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Global demand for rice germplasm and the role of the IRRI Genetic Resources Center

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Abstract

The International Rice Research Institute (IRRI) holds the world's largest collection of rice diversity, with more than 130,000 accessions of cultivated rice and wild species. We examine the patterns of germplasm use from IRRI using genebank distribution data and results from the 2019 survey of germplasm recipients. Between 2012 and 2018, there were a total of 2,174 requests for rice germplasm from more than 1,000 unique requestors. Requests for germplasm outside IRRI were received from 63 countries in all regions of the world, with a majority from Asia. IRRI distributed germplasm externally to requestors from universities (32%), national programs (14%), private companies (9%) and individuals, including farmers (24%) as well as other CGIAR centers (3%). Important traits sought for include tolerance to environmental stresses, followed by tolerance or resistance to biotic stresses. The majority of survey respondents confirmed the usefulness of IRRI germplasm for research, breeding, characterization, and evaluation. Taken together, the findings demonstrate the crucial role of IRRI's international rice genebank as a key germplasm source for rice improvement.

Suggested citation

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Acknowledgement

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Introduction

This study examines patterns of germplasm use for the largest rice genebank in the world, the International Rice Research Institute (IRRI) Genetic Resources Center. Rice is a staple food for more than half of the world's population. In 2019, over 755 million tons were produced in 143 countries (FAOSTAT, 2021). Research, breeding, and other crop improvement efforts have focused on enhancing yield gains and addressing consumer preferences in quality and nutrition. As a result, global rice productivity has continued to increase over the last several decades (Figure 1). However, while productivity is still increasing overall, the rate of increase has been declining (Figure 2). Maintaining productivity growth is crucial because challenges continue to evolve with climate change and the emergence of new pests and pathogens. IRRI scientists estimated that it generally takes 8 to 10 years to breed new crop varieties using traditional techniques (Brar and Parminder, 2010).

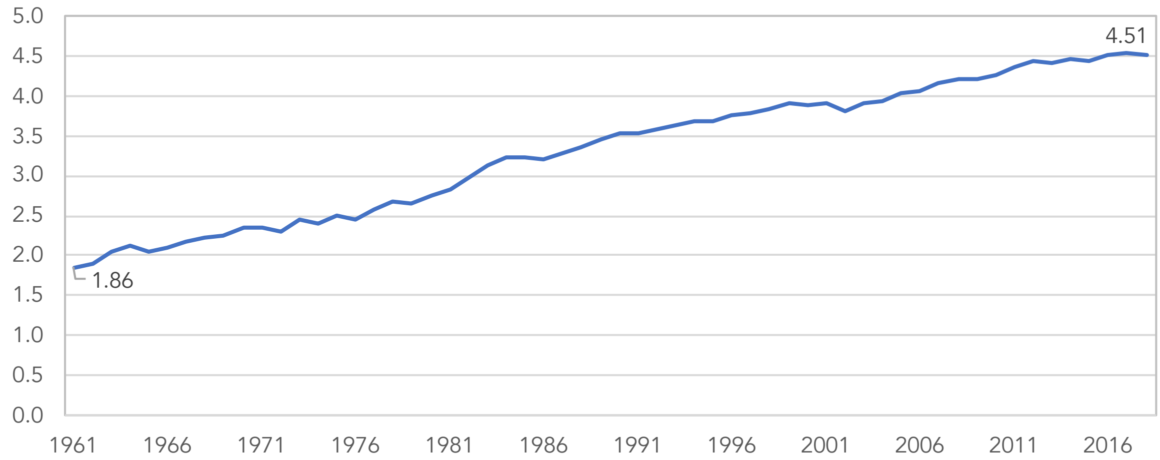

Figure 1. Paddy yield, tons per hectare
Data processed by authors from: World Rice Statistics, IRRI (USDA). Y-axis unit: tons/hectare

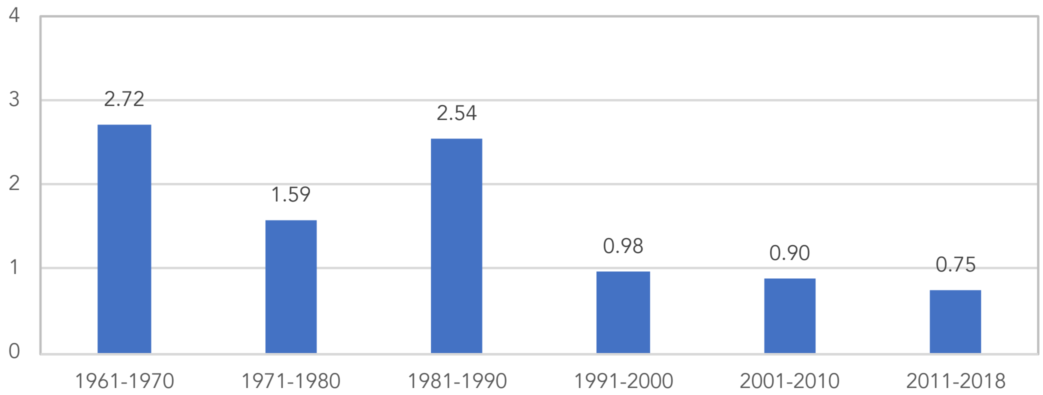

Figure 2. Annual rice yield growth, average for each period
Data processed by authors from: World Rice Statistics, IRRI (USDA). Y-axis unit: % growth rate

Rice diversity

While the country origin of rice is debated, the center of diversity is known to be in tropical Asia—the top consuming and producing region for the crop. Rice is planted in "an extraordinarily high portion" of farmlands in South, Southeast, and East Asia according to *Rice Almanac* (Maclean et al. 2013). There are approximately 23 species of rice belonging to the genus *Oryza* and two are most important for global consumption: *O. sativa*, cultivated worldwide, and *O. glaberrima*, grown mainly in parts of Africa (Jacquemin et al. 2013). Currently, thousands of rice varieties are grown in more than 100 countries (Maclean et al. 2013). These species make up the genetic foundation for crop improvements, which are necessary to sustain growth in rice production.

The international rice genebank

IRRI, founded in 1960 by the Ford and Rockefeller foundations with support from the Government of the Philippines, is an international agricultural research organization based in Los Baños, Philippines. The international rice genebank at IRRI (officially, the T.T. Chang Genetic Resources Center) was officially established in 1977. Shortly after IRRI's founding, scientists began to assemble a germplasm collection to support its breeding work (Jackson 1997). Today, IRRI holds the world's largest collection of rice diversity, with more than 130,000 accessions of cultivated rice and wild species. About 37% of the accessions are traditional cultivars or landraces, 10% are breeding materials or advanced cultivars and 3% are wild relatives.

Most accessions are maintained in an active collection at 2–4°C and at -20°C for long-term storage. Seed is tested regularly for viability and regenerated if the germination rate falls below 85%. Approximately 95% of the accessions at IRRI are also safety-duplicated both in the Svalbard Global Seed Vault in Norway and in the United States National Plant Germplasm System (NPGS). The top ten countries that provide the most germplasm sources to IRRI are presented in Table 1; that all these countries are in Asia highlights the importance of this region as the center of rice diversity.

