks, costs and benefits of introducing new germplasm into well-established cultivar lineages. With regard to such modern breeding program technologies and the necessary technical expertise to make use of them, 16–26% of responding programs reported being seriously or severely constrained or endangered by lack of access to current equipment and expertise for phenotypic measurement of crop characteristics, 23–39% reported similar lack of access to modern genotyping technologies, and 24–27% of breeding programs reported being seriously or severely constrained or endangered by lack of access to tools and expertise needed to manage and integrate large quantities of detailed phenotype and genotype data in service of breeding program operations. Roughly one-half to two-thirds of responding plant breeding programs reported being at least somewhat constrained in these areas.

Among the three core breeding program activity areas (aside from administrative tasks or other activities not directly related to plant breeding), variety development activities were estimated to occupy 33.5% of FTE (2.2 FTE on average), with prebreeding activities accounting for the remainder: 24.1% (1.58 FTE) on germplasm enhancement and 42.4% (2.78 FTE) on plant breeding research. This finding has implications for the ongoing discussion about the role of public-sector plant breeding programs in the overall plant breeding capacity of the United States. Some have focused on the decline of cultivar releases from public-sector programs, an important issue since, as noted in the USDA *Roadmap* document, improved varieties for some important crops or markets are unlikely to attract private investment, and, therefore, it is important that variety development receives reliable continuing public support. However, germplasm enhancement and research of direct relevance to breeding program needs are also critical, at-risk components of public plant breeding programs. These prebreeding activities have long-term implications for both public- and private-sector crop improvement efforts. The USDA *Roadmap* lists research "to locate new traits in wild germplasm and transfer it into parental lines that breeders can readily use" as an example of work that "requires long-term commitment and a robust ability to absorb results that come slowly or are even disappointing" and thus illustrates "the role of USDA in providing public benefits that would be difficult for a private-sector enterprise to justify."

Moreover, many public plant breeding programs have long-term, integrated approaches to plant breeding research, germplasm enhancement, and variety development—all three legs of the plant breeding stool. These integrated programs (and the public plant breeding program network as a whole) address regional, national, and international needs that, in many cases, would be prime examples of market failure without continued public funding, since structural incentives for large, fast, low-risk returns on investment push private companies away from these challenges. The data reported here adds to the evidence that public plant breeding programs are at risk of disappearing without reinvigorated, stable, long-term access to funding, technology, knowledge, and expertise. United States plant breeding capacity as a whole (both public and private) and, more broadly, U.S. food security, natural resource resilience, and public health will erode if the trajectory of declining budgets and reduced staffing and expertise in public plant breeding programs is allowed to continue.

Although the total number of selective plant breeding programs in U.S. public institutions is not precisely known, especially given the granular way that programs were defined for this study, we believe the sample reported here is large enough to represent a substantial portion of U.S. plant breeding capacity as a whole. Each of the participating programs established an account on the NRSP10 website to complete the survey. Publicizing a map of the United States showing the locations of participating programs has encouraged an additional 98 programs to register (https://www.nrsp10.org/index.php/us-breeding-program). The project team hopes to offer all U.S. public plant breeding programs periodic opportunities to create or renew their survey and map database entries in future years in order to generate expanded updates of this study and support the ongoing efforts of the PBCC and the NAPB to raise awareness about the status, importance, and future of plant breeding in the United States.

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SUPPORTING INFORMATION

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

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