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The Future of Public and Private Plant Breeding According to Plant Scientists

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The Future of Public and Private Plant Breeding According to Plant Scientists

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Abstract

Plant breeding has been effective in addressing food insecurity by increasing agricultural yields and productivity. Historically, public plant breeding programs have long-term, integrated approaches to plant breeding research, germplasm enhancement, and variety development, but as funding is reduced the future is less certain as to areas of focus. This survey builds off those before it and asks the next logical question, if a divergence between private and public breeding is taking place, what aspects should each sector focus on? The impetus of this study was to ask opinions of plant breeders globally regarding the direction they believe the public and private sectors are moving in the future and to find the significant differences across subsets of the data. Survey distribution resulted in 822 total responses from plant breeders working in public and private sectors across the world. The respondent was asked to identify which attribute (biofortification, disease resistance, yield enhancement, pest resistance, etc.) their sector should pay the most and least attention to in the future. From a series of 6 choice questions, the preference shares of the attributes are found according to various subsets. Disease resistance was found to have the largest preference share in the private sector but climate change for biotic/abiotic stress had the largest preference share in the public sector. The preference shares of climate change for biotic/abiotic stress were statistically different across the public and private sectors, but not when comparing major and minor crops. The findings of this study show the direction and priorities of the public and private sectors as well as provide insight on the areas that are losing attention within plant breeding.

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Introduction

Food security is an issue that humanity is continuously battling. In 2020, 928 million people (approximately 12% of the global population) were classified as severely food insecure (FAO 2021). Food demand is expected to increase between 60% (Alexandratos and Bruinsma 2012) and 110% (Tilman et al. 2011) from 2005 to 2050 as a consequence of an increasing global population, growing global economy, and increasing demand for cereal crops used in livestock feed (van Dijik et al. 2021; Ray et al. 2013; FAO 2009). Global food supply also faces challenges. Climate change (Ray et al. 2019; Wheeler and Von Braun 2013; Müller et al. 2011; Lobell, Wolfram, and Costa-Roberts 2011), increasing climate variability (FAO 2021; Hasegawa et al. 2021; Holleman et al. 2020; Ray et al. 2015), decreasing water availability (Dolan et al. 2021; World Economic Forum 2015; Chakraborty and Newton, 2011; Kang, Shahbaz, and Xiaovi 2009), and an increasing emphasis on reducing the use of inputs and fossil fuels (USDA 2015; White 2012; Polack, Wood, and Bradley 2008) are examples of factors pressuring global food production. Climate variability and extreme weather events alone are estimated to account for 32-39% of observed yield variability in the major staple crops (maize, rice, wheat, and soybeans) globally (Ray et al. 2015).

Plant breeding has historically been effective in addressing food insecurity by increasing agricultural yields and productivity (Qaim 2016; Pingali 2012; Pachico, Hertford, and de Janvry 2000). During the Green Revolution, global cereal yields rose 2.4% annually between 1961 and 1966 (Huang, Pray, and Rozelle 2002). Between 1960 and 2010, cereal crop production tripled, while the inland area cultivated only increased by 30% (Wik, Pingali, and Brocai 2008). Crop research, infrastructure, market development, and policy support all contributed to the success of the green revolution.

According to a Special Project on Impact Assessment study, over 8,000 high yielding or modern varieties (MVs) were released by the year 2000, encompassing 11 different crops (Evenson and Gollin 2003). In low-income countries, adoption rates of modern varieties have reached 63% (Pingali 2012). The widespread adoption of MVs (Evenson and Gollin 2003) highlights the role of plant breeding in agricultural development. However, from 1987 to 2001, growth rates of cereal yields globally began to slow in several staple crops, and investment in agriculture (crop research, infrastructure, market development, and policy support) began to decline (Pingali 2012; Huang, Pray, and Rozelle 2002; Alston, Pardey, and Roseboom 1998). The MVs introduced during the Green Revolution relied on irrigation and fertilizer use (Qaim 2020; Evenson and Gollin 2003), which became a concern as environmental factors grew.

New Plant Breeding Technologies (NPBTs) have emerged in response to growing environmental pressures and increasing food demand (de Lange et l. 2022; Enfissi et al. 2021; Qaim 2020). NPBT methods have been used to develop pest and disease resistance in crops (Olivia et al. 2019; Bravo et al. 2011), increase the ability to withstand abiotic stresses (Villalobos-López et al. 2022; Wu et al. 2019; Eshed and Lippman 2019), and improve nutrition (Enfissi et al. 2021; Zaidi et al. 2019; Eshed and Lippman 2019; De Steur 2012). Additionally, NPBT methods facilitate faster breeding processes (Hickey et al. 2019; Vats et al. 2019; Schaart et al. 2015) and allow crops to rapidly adapt to changing conditions, such as climate variability and shocks (Bailey-Serres et al. 2019). Examples of NBT methods include zinc-finger nuclease, oligonucleotide-directed mutagenesis, cisgenesis and intragenesis, RNA-dependent DNA methylation, grafting on GM stock root, reverse breeding, agro-infiltration and synthetic genomics (de Lange et al. 2022; Lusser et al. 2011).

With the development of NPBTs, there are uncertainties as to how changes in technology will affect the public and private plant breeding industries. Public plant breeding programs often focus on crops that are important to society but may not be profitable due to long generation times or are a regional specialty (niche markets) (Evans and Coe 2021). Public programs are also responsible for training the next generation of plant breeders (Guner and Wehner 2003; USDA 2015; Heisey, Srinivasan, and Thirtle 2002). On the other hand, private plant breeding programs tend to focus on large global markets that can provide large financial returns (Evans and Coe 2021). Morris, Edmedades, and Pehu (2006) stated that there were four major paradigm shifts in plant breeding that resulted from a traditionally publicly dominated sector to one that now relies on the private sector. First, the commercialization of agriculture has reduced public funding for agricultural research, forcing public institutions to become more self-supporting and shift plant breeding to crops that can benefit from seed sales or royalties. Second, strengthening intellectual property rights has increased the incentive for private firms to invest more in plant breeding. Third, the privatization of the plant breeding industry has resulted in smaller seed companies being taken over by larger competitors who can exercise greater market power and bring larger amounts of R&D to provide a stream of innovative products. Fourth, the decline in official development assistance for agriculture reduced support for public investment in agricultural research and scientific capacity building. One of the largest concerns about these four trends is that private firms have little incentive to invest in an activity whose benefits accrue over the long run (food security as an example) because plant breeding skills are not company specific, and breeders often move from firm to firm.

The seminal survey assessing the status of public and private plant breeding in the United States was conducted as part of the U.S. National Plant Breeding Study with support from the USDA. Frey (1996) analyzed the human and financial resources devoted to plant breeding research and development across the United States. Human resources were measured in Science Person Years[1] (SYs), and annual dollar expenditures were derived from the data collected. Frey (1996) reported that the number of science person years devoted to private plant breeding research and development in the U.S. was expected to grow by 32 SYs per year, while the public sector was expected to decrease by 2.5 SYs per year from 1990-1994. Graduate level plant breeding programs lost 30 positions (6% of the total) from 1980 to the mid-1990s (Frey 1996). In 1994, the private sector was estimated to spend $338 million annually on plant breeding research and development, while the public plant breeding sector was estimated to spend $213 million annually (Frey 1996).

Previous surveys have worked on updating Frey's findings (Traxler et al. 2005; Sylak-Glassman et al. 2016; Shelton and Tracy 2017). Traxler et al. (2005) reported that since Frey (1996), overall SYs in the United States decreased by 10% and 13 out of 16 crop categories reported decreases in SYs in the public plant breeding sector. Sylak-Glassman et al. (2016) built off the work done by Frey (1996) and Traxler (2005) and found that 55% of State Agricultural Experiment Stations reported a decrease in SYs allocated to the development of cultivars and 23% experienced no change, leaving only 21% that experienced an increase in SYs. Sylak-Glassman et al. (2016) found that since 2008, 35% of plant breeding graduate students stayed in the public sector (domestic or international) with the remaining entering the private sector. These surveys quantify the shift of human and financial resources to the private plant breeding sector. This could be increasing the paradigm shift from public to private breeding that Morris, Edmedades and Pehu (2011) expressed concern about.

[1] Defined as "the work done by a person who has responsibility for designing, planning, administering (managing), and conducting (a) plant breeding research, (b) germplasm enhancement, and (c) cultivar development in one year." (Traxler et. al 2005)

Additional studies have looked further into the resources available to the public plant breeding sector. Guner and Wehner (2003) conducted a survey specifically focusing on land-grant universities in the United States and their training of plant breeding students. They reported that while 47 land-grant universities offered plant breeding degrees, only seven universities averaged seven or more plant breeding graduates per year from 1995-2000 (Guner and Wehner 2003). Coe et al. (2020) focused on the current state of pant breeding resources and found that from 287 public institutions in the United States, approximately 80% reported annual budgets of $400,000 or less (Coe et al. 2020).

In their survey, Sylak-Glassman et al. (2016) found that 28 academic institutions in the United States had at least one cultivar development program stop within the past ten years. The two most common reasons that cultivar development programs were dropped in U.S. public institutions were a lack of funding and the retirement of faculty members who were not replaced (Sylak-Glassman et al. 2016). With almost half of the public breeders being 60 or older (Coe et al. 2020), it is a concern that many breeders will retire without replacement in public institutions. Shelton and Tracy (2015) also found this to be a concern, with 55% of their respondents having been employed in public plant breeding for over 21 years.

Intellectual property rights are another driving factor in the schism between private and public breeding, specifically in high-income countries (Morris, Edmeades, and Pehu 2006). Legislation concerning plant variety rights emerged in Europe in the 1960s (Byerlee and Dubin 2010), followed by the United States in 1970 and Australia and Canada between the 1980s and 1990s (Heisey, Srinivasan, and Thirtle 2001). The passing of legislation stifled the freedom to operate and reduced the exchange of information internationally and domestically (Byerlee and Dubin 2010). Shelton and Tracy (2017) acknowledge that the royalties from intellectual property protection help address the funding struggles but contrast the benefits with the drawbacks of restricted sharing agreements and "potential patent thickets" that require additional resources to navigate and slow development.