Table 1. Origin of rice accessions conserved at IRRI

Country	Number of accessions
India	18,441
Laos	15,813
Indonesia	10,453
Philippines	9,699
China	9,280
Bangladesh	7,472
Thailand	6,705
Vietnam	5,108
Cambodia	4,978
Malaysia	4,961
Other	42,591
Not specified	3,383

Data source: Genesys (https://www.genesys-pgr.org/)

Rice user survey

The first and only user survey implemented by the IRRI rice genebank was conducted in 1995—24 years ago. In that pioneering work, Loresto et al. (2000) documented (1) how requested germplasm was used, (2) traits identified and used in breeding or crop improvement, (3) methodologies developed, and (4) other contributions made to rice science. The study contacted 200 users of IRRI's rice germplasm in Bangladesh, Indonesia, Japan, Korea, Thailand, the UK and the US during the period from 1989 to 1994 and received responses from 48. The results confirmed the importance of the IRRI rice collection in evaluating for biotic and abiotic stresses. To our knowledge, no follow-up study had been conducted since.

1. Economic value of rice germplasm

Plant genetic resources (as seeds or germplasm) are used in many ways with farmers planting crops as the most obvious and direct application. However, rice germplasm from IRRI is mainly used at an earlier stage by researchers seeking to develop improved varieties. Indeed, conserved plant genetic resources have economic value even if they are not currently being used because they offer tools for future research and breeding (Smale and Jamora 2020). Financing a genebank for future generations through a trust (e.g., the Crop Trust's endowment fund) is an explicit recognition of its long-term value. The availability of genetic diversity is an important foundation to enable improvement of rice in the future.

There is ample evidence that the continuous release of improved varieties by plant breeding programs has brought about social and economic returns that far outweigh the costs of investment. The economic impacts of the initial diffusion of modern rice varieties across Asia from the 1960s through the 1980s is one of the most documented achievements in international agricultural research and development assistance.

In 1997, Evenson and Gollin estimated the value of farm-level benefits from crop improvement that would be gained by adding 1000 additional accessions to the rice collection maintained by the International Network for the Genetic Evaluation of Rice at USD 325 million. A 2011 study by Brennan and Malabayabas demonstrated that there have been large and sustained yield gains flowing to the Philippines, Indonesia and Vietnam resulting from IRRI's work on varietal improvement. The estimated total benefits averaged USD 1.46 billion (in constant 2009 dollars) per year across the three countries. Raitzer et al. (2015) estimated similar substantial returns attributable to IRRI for varieties released after 1989 in Bangladesh, Indonesia and the Philippines. Shi and Hu (2017) confirmed that germplasm from IRRI has contributed 16.4% of genetic materials to rice varieties developed in China between 1982 and 2011. A recent study by Villanueva et al. (2020) estimated the contribution of IRRI's genetic resources to varietal improvement and rice productivity of farmers in eastern India, showing that 45% to 77% of the genetic composition of improved rice varieties was derived from the genes of IRRI genebank accessions and that a 10% increase in the genetic contribution of IRRI's materials to an improved rice variety is associated with a yield increase of 27%.

Despite these high returns, questions about the value of germplasm and levels of genebank use continue. In 1997, Wright identified four fundamental information gaps about genebanks: (i) who uses genebanks; (ii) why users want germplasm; (iii) what kind of germplasm is used; and (iv) what characteristics users are seeking. Day-Rubenstein et al. (2006) and Smale and Day-Rubenstein (2002) addressed these questions by surveying users of the US NPGS. We applied similar methods and address the same information gaps using data from IRRI and the results of a user survey implemented between April and May 2019.

This study was motivated by a need to document and understand how genebank users make use of genetic resources and the additional services the IRRI genebank provides to enhance access to and promote the use of rice germplasm. The findings debunk a misconception that accessions stored in genebanks are rarely used and provide additional justification for why genebanks must be supported in the long-term.

2. Data and Methods

Data presented here are compiled from three sources: (1) a summary of all rice germplasm distributions from 2012 to 2018 provided by the IRRI Genetic Resources Center; (2) data produced from a survey of end-users of rice germplasm across multiple countries; and (3). accession-level data uploaded by the IRRI genebank to the Genesys platform (https://www.genesys-pgr.org/).

The IRRI user survey, implemented between 8 April 2019 and 4 May 2019, is the only attempt to obtain structured feedback from genebank end-users in multiple countries on their use of rice germplasm since 1995. The user survey was part of a broader initiative by the CGIAR Genebank Platform to evaluate the performance of the international genebanks. We developed a questionnaire based on the questions posed by Wright (1997), which allows comparison with the US NPGS study by Smale and Day-Rubenstein (2002).[1]

Past user surveys of the CGIAR genebanks have had low response rates, such as 27% for a survey on banana (Bioversity in Garming et al. 2010), 10% for potato (CIP in Galeano et al. 2020), and 24% for rice (IRRI in Loresto et al 2000). The response rates for the US NPGS study ranged from 23% to 45% by crop, with the lowest response rates for potato and the highest in wheat, while there were too few responses for cotton, rice, sorghum and squash for statistical analysis. Thus, the current survey was designed to be concise to improve the response rate and take up less of the respondents' time. We developed 21 questions addressing genebank service quality and user needs.

Each unique requestor between 2012 and 2018 with a valid email address was sent a link to the survey asking for information on the quality and state of the germplasm accessions that they received and their level of satisfaction with the services provided by IRRI's Genetic Resources Center. The first survey link was sent to 694 target respondents with valid email addresses (out of 1,005 unique names) using the CGIAR Genebank Platform's official email address. Three follow-up reminders were sent with support from the current genebank manager of IRRI.[2] The use of an online survey was appropriate considering that 82% of germplasm requests in the previous 4 years had been sent by email. We received 244 valid responses (a 35% response rate), and respondents took, on average, 11 minutes to complete the survey.

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[1] The US NPGS is a system of germplasm collections across the country with a centralized facility for coordination, quarantine, and long-term seed storage. In terms of size, the US NPGS is the largest national genebank in the world with nearly 600,000 accessions of the world's most commonly grown crops. See also: https://npgsweb.ars-grin.gov/gringlobal/query/accessionsbysite.aspx

[2] 1st email sent: 8 April (by the Genebank Platform); 2nd email sent: 12 April (by the IRRI genebank); 3rd email sent: 21 April (by the Genebank Platform); 4th email sent: 30 April (by the IRRI genebank).

3. Results

a) *Who requests germplasm?*

Between 2012 and 2018, there were a total of 2,174 requests for rice germplasm from 1,005 unique requestors, with an average of 247 requests in the last 3 years (Table 2). Most requestors (71%) requested only once in the past 7 years, but some made multiple requests ranging from two (14%) to more than 20 (0.9%). Approximately half of the requests came from IRRI internal users, which confirms the integrative service provided by the genebank to IRRI's research and breeding platforms.

IRRI distributed germplasm externally to requestors from universities (32%), national programs (14%), private companies (9%), other CGIAR centers (3%), and individuals, including farmers (24%). Requests for germplasm outside IRRI were received from 63 countries in all regions of the world, with a majority from Asia (71%) followed by those from Europe (16%). The top ten countries with the most requests for rice germplasm are presented in Table 3. Outside of the Philippines, requestors in China and India made the most requests. China and India are also the top rice-producing countries in the world, with about 203 and 164 million tons of paddy rice harvested, respectively, in 2018.[3] The geographical distribution of germplasm recipients appears to mainly reflect the production zones of rice as well as the technological and scientific capacity to use received rice genetic resources.

User survey

Responses were received from users in 48 countries (out of 63), representing all geographical regions. The majority were from countries in Asia (69%), followed by Europe (17%). About two-thirds of survey respondents (66%) had requested germplasm more than once in the previous 7 years. Forty percent of the respondents had requested germplasm in the previous year, indicating that it is probably easier to get responses from recent users (which demonstrates the importance of regularly seeking feedback).