The decline in human resources in the public plant breeding system, issues surrounding funding, and the increasing presence of intellectual property rights have led to articles that examine the division between public and private plant breeding (Heisey, Srinivasan, and Thirtle 2001; Morris, Edmeades, and Pehu 2006; Heisey, Srinivasan, and Thirtle 2002). There have been various meetings (Gepts and Hancock 2006; Hancock and Stuber 2008; USDA 2015; Lusser 2014; Sligh and Lauffer 2004) where plant breeding experts have come together to discuss the uncertain future of the field.

A symposium in 2005 (Gepts and Hancock 2006) was held to discuss "the future of plant breeding education at public institutions." Private, public, and international breeding programs were all represented. This symposium defined plant breeding, addressed the need to promote awareness of the plant breeding industry, and discussed industry concerns and possible solutions. The participants suggested more private industry involvement in the training of plant breeding students through guest lectures, internships, and financial support. Ideas to promote public awareness of plant breeding included utilizing students to interact with conservation organizations and using alumni to recruit more plant breeding students. A workshop in 2007 (Hancock and Stuber 2008) established formalized leadership to express and advocate for the science and industry of plant breeding. This workshop had participants from both the public and private plant breeding sectors. In 2013 the USDA held a "Stakeholder Listening Session on Plant Breeding," where they collected input from stakeholders. The session revealed "areas of broad national agreement," such as the importance of educating the next generation of plant breeders, the need for stabilizing funding, and focus directed toward intellectual property rights issues. “Appropriate public/private balance in plant breeding” was revealed to be an area of debate (USDA 2015). These are just a few steps that have been taken to open discussion and promote problem-solving to address the concerns found in assessments of the plant breeding industry.

Public plant breeding programs face challenges in order to continue working towards food security, such as the lack of human and financial resources that will be required as New Plant Breeding Technologies continue to emerge and evolve. Existing surveys have quantified the declining resources in the public sector and identified it as a growing issue. To date, the literature has verified the presence of a paradigm shift in public versus private funding for plant breeding but there is a void as to which aspects of plant breeding each sector should “focus” on moving forward.

The impetus of this study was to ask opinions of plant breeders globally regarding the direction they believe the public and private sectors are moving in the future. Responses have been collected from plant breeders working across the globe on over 14 crops, reflecting both the public and private sectors. The result is an aggregated perspective of strengths and challenges as well as identification of areas that deserve priority to better understand the future of plant breeding globally. Historically, 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), but as funding is reduced the future is less certain as to areas of focus. Our survey builds off those before it (Frey 1996; Guner and Wehner 2003; Traxler et al. 2005; Shelton and Tracy 2017; Coe et al. 2020) and asks the next logical question, if a divergence between private and public breeding is taking place, what aspects should each sector focus on? It could be that the future role of public plant breeding is to train the next generation of private plant breeders and simply build capacity in the industry. However, knowledge of plant breeding as an impure public good, may not always be produced at the socially optimal level by private firms. Heisey, Srinivasan and Thirtle (2001) state that the public plant breeding sector will yield the largest social returns if it focuses on research directed at carefully identified "problem areas" and research with clear public good components. Our study sets out to ask plant scientists what are the "problem areas" that the public sector should focus on and what are the areas that the private sector should focus on moving forward.

Data Collection

This study utilized an online survey to target plant scientists globally. The survey was distributed to scientists working in a wide range of plant science fields including pathology, physiology, entomology, and/or plant breeding. A diverse representation of plant science fields and geographic locations was crucial to obtain a global perspective on the future of plant breeding.

The survey distribution list was created deliberately and focused on plant scientists that possessed the fundamental knowledge of plant breeding needed to complete the survey. Contacts were gathered through websites of plant scientist platforms, plant science societies, universities, and private companies globally. The sample was skewed towards the public sector as many private companies in the plant breeding/science arena do not provide email addresses for their employees. The Web of Knowledge database was also used to obtain plant scientists' contacts who had conducted research in the broad field of plant science. The final distribution list consisted of 6,294 distinctive email addresses.

The initial survey was sent out on April 4th, 2022, and a reminder email was sent two weeks later for those who had not completed the survey. The complete survey is located in

Appendix A. The survey closed on May 4th, 2022, with a total of 822 responses; however, incomplete responses (27.98%) or indicated a high school academic level (2.68%) were removed from the data set. The final data sample consisted of 583 completed responses. A total of 408 useable responses were a result of the initial email, and an additional 175 useable responses were collected from the follow-up email.

Qualtrics was used to administer the survey via email distribution. University of Arkansas Internal Review Board (IRB) approval was obtained for the survey on 03/08/2020 (protocol number 2102314838). Participants were provided with a written consent form they had to agree to prior to the beginning of the survey which stated that is was voluntary and that they could quit the survey at any time. The survey was anonymous, and participants received no payment for completion.

Best-Worst Scaling

The objective of this study is to elicit what plant breeders feel the future direction is for the public and private sectors and to determine which regions/crops/and breeding attributes each sector should focus on moving forward. The Best-Worst Scaling approach (BWS) was used in an attempt to answer these questions as it provides a higher discriminatory rate between items compared to traditional rating scales (such as Likert) in which respondents can allocate the same level of importance to multiple items (Okpiaifo et al. 2020). The simplicity of the questions allows for more robust data collection with less burden on respondents (Bazzani et al. 2018; Cohen 2009). Additionally, the BWS method has been shown to provide better outcomes than other value measuring methods that employ rating or ranking scales, such as Rokeach's Value Survey, Kahle's List of Values, Mitchell's Values and Life Styles, and Schwartz's Values scale (Lee, Soutar, and Louviere 2007; Bazzani et al. 2018).

The BWS question blocks were created using a Nearly Balanced Incomplete Block Design. There were eight BWS questions, each displaying six different attributes. Respondents were asked to select which attribute should receive the most attention and least attention for the future, given their primary sector (public or private). Each attribute appeared four times throughout the block. The order of the questions, and the order of the attribute choices within each question were randomized to control for any effects from the order of choice sets (Cohen 2009).

The 12 attributes that participants could select between were: disease resistance (Olivia et al. 2019; Bravo et al. 2011), climate change for biotic/abiotic stress (Villalobos-López et al. 2022; Yu et al. 2022; Eshed and Lippman 2019), yield enhancement (Wik, Pingali, and Brocai 2008), pest resistance (Russell 1978), market-value added enhancement of attributes (Yu et al. 2017; De Steur et al. 2015), yield by environment genomic prediction (Millet et al. 2019), digital agriculture (Shakoor et al. 2019; Taranto et al. 2018), CRISPR (de Lange et al. 2022; Chilcoat, Doane, and Yu 2017), seed delivery (Afzal et al. 2020), plant-based protein (Xu, Towler, and Weathers 2018), biofortification (Bouis 2018; De Steur et al. 2015), and bio-physical/deterministic modeling (Loppini et al. 2020). While not an exhaustive list of potential focus areas, given that survey participants were not compensated for their time, brevity was key for a robust completion rate.

Survey Method

At the beginning of the survey, each respondent was asked about their academic level, primary research sector (public or private), primary research field (plant breeding, physiology, pathology, entomology, other [asked to specify]), primary region of research focus (Africa, Asia, Europe, Oceania, North America, South America, or no location focus), and primary crop of research focus[2] (wheat, maize, soybean, rice, potatoes, cassava, sorghum, millet, yams, plantains, vegetables, fruits, legumes, or other [asked to specify]). Only one choice could be selected for each question in an attempt not to disentangle results for a plant scientist who worked in multiple crops and multiple regions. While not ideal as many plant scientists work across regions, from an econometric viewpoint, it was not feasible to weight areas of focus by region as the weights could be heterogenous across attributes (crop type, for instance). Throughout the survey, questions were customized to the respondent's sector of focus. Questions that contain "(public/private)" were programmed to autofill based on the respondent's indicated sector.

Public Sector Funding

Public funding for plant breeding programs has shown to have been decreasing in the U.S. since the end of the Green Revolution (Shelton and Tracy 2017; Guner and Wehner 2003; Frey 1996) and the shift from a publicly dominated sector to one that is privately dominated has raised social welfare concerns (Coe et al., 2020; Morris, Edmedades, and Pehu 2011). We examined the current state of public sector funding in our survey as well as explored trends on a global scale with the following question:

> *Given that you are in the public sector, what percentage of your budget, on average, is funded by the private sector (for profit)?*

Participants could choose between 0%, 1%-20%, 21%-50%, and over 50%. The results from this question can provide insight into the relationship of funding sources of public plant breeding programs by region and show themes of private investment.

[2] Crops were split into major crops and minor crops for all further analysis. Major crops include wheat, maize, soybean, rice, potatoes, cassava, sorghum, millet, yams, and plantains. Minor crops include vegetables, fruits, legumes, and other.

Best/Worst Scaling

After background information was gathered from the respondent, participants were given six BWS choice sets. Before starting the question block, the following message was shown:

> *In this section, we will ask a series of questions that look similar, but their differences will play an important role in determining where the (public/private) sector plant science community believes its future direction is moving.*

The purpose of this introduction to the following questions was to emphasize that even though the questions looked similar, the items listed differed.

Figure 1 is an example of a BWS question used in the survey for a participant who said they primarily worked in the public sector.

> *Which of the following attributes do you think the public sector should give the most attention to, and which attribute should the public sector give the least attention to in the future?*
> *Please, check only one attribute as the most important and only one attribute as the least important.*

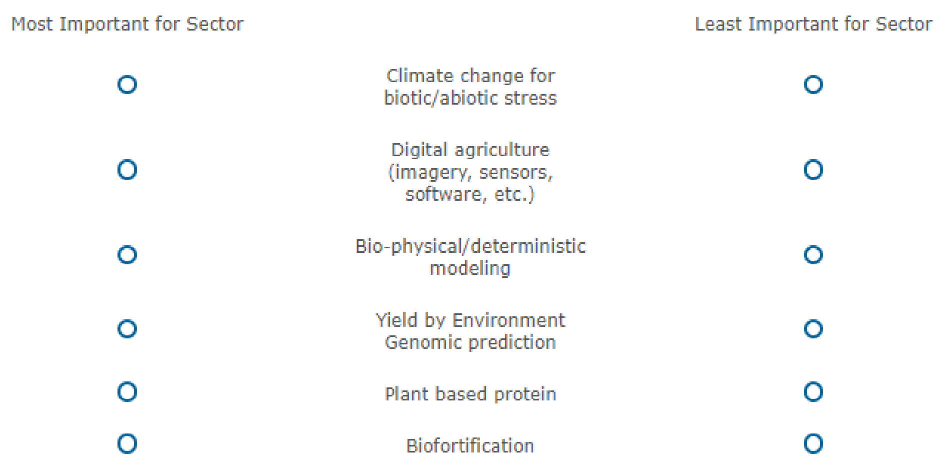

Figure 1. BWS Example Question for a Participant who Indicated They Primarily Worked in the Public Sector

Climate Change and Digital Agriculture

After the BWS section of the survey was complete, four follow-up questions were included to gather more specific information regarding attributes encompassing a wide range of topics. If the respondent selected climate change for biotic/abiotic stress as a “most important” topic of focus at least once, they were asked a follow-up question to specify between abiotic and biotic stress:

> *Given your opinion that the (public/private) sector should focus on climate change for (abiotic/biotic) stress, which area of focus should the public sector place research emphasis on?*

The abiotic choices were drought stress (Farooq et al. 2009), heat stress (Semenov and Shewry 2011), salinity stress (Parihar et al. 2015), flood stress (Villalobos-López et al. 2022), toxin stress (Foy 1988), and cold stress (Villalobos-López et al. 2022). Only one answer choice could be selected. The biotic choices were increased presence/severity of pathogens (fungi, bacteria, etc.) due to climatic change (Velásquez, Castroverde, and He 2018), increased presence/severity of insects due to climatic change (Mou 2011), increased presence/severity of weed pressure due to climatic change (Mou 2011), the introduction of new pathogens (fungi, bacteria, etc.) due to climatic change (Nnadi and Carter 2021), and introduction of new weed species due to climatic change (Ziska, Blumenthal, and Franks 2019). Only one answer choice could be selected.

If the respondent selected digital agriculture as a most important topic of focus at least once, they were asked what explicitly warranted the most attention from their (public/private) sector. The options were UAVs (drones, satellite imagery, precision agriculture applications, internet of things (integrated sensors), machine learning/artificial intelligence, apps for real-time decision-making, and others (asked to specify). Only one answer choice could be selected. The responses to these questions can be used to expand on which areas of climate change and digital agriculture are most important to the future of plant breeding based on sector, major/minor crop, and region.

Public Sector Breeding Moving Forward

Five additional questions regarding the future of public plant breeding were included at the end of the survey. Two questions asked about future interactions with the sector that did not correspond with the respondent's indicated area of work:

> *Given that you are predominately in the (public/private) sector, do you feel like you will be collaborating more or less with the (sector that was not the respondent's focus) sector in 10 years?*

The answer choices given were 1- More or 2- Less. This question was given to all survey participants.

> *Given that you are in the public sector, do you see yourself commercializing research from your program in the private sector?*

The answer choices given were 1- Yes or 2-No. This question was only given to public sector participants.

These two questions provide insight into if the interactions between the public and private sectors are expected to grow or decrease from the perspective of a plant scientist. Next, the survey asked:

> *In your opinion, what should the future of the plant sciences in the public sector primarily focus on? (choose one)*

This question was given to all respondents. The choices were as follows: educating the next generation of plant scientists, conducting primary research to enhance plant science, becoming more integrated into research to support private industry, and filling the gap on research in which the private industry shows no/little interest. The recent schism between public and private plant breeding has left the future role of public plant breeding unclear (USDA 2015; Morris, Edmeades and Pehu 2006; Heisey, Srinivasan, and Thirtle 2001). The responses to this question elicit the views of all the plant scientists and provide the potential for comparisons between the sectors, major crops/minor crops, and across regions.

Coe et al. (2020) surveyed 278 U.S. public breeding programs about staffing levels, budgets, access to needed personnel, and access to technology. Their results showed a decrease in full-time employees, consistent with past studies (Frey 1996; Guner and Wehner 2003; Traxler et al. 2005; Shelton and Tracy 2017). We presented Coe et al.'s (2020) findings to our participants and sought to explore if the study's findings were a concern and in what capacity. We provided the following statement:

> *Many public programs reported that budget shortfalls or uncertainty "endangered or severely constrained" their ability to conduct meaningful research. A recent 2020 study of 278 public breeding programs in the United States indicated that 21.4% of public breeding programs reported a decline in full-time employees (FTE) over the past five years.*

Respondents could choose from the following: 1- This is not a concern as it is likely a function of the private sector simply increasing funding in breeding sectors once dominated by the public sector, 2-This is a trend likely true globally, 3- This is a threat to regional/global food security, and 4- This trend is likely not true in my region. Participants could select more than one answer choice. With the results of this question, we are given insight into expert opinion on the shifting dynamic of the plant breeding industry.

Econometric Analysis

Data analysis was conducted using a discrete choice framework, consistent with the random utility theory (McFadden 1974), and estimated random parameter (RP) maxdiff models. This assumes that respondents simultaneously choose the pair of best and worst items that maximize the difference between the two selected items on an underlying scale of importance (Cerroni et al. 2021; Finn and Louviere 1992).

Assuming that there are J items listed in each choice set t, then the number of possible pairs is $J(J-1)$. The observable level of importance of the item j on the underlying scale is defined as λ_i, while the unobservable level of importance of respondent i is given by $I_{ij} = \lambda_j + \varepsilon_{ij}$, where ε_{ij} is the random error term. The maxdiff model follows the random utility theory (McFadden 1974), where the probability that respondent i selects item j as the best and item k as the worst in choice set t equals the probability that the difference in utility of the selected items (I_{ij} and I_{ik}) is greater than all the other possible differences $M = J(J-1) - 1$ in the choice set. Assuming that the error terms are independently and identically distributed (iid), the probability is represented by the multinomial logit model.

$$P_{ijkt} = exp(\lambda_{ijt} - \lambda_{ikt}) \,/\, \sum_{l=1}^{J} \; \sum_{l=1}^{J} exp(\lambda_{ilt} - \lambda_{imt}) - J \tag{1}$$

The estimated λ_j represents the importance of item j relative to some item that is normalized to zero for identification purposes. In this analysis, "Seed Delivery" was the item normalized to zero.

To account for heterogeneity in preferences for the various attributes, we estimate a random parameter logit (RPL) model. The RPL model assumes that the estimated parameters λ_j are distributed according to a multivariate normal distribution. The model uses simulation methods (maximum simulated likelihood estimator) to provide estimates of mean and standard deviation for each coefficient.

To ease interpretation, preference shares (an estimate of how much importance each attribute has over the others or the probability that an attribute is picked as more important than another) for each attribute were then estimated using the RPL model as follows:

$$S_j = \; e^{\widehat{\lambda_J}} / \sum_{k=1}^{j} e^{\widehat{\lambda_l}} \tag{2}$$

A distribution of 500 preference shares for each item j was drawn from a multivariate normal distribution created using the means and standard deviations estimated for each item j from our RPL model. The bootstrapping method (Krinsky and Robb 1986) was implemented to create these distributions.

Subsets of the survey data were created based on sector (public/private), crop (major/minor), and region (N. America, S. America, Europe, Africa, Oceania, and Asia) to elicit comparisons. For example, to compare the preference shares of the public and private sectors, our data was separated into two subgroups ($S_{j,public}$ and $S_{j,private}$) and separate RPL models were estimated accordingly. The overall quality of preferences estimated using the two RPL models was tested using the likelihood ratio test (LRT) (Swait and Louviere 1993). The LRT requires the estimation of an RPL model on the pooled sample while controlling for potential differences in scales across the two data sets. The LRT is based on the test statistic

$$\lambda = -2[L_{\mu} - \left(L_{private} - L_{public}\right)] \tag{3}$$

where L_{μ} is the log-likelihood value from the estimation of the RPL model using the pooled model, L_{public} is the log-likelihood value from the estimation of the RPL model using the public sector subgroup and $L_{private}$ is the log-likelihood value from the estimation of the RPL model using the private sector subgroup. The test statistic is asymptotically chi-squared distributed with $K + 1$ degrees of freedom, where K is the number of coefficients estimated in the three models.

If the null hypotheses of overall equality of preferences between the public and private subgroups is rejected, we test if the differences in pairs of preference shares ($\Delta S = S_{j,private} - S_{j,public}$) are statistically significant using Poe et al.'s (2005) tests. We used adjusted p-values to ensure the significance levels were 95% or greater when multiple comparisons were made.

This process was repeated for major/minor crops and regional subgroups. Regional comparisons were made between two continents and then by comparing each continent[3] to the

[3] Africa, Europe, and North America were the only continents used individually because the other regions lacked enough responses for analysis.

rest of the world[4] (ROW). The comparisons made were public vs. private, major crop vs. minor crop, North America vs. Europe, North America vs Africa, Europe vs. Africa, North America vs. ROW, Europe vs. ROW, and Africa vs. ROW.

Results

Survey Responses

The survey resulted in 583 usable responses for analysis. Table 1 illustrates the descriptive statistics of the response pool, including academic level, sector, field, primary crop focus, and primary region of work.

Table 1. Demographics of survey participants in percentages

Academic Level (%)		Crop Type (%)	
B.S.	5	Major	43
M.S.	12	Minor	57
Ph.D., J.D., or PHE	83	Region (%)	
Sector (%)		Africa	21
Public	80	Asia	8
Private	20	Europe	26
Field (%)		Oceania	1
Plant Breeding	44	North America	31
Physiology	11	South America	4
Pathology	12	No Location Focus	10
Entomology	2		
Other	30		

Total observations= 583

The majority (83%) of participants hold a Ph.D. J.D. or PHE in a plant science discipline. Regarding crop type[5], 57% of respondents work with minor crops, while 43% work with major crops. The response pool is predominantly active in the public sector (80%), which is expected given the limited access to emails addresses available from private companies compared to the

[4] In each comparison, the "rest of world" included all responses except those from the region of comparison. This ensured the region was not compared to itself.
[5] Major crops include wheat, maize, soybean, rice, potatoes, cassava, sorghum, millet, yams, and plantains. Minor crops include vegetables, fruits, legumes, and other.

public sector.

Appendix B shows the breakdown by specific primary crop respondents work with. There were 13 crop options and an “other” option. When looking at each sector, “other” was the most commonly selected choice, making up 35% of the public and 34% of the private sectors. This is also consistent across North America (35%), Europe (45%), and Africa (29%). However, rice is the most common crop in Asia (30%) and South America. (55%).

RPL Pooled Model

The pooled RPL results are presented in Table 2. The results are relative to the omitted attribute, *seed delivery,* and indicate that all specified attributes are statistically significant (P<0.01). The RPL models for each subset (public/private sector, major/minor crops, and region) are given in Appendix C.