Table 2. Number and breakdown of germplasm requests, 2012 to 2018

Year	Internal	External	Total requests	% Internal
2012	151	251	402	38%
2013	195	152	347	56%
2014	161	196	357	45%
2015	182	145	327	56%
2016	128	112	240	53%
2017	166	121	287	58%
2018	118	96	214	55%
Total	**1,101**	**1,073**	**2,174**	**51%**
Average, 2012-2018	157	153	311	51%
Average, last 3 years	137	110	247	56%

Notes: Internal=requests from IRRI staff; External=requests from outside IRRI; % Internal= Internal/Total requests. Data source: IRRI Genetic Resources Center.

[3] Source: World Rice Statistics, IRRI (USDA). ricestat.irri.org

Table 3. Ten countries with the most requests from 2012 to 2018

Rank	Country	Region	Number of requests		Number of accessions	
1	Philippines*	Asia	416		8,508	
2	China	Asia	91		18,301	
3	India	Asia	83		8,549	
4	United States	Americas	65		3,687	
5	United Kingdom	Europe	47		947	
6	Japan	Asia	35		2,158	
7	Netherlands	Europe	31		615	
8	Korea, Rep.	Asia	23		2,689	
9	Bangladesh	Asia	19		748	
10	Germany	Europe	18		1,257	
Sub-total, top 10 external			828	77%	47,459	61%
Others, external			245	23%	30,180	39%
Total external			1,073	49%	77,369	34%
Total internal+			1,101	51%	152,497	66%
Grand total			**2,174**		**230,136**	

Notes: *Excludes internal distribution to IRRI's breeding and research programs. + Internal distribution to IRRI's breeding and research programs. Data source: IRRI Genetic Resources Center

b) What kind of germplasm is requested?

The IRRI genebank conserves different germplasm types to serve different research and breeding objectives. Demand for advanced breeding materials and genetic stocks implies an active breeding program. Landraces and wild relatives are often used for resistance traits as well as for basic research. According to the data in Genesys, 37% of accessions conserved at IRRI are landraces, 9% are breeding or research materials and 8% are genetic stock (Figure 3).

User survey

The 2019 user survey confirms that most accessions distributed in the past 7 years were landraces or traditional cultivars (62%), breeding or research materials (41%), advanced or improved cultivars (29%) and wild species (27%) (Figure 4). Genetic stocks were also requested by around 22% of the respondents. Because most respondents requested germplasm samples multiple times and each sample could be intended for multiple purposes, the percentages across purposes sometimes totaled more than 100%. These data confirm that the IRRI collection is an important source of traditional rice cultivars and landraces.

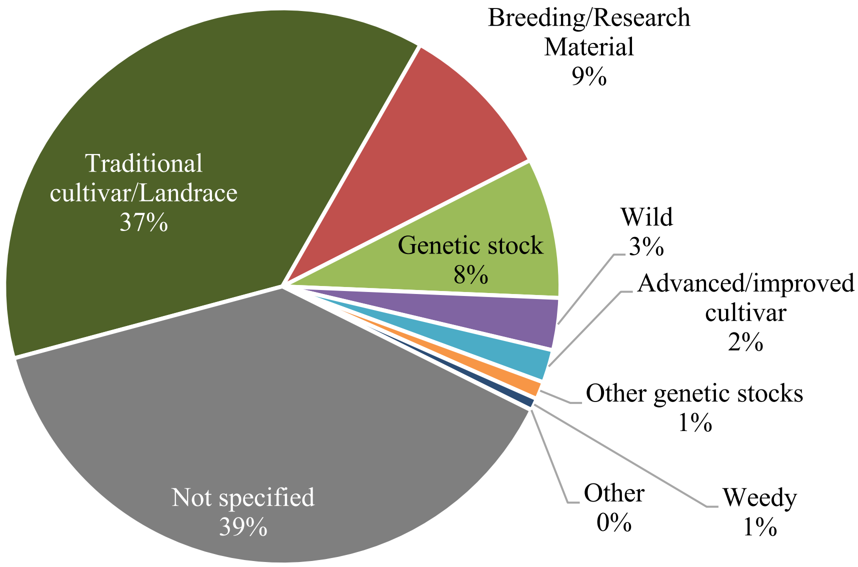

Figure 3. Types of germplasm materials in the IRRI rice collection
Notes: % of total accessions. Total accessions in Genesy=132,141
Data source: Genesys (https://www.genesys-pgr.org/a/overview/v2dkL7D17ER)

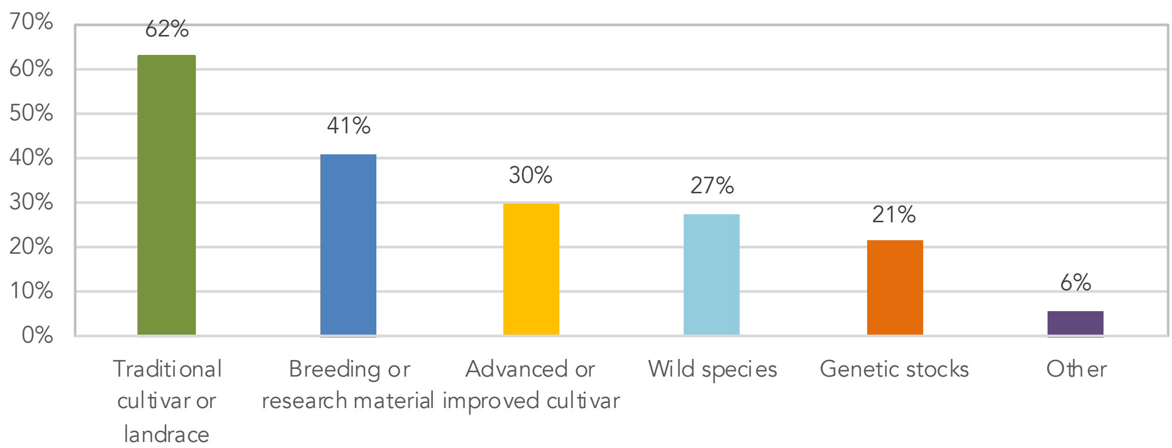

Figure 4. Types of germplasm materials received from IRRI in the past 7 years
Data source: IRRI 2019 user survey. Y-axis unit: % of respondents

c) Why is germplasm requested

(i) Purpose of request

The IRRI genebank distributes different rice genetic materials for different purposes and asks requestors to specify their intended purpose in a request form. Providing rice genetic materials for basic research and evaluation for traits are important functions of the genebank. IRRI identifies ten purposes for requesting germplasm in the request form, as follows:

1 = Research
2 = Crop Improvement
3 = Evaluation
4 = Characterization
5 = Multiplication/Rejuvenation
6 = Other purposes
7 = Restoration
8 = Rejuvenation with characterization
9 = For further distribution
10 = Direct use by farmers without SMTA

Figure 5 illustrates the intended uses of germplasm requests, as indicated in the request forms. On average, two-thirds of requests for rice germplasm were intended for research (51%) and evaluation (25%). However, it is important to differentiate between the total number of requests and the total number of samples sent for various purposes. The 1995 user survey confirms this delineation (Figure 6). More requests were made for research, but more germplasm samples were needed for evaluation purpose. Both activities are indicative of active rice improvement programs worldwide.

User survey

Survey respondents confirmed the usefulness of IRRI germplasm for research, breeding, characterization, and evaluation. About 83% of respondents found the germplasm to be moderately or extremely useful for their research and at least 13% of samples requested were still being evaluated at the time of the survey (Figure 7). Rice germplasm received from IRRI is less frequently used for direct planting or educational purposes.