Table 2. Random Parameter Logit Model results for the pooled dataset

Attributes	RPL		
Disease Resistance	3.040	***	(0.094)
SD	2.674	***	(1.04)
Pest Resistance	2.391	***	(0.091)
SD	2.404	***	(1.05)
Plant-Based Protein	0.385	***	(0.081)
SD	2.854	***	(0.089)
Biofortification	0.383	***	(0.080)
SD	2.702	***	(0.086)
Digital Agriculture	1.162	***	(0.090)
SD	2.543	***	(0.084)
Climate Change for Biotic/Abiotic Stress	4.121	***	(0.095)
SD	3.212	***	(0.093)
CRISPR	1.016	***	(0.089)
SD	3.520	***	(0.096)
Market Value-Added Enhancement of Attributes	1.063	***	(0.075)
SD	3.313	***	(0.086)
Yield by Environment Genomic Prediction	2.267	***	(0.090)
SD	3.104	***	(0.094)
Bio-Physical/Deterministic Modeling	-0.461	***	(0.088)
SD	2.670	***	(0.089)

Yield Enhancement	2.729	***	(0.087)
SD	3.086	***	(0.092)
Log-likelihood	-10615		
AIC	21383.76		
BIC	21880.230		

****P<0.01, **P<0.05, *P<0.10.*
Parentheses denote standard error.

Public/Private Sector Comparison

Table 3 highlights the market shares derived from the RPL subset results for the public and private sectors given in Table C1. Market/preference shares, in this sense, can be viewed as what each respondent thought the primary focus of each sector (public/private) should be in the future. Climate change for biotic/abiotic stress holds the largest preference share (57.55%) in the public sector, while disease resistance holds the largest preference share (29.82%) in the private sector. This result makes intuitive sense as the private sector can likely obtain patents for disease-related issues, and the opportunity for financial returns is anticipated to be higher. In contrast, climate change and its effects will receive the most attention from plant breeders in the public sector, which is likely a function of forward-thinking for the public good, which may not materialize in economic returns in the immediate future.

There are significant differences (P< 0.01) between the sectors for climate change, market value-added enhancement of attributes, and seed delivery. The difference between public and private sector preference shares regarding climate change is 32.78% (57.55% and 24.77%, respectively). This is likely because climate change is considered a public good where progress is more long-term and knowledge gains can be transferable across companies as plant breeders move between employers. Other differences are significant but small in magnitude; the differences for market value-added and seed delivery are less than 5%.

The results from Table 3 support concerns over the decreasing human and financial resources available in the public plant breeding sector. The shift in the plant breeding sector from public to private industry will result in potentially less attention focused on addressing climate change.

Table 3. Preference shares (in %) of focus attributes by sector and their differences

	Preference Share (%)			
Attribute	Private Sector	Public Sector	Difference (%)	
Disease Resistance	29.82	12.95	16.87	
Climate Change for Biotic/Abiotic Stress	24.77	57.55	-32.78	***
Yield Enhancement	18.16	9.28	8.88	
Pest Resistance	9.40	7.23	2.17	
Market Value-Added Enhancement of Attributes	5.56	0.93	4.63	***
Yield by Environment Genomic Prediction	5.06	6.76	-1.70	
Digital Agriculture	2.31	1.45	0.86	
CRISPR	2.05	1.49	0.56	
Seed Delivery	1.56	0.40	1.16	***
Plant-Based Protein	0.74	0.66	0.08	
Biofortification	0.33	0.96	-0.64	
Bio-Physical/Deterministic Modeling	0.25	0.35	-0.10	*

****P<0.01, **P<0.05, *P<0.10.*

Major/Minor Crop Comparison

Table 4 shows the preference shares for the major and minor crop subgroups derived from the RPL results in Table C2. Climate change, disease resistance, and yield enhancement hold the highest value among major and minor crop subgroups. The differences were insignificant for these attributes (P< 0.10). This analysis suggests that when comparing the future focus between major and minor crops, there is no divergence, in contrast with the public and private sector focus conclusions.

Table 4. Preference shares (in %) of focus attributes by crop (major/minor) and their differences

	Preference Share (%)		
Attribute	Major Crops	Minor Crops	Difference (%)
Disease Resistance	10.92	19.55	-8.63

Climate Change for Biotic/Abiotic Stress	57.59	45.66	11.93	
Yield Enhancement	10.69	9.99	0.69	
Pest Resistance	5.99	8.75	-2.76	
Market Value-Added Enhancement of Attributes	1.27	1.72	-0.45	**
Yield by Environment Genomic Prediction	8.61	6.93	1.69	
Digital Agriculture	1.37	2.30	-0.93	
CRISPR	1.21	2.34	-1.14	
Seed Delivery	0.42	0.66	-0.24	**
Plant-Based Protein	0.56	0.98	-0.41	
Biofortification	1.01	0.73	0.28	
Bio-Physical/Deterministic Modeling	0.37	0.40	-0.03	**

****P<0.01, **P<0.05, *P<0.10.*

Regional Comparison

Regional preference shares were calculated for Europe, Africa, and Asia and are presented in Table 5. The results were derived from the RPL models in Tables C3 and C4. Asia, Oceania, South America, and No Location Focus did not have enough observations to calculate individual preference shares.

Regional head-to- head comparisons as well as the difference between a specific region and the rest of the world was also of interest to this study. To accomplish this, preference shares were calculated for the “rest of the world,” which included all regions except the one used for comparison. For example, preference shares were calculated for the world (without Africa) to find differences between Africa and the rest of the world. This resulted in three additional subsets (all responses excluding North America, all responses excluding Europe, and all responses excluding Africa). These values are given in Table 5, and their differences are shown in Table 6.

Climate change was seen as the greatest area of focus across all regions. The preference shares for climtate-focused research were over 50% for North America (61.07%) and Europe (54.95%). Disease resistance has the second-largest area of focus across all regions, except for

Africa, where yield enhancement holds the second-highest area of future focus (20.01%). The African result is expected as increasing food security via yield enhancement is likely the thrust of many breeders in Africa, whereas the rest of the world may be focusing more on yield maintenance breeding.

The largest difference (P< 0.01) was between North America and the rest of the world, where the preference share for climate change is 13.16% larger in North America. Interestingly, differences (P< 0.05) regarding CRISPR are minimal (<1.5%) and only occur in half of the comparisons (North America v Europe, Europe v Africa, and North America v World). This does not support concerns about NPBTs leading to further divergence in the plant breeding industry across regions.

Climate Change and Digital Agriculture

In total, 79% of respondents chose climate change as the most important at least once during the BW choice sets.[6] These respondents were asked if they believed biotic or abiotic stress was the most important for future attention. The percentages for these responses are given in Table 7. When looking at the participants who chose climate change as most important at least once during the BW block, 67% said that abiotic stress specifically was more important, and 33% chose biotic stress as most important. Abiotic stress was chosen as "most important" more often than biotic stress across all subgroups.

Table 8 illustrates the specific areas respondents believe deserve the most future attention for biotic and abiotic stress research. Drought stress was the leading attribute across all subgroups, with a robust average of 73%. Heat stress was considered the second most important

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[6] Ideally, we would have included each biotic and abiotic stress in the BW choice options but given the number of potential choices, this would have resulted in a survey which would have been too long given the fact there was no compensation for completion.

are of future research across all subgroups, with an average of 19%.

Increased presence/severity of pathogens due to climatic change was selected as the area which necessitated the greatest research focus regarding biotic stress, and the second was the introduction of pathogens due to climatic change. Minor crops are the exception, where the reverse is true.

When analyzing the percentage results, it is important to consider how many participants responded to each question. For example, 100% of respondents working in South America said that the most important area of focus concerning biotic stress was increased presence/severity of pathogens. Table 8 shows that of those working in South America, only four people answered this question.

Table 7 illustrates that only 28% of participants selected digital agriculture as the most important at least once throughout the BW block. Table 9 shows the responses regarding the particular area of digital agriculture that respondents believe warranted the most future attention. Precision agriculture was the leading response across all subgroups (robust average of 47%). There was no consistency among the other answer choices.

Table 5. Preference shares (in %) of future ressearch focus attributes by region

	Preference Share (%)					
Attribute	North America	Europe	Africa	World (without North America)	World (without Europe)	World (without Africa)
Disease Resistance	14.38	21.03	9.56	15.09	14.42	16.45
Climate Change for Biotic/Abiotic Stress	61.07	54.95	46.52	47.91	48.23	52.23
Yield Enhancement	6.77	6.75	20.01	13.56	12.53	9.34
Pest Resistance	9.73	6.93	4.95	6.13	7.85	7.97
Market Value-Added Enhancement of Attributes	1.15	0.32	4.24	1.53	2.26	1.10
Yield by Environment Genomic Prediction	3.70	5.31	6.61	8.54	7.86	6.83
Digital Agriculture	1.05	0.87	2.21	1.93	2.11	1.65
CRISPR	0.95	1.87	0.49	2.00	1.58	2.07
Seed Delivery	0.12	0.29	3.32	0.90	0.67	0.33
Plant-Based Protein	0.32	1.19	0.30	0.97	0.64	0.91
Biofortification	0.42	0.39	1.54	1.05	1.31	0.71
Bio-Physical/Deterministic Modeling	0.32	0.10	0.27	0.39	0.54	0.39

Table 6. Differences (in %) between preference shares of future research focus attributes by region

	Differences (%)					
Attribute	ΔS(North America vs. Europe)	ΔS(North America vs. Africa)	ΔS(Europe vs. Africa)	ΔS(North America vs. World [a])	ΔS(Europe vs. World [a])	ΔS(Africa vs. World [a])
Disease Resistance	-6.65 **	4.82	11.47 **	-0.71 **	6.61 **	-6.89 **
Climate Change for Biotic/Abiotic Stress	6.13	14.55 **	8.43	13.16 ***	6.72	-5.71 *
Yield Enhancement	0.03	-13.24 *	-13.26 **	-6.79	-5.78 **	10.67 **
Pest Resistance	2.80	4.79 ***	1.99 **	3.61 **	-0.92	-3.03 **
Market Value-Added Enhancement of Attributes	0.83 **	-3.08	-3.91 *	-0.38 **	-1.94 **	3.13

Yield by Environment Genomic Prediction	-1.61		-2.91	**	-1.30	*	-4.84	***	-2.55		-0.23	
Digital Agriculture	0.18	**	-1.16		-1.34	**	-0.88	*	-1.24	**	0.56	
CRISPR	-0.93	**	0.46		1.39	**	-1.05	**	0.30		-1.59	
Seed Delivery	-0.17	**	-3.20	***	-3.02	***	-0.78	***	-0.37	***	2.98	***
Plant-Based Protein	-0.86	**	0.02		0.89	**	-0.64	**	0.55	**	-0.61	
Biofortification	0.04	**	-1.12	***	-1.16	**	-0.63	***	-0.92	***	0.83	**
Bio-Physical/Deterministic Modeling	0.22	**	0.06		-0.16		-0.06		-0.44		-0.13	

****P<0.01, **P<0.05, *P<0.10.*

[a] "World" does not include the region of comparison. For example, "Europe vs World" is the difference between Europe and the World (without Europe) shown in Table 5.

Table 7. Percentage of respondents that selected climate change or digital agriculture as the most important area of future research at least once during the BW block

	Total (%)	Public (%)	Private (%)	North America (%)	Europe (%)	Africa (%)	Asia (%)	South America (%)	Major Crops (%)	Minor Crops (%)
Climate change for biotic/abiotic stress was selected as most important at least once during the BW block	79	82	66	76	79	85	70	95	85	75
Abiotic Stress was selected as the most important in regard to climate change.[a]	67	68	60	66	71	57	68	81	66	68
Biotic Stress was selected as the most important in regard to climate change.[a]	33	32	40	34	29	43	32	19	34	32
Digital Agriculture was selected as the most important at least once during the BW block	28	29	27	29	22	38	27	27	26	30

[a] The percentage for biotic/abiotic selections is derived from the number of people who selected climate change as most important during the BW block. For example, 79% of respondents chose climate change in total. Of the 79%, 67% chose abiotic stress, and 33% chose biotic stress.

Table 8. Total number of respondents that chose abiotic or biotic stress as the most important area of future research and specific areas of abiotic/biotic stress that warrant the most future attention according to respondents in percentages

	Total	Public	Private	North America	Europe	Africa	Asia	South America	Major Crops	Minor Crops
Abiotic Stress was selected as most important at least once (total number of responses)	309	264	45	91	84	60	21	17	139	170
Drought Stress (%)	73	71	87	70	79	85	67	47	71	75
Heat Stress (%)	20	22	7	20	18	15	19	29	22	18
Salinity Stress (%)	3	2	4	2	1	-	10	12	3	2
Flood Stress (%)	2	3	-	4	1	-	-	6	3	2
Toxin Stress (%)	-	-	-	1	0	-	-	-	1	-
Cold Stress (%)	2	2	2	2	1	-	5	6	1	2
Biotic Stress was selected as most important at least once (total number of responses)	152	122	30	47	35	45	10	4	72	80
Increased presence/severity of pathogens (fungi, bacteria, etc.) due to climatic change (%)	55	57	43	53	51	53	70	100	57	53
Increased presence/severity of insects due to climatic change (%)	15	13	23	13	11	22	10	-	18	13
Increased presence/severity of weed pressure due to climatic change (%)	5	6	3	11	6	2	-	-	6	5
Introduction of new pathogens (fungi, bacteria, etc.) due to climatic change (%)	22	20	30	19	31	22	-	-	15	29
Introduction of new weed species due to climatic change (%)	3	3	-	4	-	-	20	-	4	1

Percentages are taken from the total number of responses to each question received with respect to each demographic of interest.

Table 9. Total number of respondents that chose digital agriculture as the most important area of future research and specific areas of digital agriculture that warrant the most future attention according to respondents in percentages

	Total	Public	Private	North America	Europe	Africa	Asia	South America	Major Crops	Minor Crops
Digital Agriculture was selected as most important at least once (total number of responses)	166	135	31	52	33	47	12	6	65	101
UAVs (drones) (%)	10	10	10	19	9	-	17	-	9	10
Satellite imagery (%)	2	2	-	-	-	2	-	-	-	3
Precision agriculture applications (%)	46	45	48	40	39	51	42	67	46	46
Internet of things (integrated sensors) (%)	8	9	6	12	12	6	0	17	9	8
Machine learning/Artificial Intelligence (%)	20	21	19	13	30	17	33	17	28	16
Apps for real-time decision-making (%)	11	11	13	13	6	19	8	-	8	14
Other (%)	2	2	3	2	3	4	-	-	-	4

Public Sector Funding

Participants who said they were predominately active in the public sector were asked:

> *Given that you are in the public sector, what percentage of your budget, on average, is funded by the private sector (for profit)?*

The results are given in Table 10. Overall, 1%-20% was the most common private sector contribution to a respondent's public sector budget. However, of those working in Africa, 47% said they did not receive funding from the private sector. Interestingly, over a quarter (26%) of public sector researchers in South America, indicated that over 50% of their research budget came from the private sector.

Table 10. The percentage of ***public*** *sector respondents' budget was funded by the* ***private*** *sector.*

	Total (%)	North America (%)	Europe (%)	Africa (%)	Asia (%)	South America (%)	Major Crops (%)	Minor Crops (%)
0%	31	21	30	47	41	26	29	33
1%-20%	45	50	48	35	46	26	49	43
21%-50%	14	17	18	8	8	21	14	14
over 50%	9	12	4	9	5	26	9	10

Public Sector Breeding Moving Forward

Tables 11-13 show the results of the questions about future collaboration between the public and private plant breeding sectors. Overall, more collaboration is expected in the future by both the private (87%) and public (84%) sectors. The regions anticipating the largest increase in collaboration between the public and private sectors were Europe (90% and 89%, respectively) and Africa (92% and 90%, respectively). In North America, a lower percentage of respondents expect collaboration, with only 64% of private sector respondents expecting more collaboration with the public sector moving forward and 79% of the public sector expecting more collaboration with the private sector.

The survey asked all (public and private) respondents what type of research they felt the public sector should focus on the most for the future. “Educating the next generation of plant scientists” had a similar response rate in the public (31%) and private (35%) sectors. This would indicate that nearly a third of public and private plant breeders thought the primary goal of the public sector moving forward should be education and not primary research. This result is surprising and troublesome as the public sector is the primary research component of many low and middle-income countries battling food insecurity.

A total of 35% of private sector respondents said that “becoming more integrated into research to support the private industry” was the most important for the public sector to focus on, while only 15% of the public sector participants selected this choice. These results show the schism concerning how active the public sector should be in conducting primary research moving into the future.

Table 11. Expected public and private sector collaboration in the future.

	Total (%)	North America (%)	Europe (%)	Africa (%)	Asia (%)	South America (%)	Major Crops (%)	Minor Crops (%)
The respondent was in the **public** sector and saw themselves commercializing research from their program in the **private** sector.								
Yes	64	56	67	78	74	63	62	65
No	36	44	33	22	26	37	38	35
The respondent was in the **public** sector and believed they would collaborate more/less with the **private** sector in the future.								
More	84	79	90	92	77	89	85	82
Less	16	21	10	8	23	11	15	18
The respondent was in the **private** sector and believed they would collaborate more/less with the **public** sector in the future.								
More	87	64	89	90	100	67	90	85
Less	13	36	11	10	-	33	10	15

*Table 12. What **public plant breeders** should focus on the most moving forward.*

	Total (%)	Public (%)	Private (%)	North America (%)	Europe (%)	Africa (%)	Asia (%)	South America (%)	Major Crops (%)	Minor Crops (%)
Educating the next generation of plant scientists	32	31	35	44	23	30	23	23	33	31
Conducting primary research to enhance plant science	29	33	12	30	37	14	34	18	29	29
Becoming more integrated into research to support private industry	19	15	35	7	23	30	27	41	18	20
Filling the gap in research in which the private industry shows no/little interest in	20	20	18	20	18	27	16	18	19	20

Table 13. Respondents' opinions on the following: Many public programs reported that budget shortfalls or uncertainty "endangered or severely constrained" their ability to conduct meaningful research. A recent 2020 study of 278 public breeding programs in the United States indicated that 21.4% of public breeding programs reported a decline in full time employees (FTE) over the past 5 years.

	Total	Public	Private	North America	Europe	Africa	Asia	South America	Major Crops	Minor Crops
Number of respondents	583	469	114	181	150	124	44	22	248	335
This is not a concern as it is likely a function of the private sector simply increasing funding in breeding sectors once dominated by the public sector. (%)	12	11	16	14	9	9	14	9	10	13
This is a trend likely true globally (%)	53	51	63	45	61	58	52	59	52	54
This is a threat to regional/global food security (%)	48	51	34	57	37	52	41	50	53	43
This trend is likely true in my region (%)	92	92	93	95	91	90	93	95	94	92

[a] Respondents were allowed to choose more than one answer. The percentages were taken from the number of observations; consequently, each column's sum will exceed 100%.

Conclusion and Discussion

Plant breeding has been pivotal in improving global food security and reducing poverty. The public-private relationships which formed the Green Revolution allowed for a take-off in crop yields until the turn of the millennium. Globally staple crop (maize, wheat, rice, and soya) yields increased by an average of 124% from 1961-2007, one of the greatest scientific achievements of mankind, but are only predicted to increase by an average of 33% from 2007-2050 (Fisher, Byerlee, and Edmeades 2011). As the world faces a growing population and increasing climatic stress, there are concerns as to how the shifting dynamics of the plant breeding industry will affect future food security. As the private industry plays a more significant role in traditionally dominated public breeding spaces (rice, wheat, and others), a paradigm shift may be underway, shifting from breeding for global food security to breeding for profit. While food security and profitability are not mutually exclusive, the marketability of some breeding traits may service producers in high-income countries more than producers in low-income countries.

Divergence

Three themes were consistent for private and public breeders throughout this study: disease resistance, climate change for biotic/abiotic stress, and yield enhancement being the areas of focus in the future. While there is a clear consensus that these areas are paramount, the relative rankings of importance differ across subsectors of breeding. For example, in the private sector, the preference shares for future research focus were found to be *disease resistance* (29.82%), *climate change for biotic/abiotic stress* (24.77%), and *yield enhancement* (18.16%). The preference shares for future research in the public sector were found to be *climate change for biotic/abiotic stress* (57.55%), *disease resistance* (12.95%), and *yield enhancement* (9.28%).