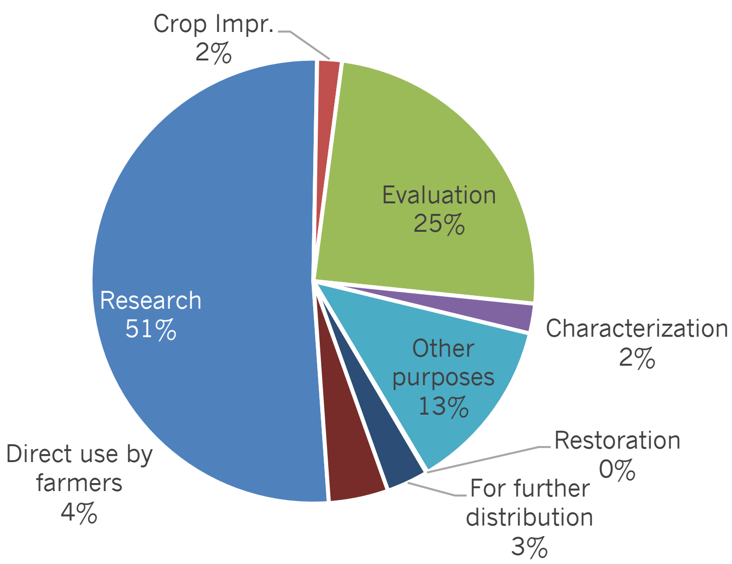

Figure 5. Intended purpose for requesting germplasm, average 2012 to 2018 (% from total requests)
Data source: IRRI Genetic Resources Center

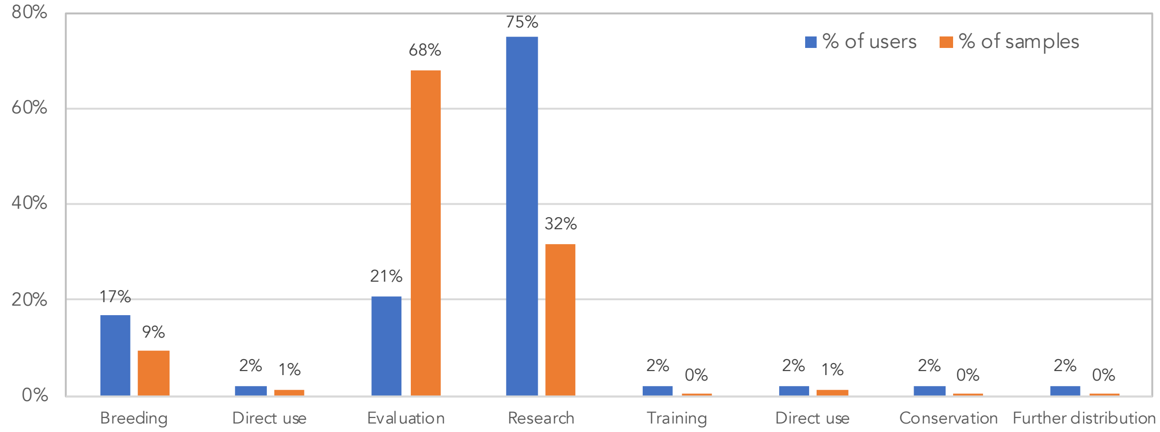

Figure 6. Intended purpose for requesting germplasm from the 1995 user survey, % of users and % of germplasm samples used
Note: Total exceeds 100% to allow for multiple uses. Data source: Loresto et al. (2000)

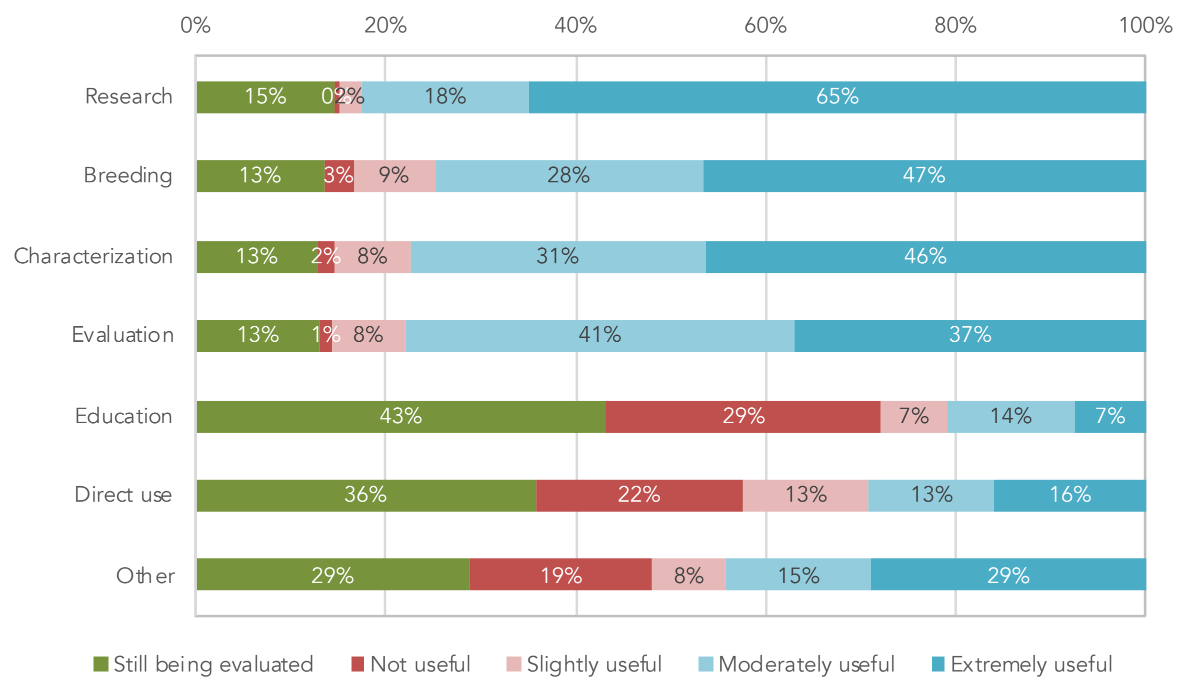

Figure 7. Usefulness of the IRRI genebank materials received
Data source: IRRI 2019 user survey. Y-axis unit=% of respondents

(ii) Traits sought

The types of traits sought by the recipients provide insight into demand for germplasm held at genebanks. IRRI identifies eight traits in its current germplasm request form, as follows:

1 = Morpho-agronomic
2 = Environmental and abiotic stresses
3 = Rice Tungro Disease (RTD)
5 = Rice Ragged Stunt virus (RRSV)
6 = Bacterial Blight (BB)
7 = Other diseases
8 = Insect pests

Out of 368 requests that specified desired traits in the request form, 55% of requestors sought accessions with tolerance to environmental stresses, followed by tolerance to diseases (29%) other than RTD, RRSV, and BB (Figure 8). The IRRI 1995 user survey had a higher proportion of respondents seeking certain morpho-agronomic traits but most of samples were used to evaluate for tolerance to environmental stresses, such as shade, cold, drought, and salinity (Figure 9). Tolerance to RRSV was also important; RRSV, carried by the brown planthopper, causes ragged stunt disease in rice and has resulted in severe yield losses in several tropical Asian countries.

User survey

Study respondents were asked to classify the traits they were looking for and the relevance of the rice germplasm received for their purposes. Several traits were identified: tolerance to abiotic stresses, tolerance or resistance to biotic stresses, yield, crop quality/nutrition or 'other'. Abiotic stresses include heat, flooding and salinity. Biotic stresses comprise pests and diseases that negatively affect plants' health and growth. Yield is the level of productivity per area planted. Quality refers to a particular characteristic of the harvested crop, including nutrient content.

Seventy-four percent of respondents confirmed they used IRRI rice germplasm for improving yield (49% stating yield was extremely relevant and 25% moderately relevant). In terms of the number of samples requested, the majority were intended for improvements in nutrition and/or quality (77% of samples). Other important traits were resistance to drought (67% of respondents and 72% of samples) and salinity (62% of respondents and 76% of samples). The total percentage of respondents and samples exceed 100% because germplasm can be evaluated for multiple traits.

The findings are slightly different from the US NPGS survey, which reported a lower proportion of germplasm samples intended for improving yield (12%), while biotic resistance or tolerance was the most frequently cited desirable traits (37% of samples) (Smale and Day-Rubenstein 2002). Tolerance to insects, other pests and diseases were also more important to respondents of the 1995 IRRI survey than those of our 2019 survey.

More respondents of our survey used IRRI materials to improve rice quality, nutrition and tolerance to drought and salinity. This result indicates a shift of interest from biotic to abiotic stress tolerance in the past two decades. Global discourse on future climate change scenarios, the United Nation's Sustainable Development Goals, and the impact of increased occurrences of extreme weather events have likely contributed to this shift.

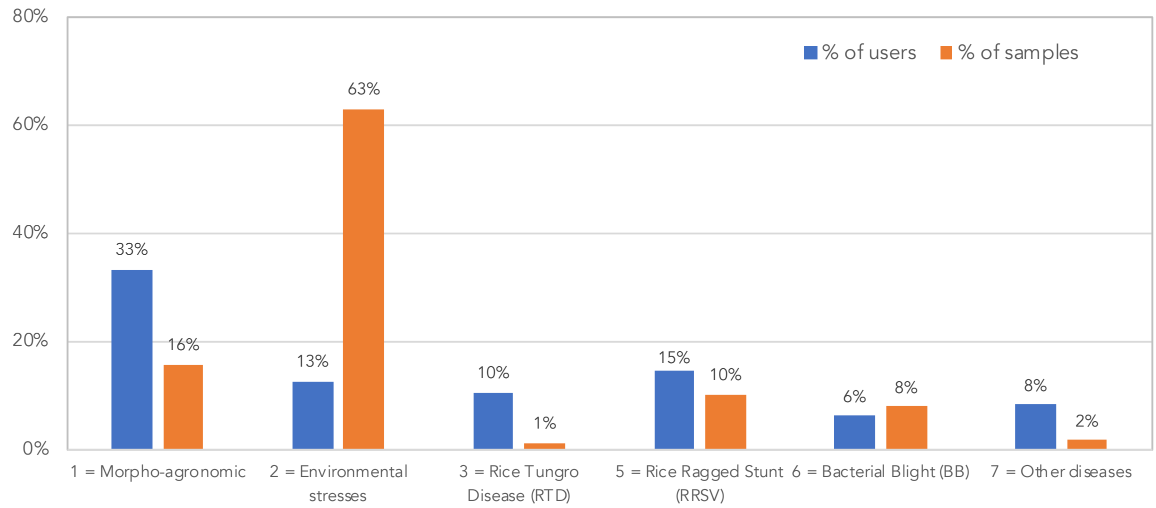

Figure 8. Traits sought (IRRI 1995 user survey), % of users and % of germplasm samples used
Note: Total exceeds 100% to allow for multiple uses
Data source: Loresto et al. (2000)

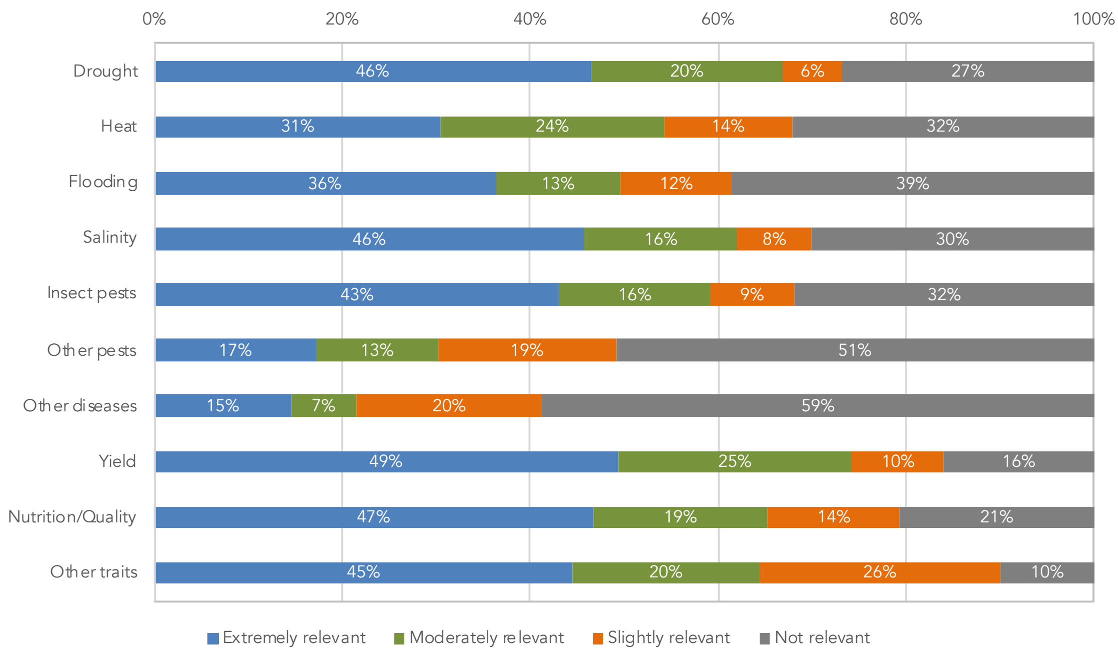

Figure 9. Traits sought and relevance to needs
Data source: IRRI 2019 user survey. Y-axis unit=% of respondents.

d) Actual use of germplasm samples

The long-term nature of agricultural research and crop breeding suggests that we almost certainly underestimated the actual use and value of IRRI germplasm materials in the current survey. First, recent users were most likely to respond, meaning that we are unable to capture some future uses of the germplasm. Indeed, some respondents were still evaluating the germplasm materials received from IRRI. Received materials can be useful but only incorporated into research activities many years later. Nevertheless, the survey confirmed the usefulness of the germplasm materials to respondents within the 7-year period covered. Figure 10 represents the usefulness of germplasm based on the year of most recent request. The total percentage of respondents and samples exceed 100% because germplasm can be used for multiple purposes.

Overall, 83% of respondents confirmed the usefulness of IRRI rice germplasm for their research (65% found the germplasm extremely useful and 18% moderately useful). In terms of the number of samples received, 91% of requested IRRI materials were confirmed to be useful for research (80% extremely useful and 11% moderately useful). The survey responses revealed similarly high rates of usefulness for characterization (77% of respondents and 87% of samples), evaluation (78% of respondents and 84% of samples) and breeding (75% of respondents and 76% of samples). Only five respondents indicated that the IRRI samples received were not useful at all for research, breeding, characterization and/or evaluation.

We also validated the usefulness of received germplasm by asking respondents to confirm key outputs that resulted from the IRRI samples they received (Figure 11). While 46% of the respondents were still evaluating the seeds for other possible uses, 95 respondents (43%) reported that they had published scientific publications using the IRRI materials as a basis for their research. Approximately 35% of the respondents had generated characterization and evaluation data, 23% produced genetic markers and another 35% identified useful traits for potential incorporation in crop improvement programs. Additionally, 19% of respondents also recognized the importance of expanded germplasm options from the IRRI genebank as a key output.