Our results indicate that respondents thought the public sector should place a greater weight (32.78%) on climate change. This is likely because climate change research, while in clear need, holds many characteristics consistent with developing public goods, where progress can be slow and financial returns small. Concerns are then raised regarding the magnitude of impact the public sector will be able to make given the diminishing human and financial resources characterizing the industry (Frey 1996; Guner and Wehner 2003; Traxler et al. 2005; Sylak-Glassman et al. 2016; Shelton and Tracy 2017). Further, as large governmental grants are shifting towards climate change resiliency in agriculture, the private and public sector responses in our survey may send a signal that the public sector should focus on areas where public funds are focused on in the future.

Of the public sector respondents in our survey, 45% reported that between 1-20% of their research budget came from the private sector. Of those working public sector breeders in Africa, 47% said that their budget did not consist of any funding from the private sector. The data illustrated the distribution of funding from the private sector and highlights the disproportionate allocation worldwide.

The focus on climate change remained a constant concern across all regions. Other important focus areas varied by region between disease resistance, yield enhancement, and pest resistance. The data shows that yield enhancement will be important in Africa (20.01% of the future preference share). The importance of yield enhancement, coupled with 47% of respondents working in Africa reporting that 0% of their budget comes from the private sector, leads to concerns about public-private relationships in Africa moving forward to fight food insecurity.

This study also explored the concern that NPBTs would contribute to the schism between public and private plant breeding sectors, given potential high capital requirements. The preference shares for CRISPR (a leading NPBT) with respect to the sector, crop type, and region do not exceed 2.34% and the differences are not significant ($P<0.01$) among any of the comparisons. This would suggest, at least in the case of CRISPR, that NPBTs will not create a division between the public and private sectors.

Convergence

The importance of *climatic change for biotic/abiotic stress*, *disease resistance*, and *yield enhancement* were themes among major and minor crops for both public and private breeders. There were no significant differences between major and minor crops regarding these three attributes ($P<0.10$). The data suggests that between major and minor crops, one is not disproportionately affected when looking at the divergence of the plant breeding industry.

Climatic change for biotic/abiotic stress was a top priority among all sectors, crop types, and regions, suggesting that it will warrant significant attention from plant breeding programs in the future. Additional questions on climate change show *drought stress* and *increased presence/severity of pathogens* are the most important areas of focus for abiotic and biotic stress, respectively. The results support that climate change is a problem within plant breeding that will demand attention moving into the future.

The Research Gap

When asked if "budget shortfalls or uncertainty 'endangered or severely constrained'" the respondent's ability to conduct meaningful research, 92% of respondents said that this was true in their region. This is consistent when describing responses by sector, where 92% of public sector respondents and 93% of private sector respondents said this was likely true in their region. Additionally, 51% of public sector respondents agreed that this was a threat to regional/global food security, while only 34% of the private sector considered budget shortfalls a threat. This difference is stark, where it appears that the private sector believes that while budgets are falling for the public sector, the private sector will be able to fill the food security gap left by diminishing funding to the public sector. While this may be true in many high-income countries where profits drive agricultural research and development in the private sector, it begs to question of the feasibility of the private sector filling the research void in many regions across the low-income world where profit margins could be much thinner.

This study found that the public and private sectors both agree that a reduction in funding would have implications for global food security (although the public sector thought it was more of an issue than the private sector). Compounding potential problems is the fact that only 12% of private sector respondents said that the primary focus of public sector plant breeding should be primary research, with the majority of respondents saying that the primary job should be educating the next generation of plant breeders. If this paradigm unfolds, there would appear to be a research gap regarding breeding for climate change resiliency in the future. With the private sector acknowledging the importance of research dedicated to climate change but on the other hand, believing that the role of the public sector should be to educate instead of conducting primary research, the gap is evident. If the public sector only focuses on educating plant scientists, climate change and its effects could receive less attention given the lack of opportunity for the private sector to receive returns on new developments.

This study found that both the private and public plant breeding sectors believe there will be more collaboration amongst them in the future but also predict lower funding for the public sector moving forward. One of the study's main findings is that there is a real potential for a research gap in breeding for climate change resiliency moving forward. Both the public and private sectors agreed that the public sector should focus the most on climate change moving forward, but given the reduction in public funding and the fact that most private sector breeders believe the public sector's main role is education, not primary research, could hamper climate change resiliency research. Historically, private breeders tend to focus on creating better varieties of widely-grown, high-value crops, like soya and maize. The important task of improving lower-value crops—such as plantains, potatoes, and cassava have historically been conducted by scientists at public universities and laboratories run by federal and state agencies. If the future of public breeding is not in primary research, as stated by the private breeders in this survey, society will need the private sector to fill these roles.

Public breeders often focus on long-term research in which the payoff may require many years of work, often by many individuals across various aspects of the public sector. After development and proof of concept by the public sector, the new products are often commercialized by the private sector with little or no return of funding to the public sector. The future of plant breeding should not be a competition between sectors but rather finding niches for collaboration, not annihilation, to ensure global food security. In his 1970 Nobel lecture, Norman Borlaug said, "There are no miracles in agricultural production. Nor is there such a thing as a miracle variety of wheat, rice, or maize which can serve as an elixir to cure all ills of a stagnant, traditional agriculture," which is why the future of plant breeding likely needs a robust private and public breeding sector to thrive under the pressures of population growth and a changing climate.

Limitations and Future Research

The public sector was represented at a disproportionately higher rate than the private sector in this study. This is because emails for those working in the public sector are more accessible compared to private sector databases. Many private sector employees are limited in the information they can disclose because of company policy, potentially contributing to the underrepresentation of the private sector.

A limitation important to note is that attributes had the potential to overlap. Digital agriculture had a relatively low preference across all demographics, which may be explained by the technology playing a supporting role to enhance other areas of plant breeding. While we looked at attributes such as CRISPR to give us insight into NPBTs directly, this study does not account for the other attributes that utilize NPBTs as a part of advancement. For example, the importance of disease resistance was a consistent theme, and breeders have started to use NPBTs to improve disease resistance (Schaart et al. 2016). The data from this study supports that NPBTs are not a direct reason for divergence, but the supporting roles they play in other areas is a suggested idea for future research.

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Appendices

Appendix A: Export Survey on the Future of Public and Private Plant Breeding

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Start of Block: Introduction Block

Q20 Thank you for your participation.   In this study we are interested in your perceptions about the future relationship between public and private plant science research. Your opinion is important to us and we hope that you will take 5 minutes to give us your insights.

Risks and Benefits: Your participation will provide important information about the future of plant science and plant breeding in an effort to mitigate global food insecurity. There are no anticipated risks to participating in this study.

There is no compensation for your time, which we estimate will take approximately **5 minutes**.

Voluntary Participation: Your participation in the research is completely voluntary.

Confidentiality: Your responses on the survey will be recorded anonymously. Only basic demographic information (i.e. age, gender, education etc.) will be collected.

Right to Withdraw: You are free to refuse to participate in the research and to stop participation during the survey if you choose.
If you have questions or concerns about this study, you may contact llnalley@uark.edu. For questions or concerns about your rights as a research participant, please contact Ro Windwalker, the University's Compliance Coordinator, at 1+ (479) 575-2208 or by e-mail at irb@uark.edu.

Q1 I am over 18 and I would like to participate in this research

○ Yes

○ No

Skip To: End of Survey If I am over 18 and I would like to participate in this research = No

Q9 Please indicate your academic level:

- ○ High school
- ○ Bachelor of Science
- ○ Master of Science
- ○ Ph.D., J.D., or PHE

Q2 Are you **primarily** active in the public (government, CGIAR, NGO, etc.) or private (for profit) plant science sector?

- ○ Public
- ○ Private

Display This Question:

If Q2= Public

Q7 Given that you are in the **public** sector, what percentage of your budget on average is funded by the private sector (for profit)?

- ○ 0%
- ○ 1%-20%
- ○ 21%-50%
- ○ over 50%

Display This Question:

If Q2 = Private

Q32 Given that you are in the **private** sector, what percentage of your budget on average is funded by the private sector (Federal, State, or other governmental grants)?

- ◯ 0%
- ◯ 1%-20%
- ◯ 21%-50%
- ◯ over 50%

Q5 What field do you **primarily** work in?

- ◯ Plant breeding
- ◯ Physiology
- ◯ Pathology
- ◯ Entomology
- ◯ Other (if yes, please specify)

Q3 Which crop are you **primarily** working in?

- ◯ Wheat
- ◯ Maize
- ◯ Soybean
- ◯ Rice
- ◯ Potatoes
- ◯ Casava
- ◯ Sorghum
- ◯ Millet

- Yams
- Plantains
- Vegetables
- Fruits
- Legumes
- Other (if yes, please specify)

Q4 Which region is of **primary** focus concerning the R&D activities of your research group/department?

- Africa
- Asia
- Europe
- Oceania
- North America
- South America
- No location focus

End of Block: Introduction Block

Start of Block: BW Intro

Q28 In this section we will ask a series of questions that look similar but their differences will play an **important role** in determining where the **${Q2/ChoiceGroup/SelectedChoices}** sector plant science community believes its future direction is moving.

End of Block: BW Intro

Start of Block: BW1

Q10 Which of the following attributes do you think the **${Q2/ChoiceGroup/SelectedChoices}**[7] sector should give the most attention to, and which attribute should the **${Q2/ChoiceGroup/SelectedChoices}** sector give the least attention to in the future? Please, check only one attribute as the *most* important and only one attribute as the *least* important.

Most Important for Sector		Least Important for Sector
○	Biofortification	○
○	Disease resistance	○
○	Pest resistance	○
○	Plant based protein	○
○	Bio-physical/deterministic modeling	○
○	Digital agriculture (imagery, sensors, software, etc.)	○

End of Block: BW1

Start of Block: BW2

Q12 Which of the following attributes do you think the **${Q2/ChoiceGroup/SelectedChoices}** sector should give the most attention to, and which attribute should the **${Q2/ChoiceGroup/SelectedChoices}** sector give the least attention to in the future? Please, check only one attribute as the *most* important and only one attribute as the *least* important.

Most Important for Sector Least Important for Sector

[7] The survey utilized the autofill function in Qualtrics. The code in the following questions, shown in blue, represents when a participant's previous answer to a question determined what they saw.