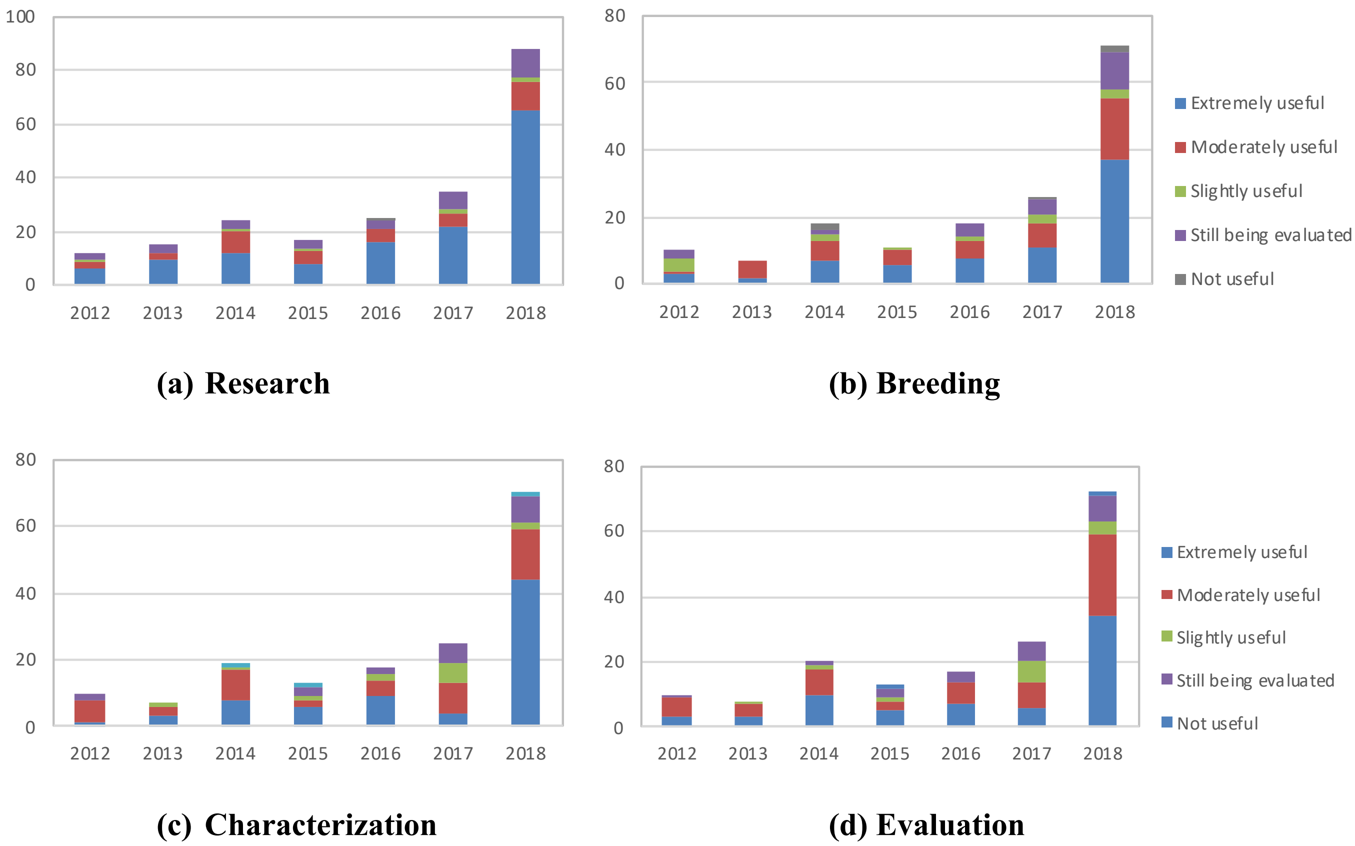

Figure 10. Usefulness of IRRI germplasm by purpose and year of most recent request
Data source: IRRI 2019 user survey. Y-axis unit=number of respondents; X-axis=year of most recent request.

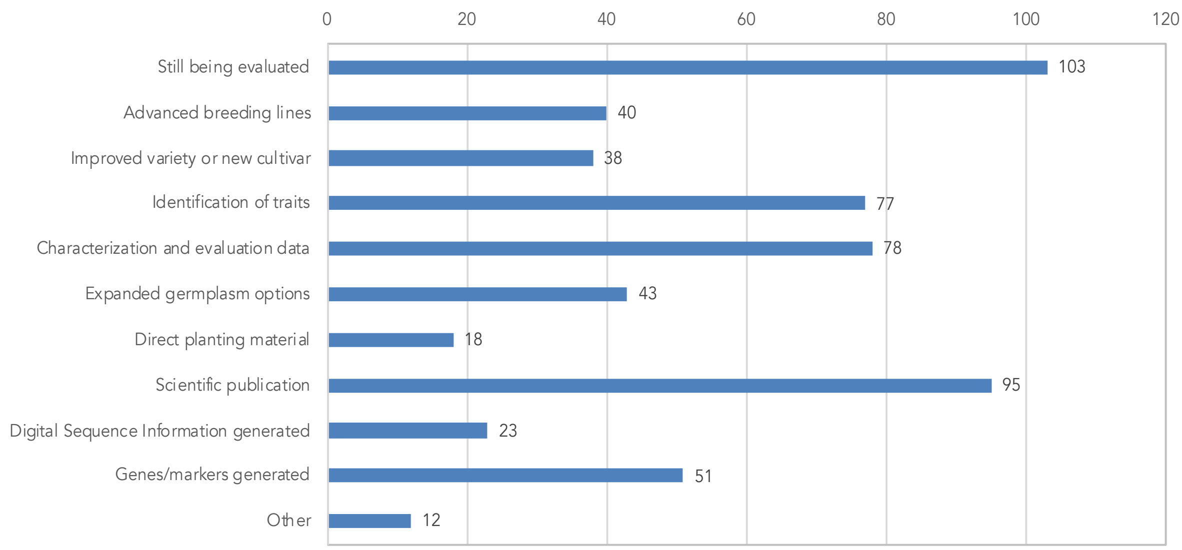

Figure 11. Key outputs from the germplasm received from IRRI
Data source: IRRI 2019 user survey. Y-axis unit=number of respondents.

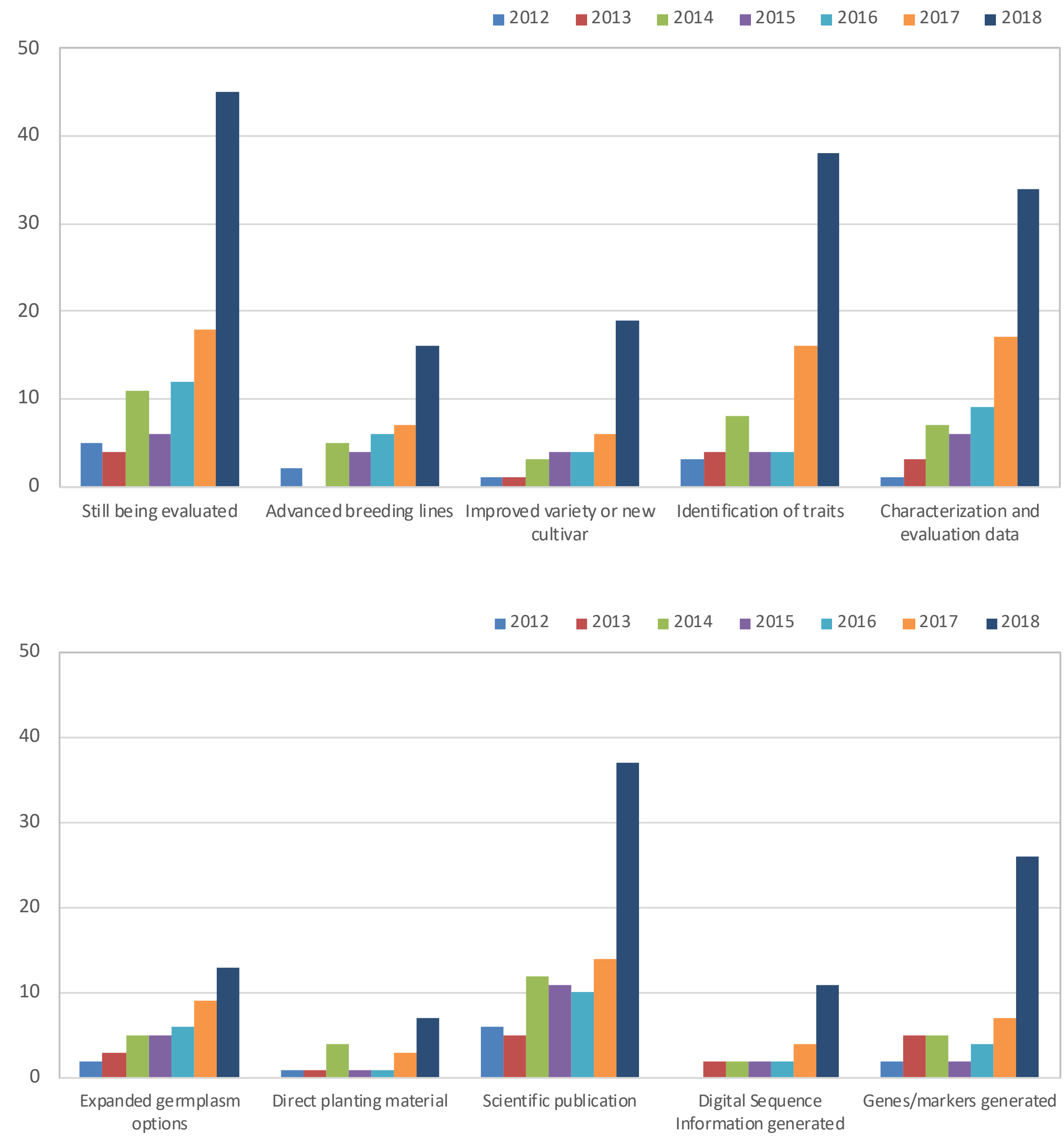

Figure 12. Key outputs from the germplasm received from IRRI, by year of most recent request
Data source: IRRI 2019 user survey. Y-axis unit=number of respondents.

e) Future demand

About half of the respondents (52%) expected an increase in their demand for IRRI rice germplasm in the next 10 years (Figure 13). A third (34%) anticipated about the same level of demand and 4% expected a decrease in their demand for IRRI materials. When asked about the types of germplasm they are likely to request, respondents indicated that while there is increased interest in wild species and genetic stocks, most will continue to source traditional cultivars or landraces from IRRI (Figure 14). Respondents anticipated greater demand for specific traits such as drought tolerance and resistance to rice plant diseases in the next 10 years (Figure 15).

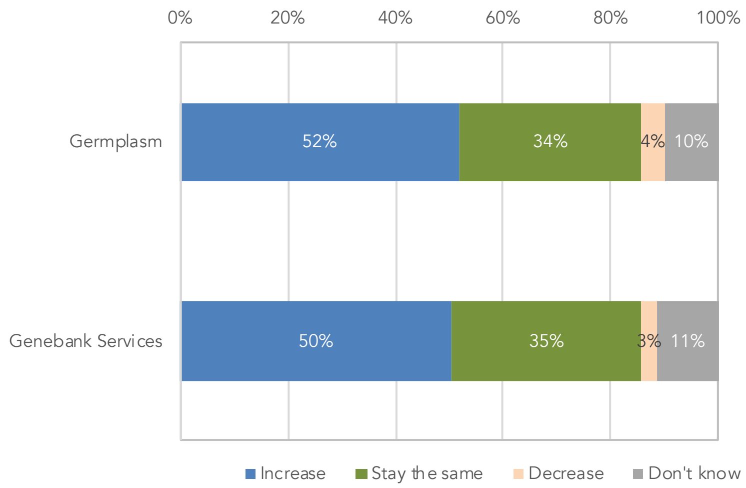

Figure 13. Changes in demand for IRRI germplasm and genebank services in the next 10 years
Data source: IRRI 2019 user survey. Y-axis unit=% of respondents.

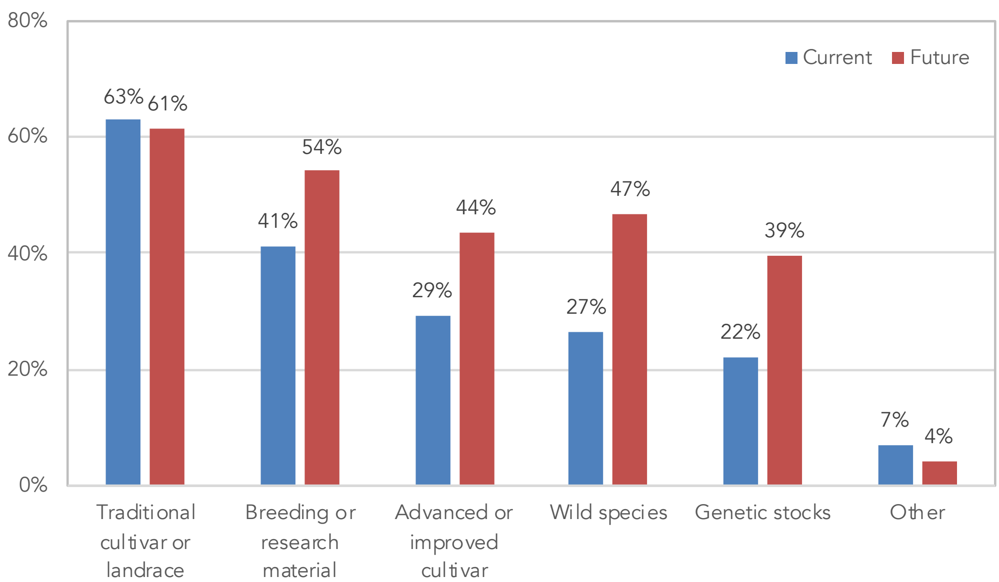

Figure 14. Current and future demand for IRRI germplasm by germplasm type
Data source: IRRI 2019 user survey. Y-axis unit=% of respondents.

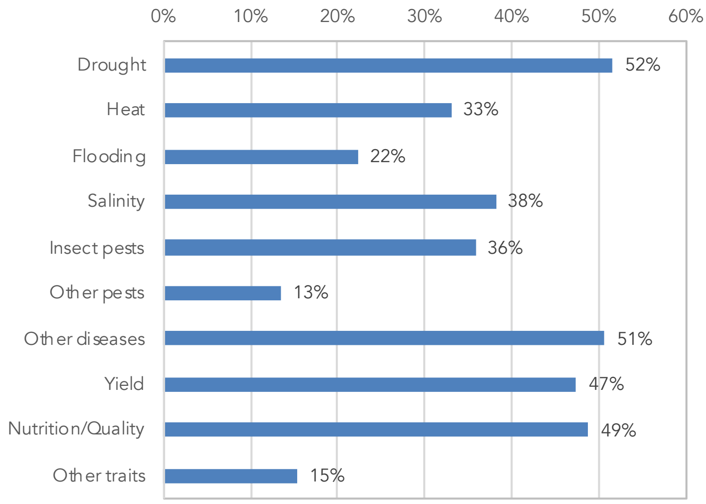

Figure 15. Traits that are relevant for future work
Data source: IRRI 2019 user survey. Y-axis unit=% of respondents

f) Alternate germplasm sources

Some respondents indicated that they had multiple sources of rice germplasm. Approximately 36% of respondents sourced rice genetic materials from IRRI exclusively and another 32% sourced exclusively from national genebanks (Figure 16). We also examined germplasm sources according to the institutional affiliation of the respondent; the results confirmed that different categories of respondents had multiple germplasm sources (Figure 17). However, in terms the total number of samples requested, respondents employed at CGIAR centers sourced more than 90% of rice seeds from the IRRI genebank (Figure 18). Respondents from universities and other learning institutions and private companies also received more seed samples from IRRI than from other sources.