○	Climate change for biotic/abiotic stress	○
○	Disease resistance	○
○	CRISPR	○
○	Plant based protein	○
○	Bio-physical/deterministic modeling	○
○	Digital agriculture (imagery, sensors, software, etc.)	○

End of Block: BW2

Start of Block: BW3

Q14 Which of the following attributes do you think the **${Q2/ChoiceGroup/SelectedChoices}** sector should give the most attention to, and which attribute should the **${Q2/ChoiceGroup/SelectedChoices}** sector give the least attention to in the future? Please, check only one attribute as the *most* important and only one attribute as the *least* important.

Most Important for Sector		Least Important for Sector
○	Market/value added enhancement of attributes	○
○	CRISPR	○
○	Plant based protein	○
○	Yield by Environment Genomic prediction	○
○	Bio-physical/deterministic modeling	○
○	Digital agriculture (imagery, sensors, software, etc.)	○

End of Block: BW3

Start of Block: BW4

Q15 Which of the following attributes do you think the **${Q2/ChoiceGroup/SelectedChoices}** sector should give the most attention to, and which attribute should the **${Q2/ChoiceGroup/SelectedChoices}** sector give the least attention to in the future?
 Please, check only one attribute as the *most* important and only one attribute as the *least* important.

Most Important for Sector		Least Important for Sector
○	Market/value added enhancement of attributes	○
○	Disease resistance	○
○	Pest resistance	○
○	Yield by Environment Genomic prediction	○
○	Seed delivery	○
○	Yield enhancement	○

End of Block: BW4

Start of Block: BW5

Q16 Which of the following attributes do you think the **${Q2/ChoiceGroup/SelectedChoices}** sector should give the most attention to, and which attribute should the **${Q2/ChoiceGroup/SelectedChoices}** sector give the least attention to in the future?
 Please, check only one attribute as the *most* important and only one attribute as the *least* important.

Most Important for Sector Least Important for Sector

◯	Biofortification	◯
◯	Climate change for biotic/abiotic stress	◯
◯	Plant based protein	◯
◯	Yield by Environment Genomic prediction	◯
◯	Bio-physical/deterministic modeling	◯
◯	Digital agriculture (imagery, sensors, software, etc.)	◯

End of Block: BW5

Start of Block: BW6

Q17 Which of the following attributes do you think the **${Q2/ChoiceGroup/SelectedChoices}** sector should give the most attention to, and which attribute should the **${Q2/ChoiceGroup/SelectedChoices}** sector give the least attention to in the future? Please, check only one attribute as the *most* important and only one attribute as the *least* important.

Most Important for Sector		Least Important for Sector
◯	Biofortification	◯
◯	Market/value added enhancement of attributes	◯
◯	Disease resistance	◯
◯	CRISPR	◯
◯	Seed delivery	◯
◯	Yield enhancement	◯

End of Block: BW6

Start of Block: BW7

Q18 Which of the following attributes do you think the **${Q2/ChoiceGroup/SelectedChoices}** sector should give the most attention to, and which attribute should the **${Q2/ChoiceGroup/SelectedChoices}** sector give the least attention to in the future? Please, check only one attribute as the *most* important and only one attribute as the *least* important.

Most Important for Sector		Least Important for Sector
○	Biofortification	○
○	Climate change for biotic/abiotic stress	○
○	CRISPR	○
○	Pest resistance	○
○	Seed delivery	○
○	Yield enhancement	○

End of Block: BW7

Start of Block: BW8

Q19 Which of the following attributes do you think the **${Q2/ChoiceGroup/SelectedChoices}** sector should give the most attention to, and which attribute should the **${Q2/ChoiceGroup/SelectedChoices}** sector give the least attention to in the future? Please, check only one attribute as the *most* important and only one attribute as the *least* important.

Most Important for Sector   Least Important for Sector

◯	Climate change for biotic/abiotic stress	◯
◯	Market/value added enhancement of attributes	◯
◯	Pest resistance	◯
◯	Plant based protein	◯
◯	Seed delivery	◯
◯	Yield enhancement	◯

End of Block: BW8

Start of Block: BW follow up

Display This Question:

If Q12 = Climate change for biotic/abiotic stress [Most Important for Sector]
Or Q16 = Climate change for biotic/abiotic stress [Most Important for Sector]
Or Q18 = Climate change for biotic/abiotic stress [Most Important for Sector]
Or Q19 = Climate change for biotic/abiotic stress [Most Important for Sector]

Q20 In one of your selections, you chose biotic/abiotic stress as something which should be focused on. Which, in your mind, warrants the most attention from the **${Q2/ChoiceGroup/SelectedChoices}** sector?

◯ Climate change for biotic stress

◯ Climate change for abiotic stress

Display This Question:

If Q20 = Climate change for biotic stress

Q21 Given your opinion that the **${Q2/ChoiceGroup/SelectedChoices}** sector should focus on climate change for biotic stress, which area of focus should the

${Q2/ChoiceGroup/SelectedChoices} sector place research emphasis on?

- ◯ Increased presence/severity of pathogens (fungi, bacteria, etc.) due to climatic change
- ◯ Increased presence/severity of insects due to climatic change
- ◯ Increased presence/severity of weed pressure due to climatic change
- ◯ Introduction of new pathogens (fungi, bacteria, etc.) due to climatic change
- ◯ Introduction of new weed species due to climatic change

Display This Question:

If Q20 = Climate change for abiotic stress

Q23 Given your opinion that the **${Q2/ChoiceGroup/SelectedChoices}** sector should focus on climate change for abiotic stress, which area of focus should the **${Q2/ChoiceGroup/SelectedChoices}** sector place research emphasis on?

- ◯ Drought stress
- ◯ Heat stress
- ◯ Salinity stress
- ◯ Flood stress
- ◯ Toxin stress
- ◯ Cold stress

Display This Question:

If Q10= Digital agriculture (imagery, sensors, software, etc.) [Most Important for Sector]

Or Q12 = Digital agriculture (imagery, sensors, software, etc.) [Most Important for Sector]

Or Q14 = Digital agriculture (imagery, sensors, software, etc.) [Most Important for Sector]

Or Q16 = Digital agriculture (imagery, sensors, software, etc.) [Most Important for

Sector]

Q29 In one of your selections, you chose digital agriculture as something which should be focused on. Which, in your mind, warrants the most attention from the **${Q2/ChoiceGroup/SelectedChoices}** sector?

- ○ UAVs (drones)
- ○ Satellite imagery
- ○ Precision agriculture applications
- ○ Internet of things (integrated sensors)
- ○ Machine learning/Artificial Intelligence
- ○ Apps for real-time decision making
- ○ Other (please specify) ____

End of Block: BW follow up

Start of Block: Other Questions

Q6 Given that you are predominately in the **${Q2/ChoiceGroup/SelectedChoices}** sector, do you feel like you will be collaborating more or less with the **${Q2/ChoiceGroup/UnselectedChoices}** sector in 10 years?

- ○ More
- ○ Less

Display This Question:
If Q2= Public

Q8 Given that you are in the **public** sector, do you see yourself commercializing research from your program in the **private** sector?

- ◯ Yes
- ◯ No

Q26 In your opinion, what should the future of the plant sciences in the **public** sector primarily focus on? (choose one)

- ◯ Educating the next generation of plant scientists
- ◯ Conducting primary research to enhance plant science
- ◯ Becoming more integrated in research to support private industry
- ◯ Filling the gap on research which the private industry shows no/little interest in

---

Q31 Many public programs reported that budget shortfalls or uncertainty "endangered or severely constrained" their ability to conduct meaningful research. A recent 2020 study of 278 public breeding programs in the United States indicated 21.4% of public breeding programs reported a decline in full time employees (FTE) over the past 5 years.
Please select all those which you believe to be true:

- ▢ This is not a concern as it is likely a function of the private sector simply increasing funding in breeding sectors once dominated by the public sector.
- ▢ This is a trend likely true globally
- ▢ This is a threat to regional/global food security
- ▢ This trend is likely not true in my region

Q27 I have been an advisor for ____ students in the last 5 years.

- ◯ MS
- ◯ Ph.D.
- ◯ both MS and Ph.D.
- ◯ not applicable

Display This Question:
If I have been an advisor for ____ students in the last 5 years. = MS
Or I have been an advisor for ____ students in the last 5 years. = both MS and Ph.D.

Q24 Over the past 5 years ___% of the MS students I either directly/indirectly supervised are now employed in the private sector

	No students	%	All Students
	0 10 20 30 40	50	60 70 80 90 100

Display This Question:
If I have been an advisor for ____ students in the last 5 years. = Ph.D.
Or I have been an advisor for ____ students in the last 5 years. = both MS and Ph.D.

Q26 Over the past 5 years ___% of the PhD students I either directly/indirectly supervised are now employed in the private sector

	No students	%	All Students
	0 10 20 30 40	50	60 70 80 90 100

Q22 If you have any final remarks concerning the answers you gave in the survey or the questions that were asked, please leave them here. Also, in case you are interested in the results of this study please leave your e-mail address here for future correspondence.

____

End of Block: Other Questions

Appendix B: Totals: crop the respondent was working with primarily

Table B1. Totals: Crop the respondent was working with primarily

	Public (%)	Private (%)	North America (%)	Europe (%)	Africa (%)	Asia (%)	South America (%)	Oceania (%)	No Location (%)	Total # of responses for each crop
Crop										
Wheat	11	9	8	15	6	11	-	50	15	**60**
Maize	12	15	10	3	27	7	9	-	19	**72**
Soybean	4	1	9	-	2	-	5	-	2	**20**
Rice	8	4	4	1	3	30	55	-	6	**41**
Potatoes	4	7	2	11	2	2	5	-	-	**29**
Cassava	3	-	-	-	10	-	-	-	-	**12**
Sorghum	1	2	2	1	2	-	-	25	-	**9**
Millet	-	-	-	-	0	-	-	-	-	-
Yams	1	-	-	-	4	-	-	-	-	**5**
Plantains	-	-	-	-	0	-	-	-	-	-
Vegetables	8	23	16	11	3	16	-	25	13	**65**
Fruits	7	5	9	7	2	14	-	-	2	**37**
Legumes	6	1	4	5	10	2	-	-	2	**29**
Other	35	34	35	45	29	18	27	-	43	**204**
Total # of responses for each subgroup	**469**	**114**	**181**	**150**	**124**	**44**	**22**	**4**	**54**	

Appendix C: RPL model results for the public/private sector, major/minor crops, and region

Table C1. Random Parameter Logit Model results for the public and private sectors

Attributes	Public RPL			Private RPL		
Disease Resistance	3.478	***	(0.109)	2.118	***	(0.215)
SD	2.492	***	(0.109)	3.507	***	(0.247)
Pest Resistance	2.919	***	(0.112)	0.999	***	(0.200)
SD	2.343	***	(0.108)	3.373	***	(0.237)
Plant-Based Protein	0.634	***	(0.095)	-1.039	***	(0.206)
SD	3.054	***	(0.104)	4.164	***	(0.270)
Biofortification	1.040	***	(0.095)	-2.364	***	(0.218)
SD	2.715	***	(0.104)	4.284	***	(0.264)
Digital Agriculture	1.297	***	(0.103)	-0.381		(0.223)
SD	2.768	***	(0.094)	3.853	***	(0.251)
Climate Change for Biotic/Abiotic Stress	4.834	***	(0.115)	1.664	***	(0.208)
SD	3.288	***	(0.105)	4.879	***	(0.263)
CRISPR	1.461	***	(0.104)	-0.181		(0.246)
SD	4.010	***	(0.113)	4.917	***	(0.314)
Market Value-Added Enhancement of Attributes	0.950	***	(0.083)	1.773	***	(0.218)
SD	3.384	***	(0.094)	4.568	***	(0.252)
Yield by Environment Genomic Prediction	2.857	***	(0.107)	0.519	**	(0.205)
SD	2.986	***	(0.099)	3.996	***	(0.249)
Bio-Physical/Deterministic Modeling	0.067		(0.104)	-2.221	***	(0.242)
SD	2.934	***	(0.100)	3.386	***	(0.248)
Yield Enhancement	3.053	***	(0.103)	2.079	***	(0.223)
SD	3.158	***	(0.101)	3.921	***	(0.276)
Log-likelihood	-8377.1			-2027.4		
AIC	16808.2			4208.712		
BIC	17387.91			4579.516		

****P<0.01, **P<0.05, *P<0.10.*
Parentheses denote standard error.

Table C2. Random Parameter Logit Model results for major and minor crops

Attributes	Major Crops RPL			Minor Crops RPL		
Disease Resistance	3.330	***	(0.155)	3.379	***	(0.126)
SD	3.056	***	(0.172)	2.739	***	(0.138)
Pest Resistance	2.724	***	(0.161)	2.580	***	(0.128)
SD	3.053	***	(0.178)	2.574	***	(0.140)
Plant-Based Protein	0.201		(0.138)	0.667	***	(0.110)
SD	3.183	***	(0.151)	3.138	***	(0.126)
Biofortification	0.946	***	(0.137)	0.361	***	(0.109)

SD	3.460	***	(0.158)	3.000	***	(0.128)
Digital Agriculture	1.083	***	(0.151)	1.257	***	(0.125)
SD	3.376	***	(0.154)	3.010	***	(0.124)
Climate Change for Biotic/Abiotic Stress	4.620	***	(0.157)	4.391	***	(0.136)
SD	3.457	***	(0.155)	3.679	***	(0.130)
CRISPR	0.918	***	(0.144)	1.547	***	(0.125)
SD	4.073	***	(0.163)	4.122	***	(0.145)
Market Value-Added Enhancement of Attributes	0.781	***	(0.120)	1.018	***	(0.101)
SD	3.466	***	(0.136)	3.768	***	(0.122)
Yield by Environment Genomic Prediction	3.066	***	(0.148)	2.195	***	(0.126)
SD	3.491	***	(0.155)	3.265	***	(0.137)
Bio-Physical/Deterministic Modeling	-0.382	**	(0.153)	-0.564	***	(0.120)
SD	3.595	***	(0.168)	2.475	***	(0.127)
Yield Enhancement	3.245	***	(0.146)	2.656	***	(0.121)
SD	3.419	***	(0.146)	3.374	***	(0.130)
Log-likelihood		-4419.12			-6037.7	
AIC		8992.316			12229.43	
BIC		9422.967			12683.23	

****P<0.01, **P<0.05, *P<0.10.*

Parentheses denote standard error.

Table C3. Random Parameter Logit Model results for the North America, Africa, and Europe

	North America			Africa			Europe		
Attributes	RPL			RPL			RPL		
Disease Resistance	4.511	***	(0.186)	1.089	***	(0.194)	2.87	***	(0.215)
SD	2.425	***	(0.206)	2.495	***	(0.217)	3.83	***	(0.263)
Pest Resistance	4.019	***	(0.192)	0.450	*	(0.199)	1.86	***	(0.217)
SD	3.196	***	(0.207)	2.236	***	(0.244)	3.64	***	(0.270)
Plant-Based Protein	0.785	***	(0.157)	-1.796	***	(0.200)	0.45	*	(0.195)
SD	3.422	***	(0.174)	3.623	***	(0.239)	3.54	***	(0.213)
Biofortification	0.602	***	(0.150)	-0.815	***	(0.203)	-0.76	***	(0.189)
SD	2.996	***	(0.180)	3.220	***	(0.199)	4.39	***	(0.245)
Digital Agriculture	1.688	***	(0.181)	-0.610	**	(0.219)	0.41		(0.229)
SD	4.031	***	(0.195)	3.127	***	(0.195)	3.41	***	(0.215)
Climate Change for Biotic/Abiotic Stress	4.556	***	(0.186)	2.861	***	(0.209)	4.50	***	(0.234)
SD	5.424	***	(0.250)	3.101	***	(0.218)	4.40	***	(0.243)
CRISPR	0.918	***	(0.188)	-1.869	***	(0.227)	1.04	***	(0.226)
SD	4.244	***	(0.223)	4.111	***	(0.240)	4.49	***	(0.235)
Market Value-Added Enhancement of Attributes	1.819	***	(0.164)	0.170		(0.169)	-0.18		(0.177)
SD	0.187	***	(0.187)	2.824	***	(0.179)	4.44	***	(0.211)
Yield by Environment Genomic Prediction	2.702	***	(0.189)	0.428	*	(0.213)	2.17	***	(0.208)
SD	3.563	***	(0.195)	3.519	***	(0.235)	3.84	***	(0.249)
Bio-Physical/Deterministic Modeling	0.135		(0.186)	-2.444	***	(0.243)	-1.14	***	(0.207)
SD	3.209	***	(0.193)	3.952	***	(0.259)	2.83	***	(0.194)
Yield Enhancement	3.951	***	(0.206)	1.468	***	(0.200)	2.27	***	(0.208)
SD	4.295	***	(0.210)	3.600	***	(0.239)	3.59	***	(0.218)
Log-likelihood	-3008			-2248.7			-2482.1		
AIC	6170.015			4651.446			5118.249		
BIC	6576.417			5028.725			5510.185		

******P<0.01, **P<0.05, *P<0.10.*

Parentheses denote standard error.

Table C4. Random Parameter Logit Model results for results for the entire data set without North America, Africa, and Europe respectively

Attributes	North America v ROW RPL			Africa v ROW RPL			Europe v ROW RPL		
Disease Resistance	2.541	***	(0.111)	3.694	***	(0.110)	2.789	***	(0.105)
SD	3.118	***	(0.142)	2.385	***	(0.117)	2.528	***	(0.122)
Pest Resistance	1.663	***	(0.111)	2.967	***	(0.110)	2.177	***	(0.104)
SD	2.661	***	(0.152)	2.369	***	(0.114)	2.560	***	(0.120)
Plant-Based Protein	-0.366	***	(0.100)	1.025	***	(0.094)	-0.351	***	(0.095)
SD	3.418	***	(0.129)	2.640	***	(0.097)	3.338	***	(0.122)
Biofortification	-0.340	***	(0.102)	0.683	***	(0.095)	0.276	***	(0.094)
SD	3.493	***	(0.126)	2.595	***	(0.097)	2.949	***	(0.118)
Digital Agriculture	0.664	***	(0.114)	1.388	***	(0.107)	0.754	***	(0.104)
SD	2.989	***	(0.121)	2.717	***	(0.105)	3.533	***	(0.125)
Climate Change for Biotic/Abiotic Stress	3.647	***	(0.111)	4.661	***	(0.116)	3.699	***	(0.104)
SD	3.154	***	(0.114)	3.481	***	(0.110)	3.612	***	(0.120)
CRISPR	0.328	***	(0.110)	1.675	***	(0.106)	0.600	***	(0.102)
SD	4.341	***	(0.136)	3.198	***	(0.104)	4.059	***	(0.129)
Market Value-Added Enhancement of Attributes	0.460	***	(0.093)	1.200	***	(0.089)	0.889	***	(0.089)
SD	3.520	***	(0.116)	3.784	***	(0.108)	3.675	***	(0.115)
Yield by Environment Genomic Prediction	1.773	***	(0.109)	2.622	***	(0.105)	2.079	***	(0.103)
SD	3.621	***	(0.133)	2.978	***	(0.107)	3.673	***	(0.127)
Bio-Physical/Deterministic Modeling	-1.165	***	(0.113)	-0.060	***	(0.102)	-0.540	***	(0.107)
SD	2.866	***	(0.125)	2.653	***	(0.101)	3.217	***	(0.119)
Yield Enhancement	2.228	***	(0.109)	3.067	***	(0.104)	2.590	***	(0.100)
SD	3.698	***	(0.129)	3.047	***	(0.106)	3.672	***	(0.122)
Log-likelihood	-7372.8			-8124.9			-8004.4		
AIC	14899.58			16403.87			16162.82		
BIC	1367.42			16881.92			16636.38		

****P<0.01, **P<0.05, *P<0.10.*

Parentheses denote standard error.

Appendix D: IRB Approval Document

UNIVERSITY OF ARKANSAS

To:	Adriaan Johannes De Lange
From:	Douglas J Adams, Chair IRB Expedited Review
Date:	03/08/2021
Action:	**Exemption Granted**
Action Date:	03/08/2021
Protocol #:	2102314838
Study Title:	CRISPR-Cas9 Drivers & Barriers - A comparative study among US, EU and African plant breeders

The above-referenced protocol has been determined to be exempt.

If you wish to make any modifications in the approved protocol that may affect the level of risk to your participants, you must seek approval prior to implementing those changes. All modifications must provide sufficient detail to assess the impact of the change.

If you have any questions or need any assistance from the IRB, please contact the IRB Coordinator at 109 MLKG Building, 5-2208, or irb@uark.edu.

cc: Lawton L Nalley, Investigator

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