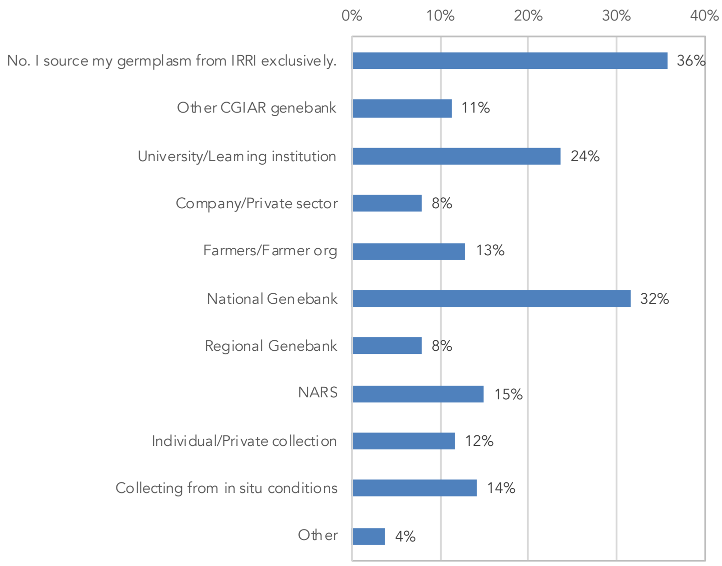

Figure 16. Germplasm sources
Data source: IRRI 2019 user survey. Y-axis unit=% of respondents.

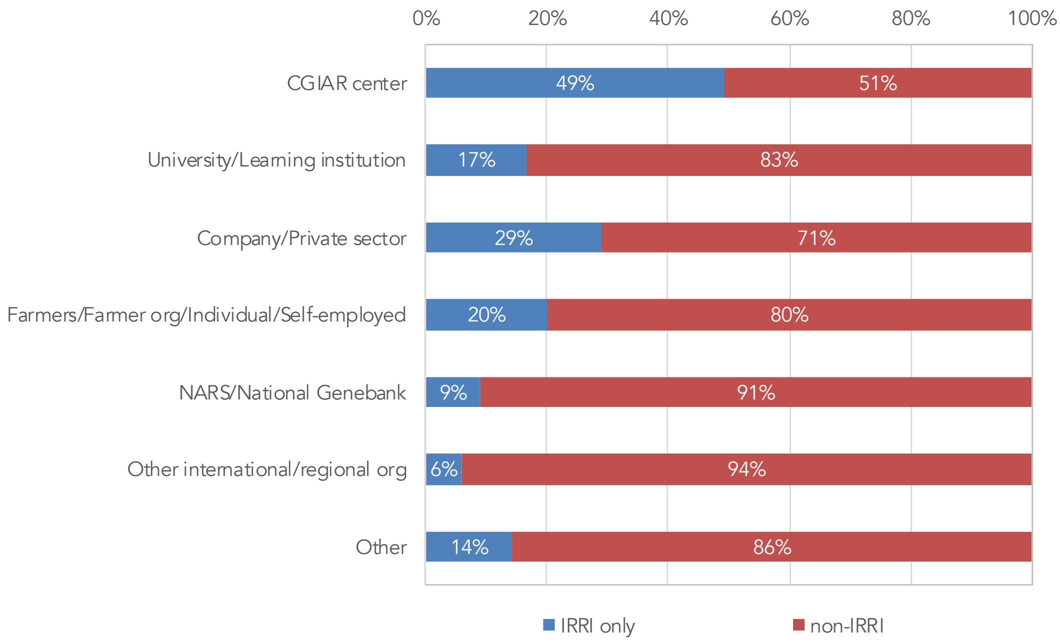

Figure 17. Sources of rice germplasm by institutional affiliation of the respondent
Data source: IRRI 2019 user survey. Y-axis unit=% of respondents

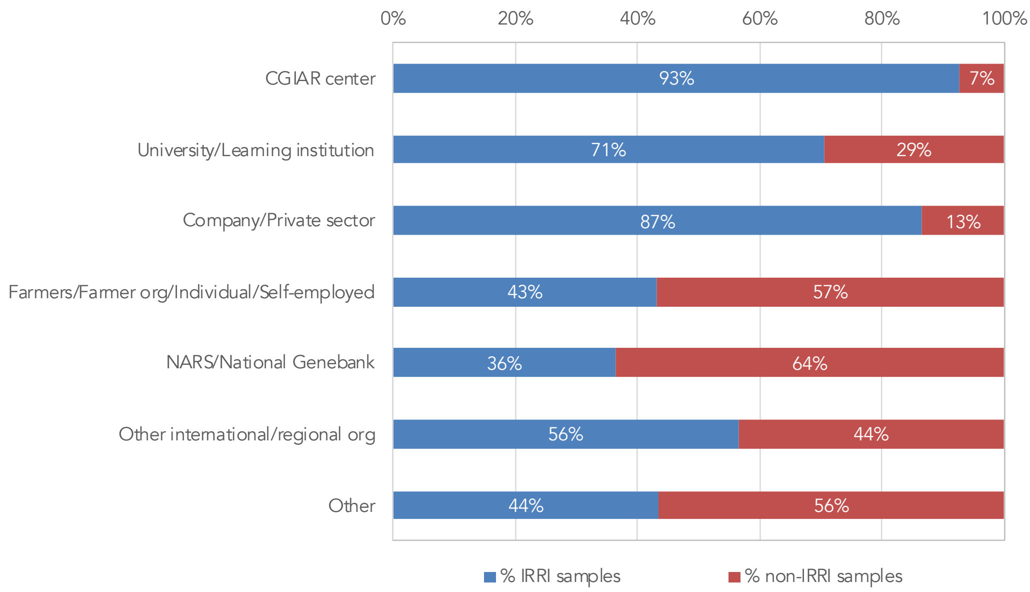

Figure 18. Sources of rice germplasm by institutional affiliation of the respondent, % IRRI versus % non-IRRI samples
Data source: IRRI 2019 user survey. Y-axis unit=% of germplasm samples requested

4. Conclusion

Taken together, the findings demonstrate the crucial role of IRRI's international rice genebank as a key germplasm source for global rice research and breeding. Recipients of materials from the genebank confirmed the usefulness of the materials for many purposes. Public sector organizations and the scientific community, particularly in developing countries, benefit from the availability of rice genetic resources now are expected to continue benefiting in the future. Indeed, the demand for germplasm and genebank services is expected to increase because of climate change and global development goals to maintain or increase crop diversity. Trends in the use of rice germplasm indicate the importance of maintaining collections that include wild species, landraces and genetic stock, as well as research and breeding accessions for developing drought tolerance and disease resistance. Obtaining improved characterization and evaluation data about the collection must be a priority for improving the use of rice germplasm from IRRI.

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