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Global demand for rice genetic resources

Nelissa Jamora[1*] and Venuprasad Ramaiah[2]

Abstract

Background: The International Rice Research Institute (IRRI) holds in trust the world's largest collection of rice diversity, with more than 130,000 accessions of cultivated rice and wild species. Between 2012 and 2018, a total of 2174 requests for rice germplasm were received from more than 1000 unique requestors. We documented and analyzed how genebank users made use of germplasm from IRRI. As we address food and nutrition security challenges in a changing context, we are motivated by the need to enhance the conservation, management, and use of rice genetic resources.

Methods: We examined the patterns of use of the IRRI genebank using distribution data and analyzed the results from a survey of germplasm recipients. The 2019 IRRI genebank user survey is the most recent attempt to obtain structured feedback from genebank end-users in multiple countries on their use of rice germplasm since 1995. We received 244 responses (a 35% response rate) out of the complete list of 694 respondents with valid email addresses. We also tested the relationship between the availability of germplasm information, proxied by the passport data completeness index (PDCI), and the demand for rice accessions, measured by the number of requests for each unique accession using a Negative Binomial regression model. We hypothesized that materials that are better documented are more frequently requested by users because they offer more useful information for targeted research and breeding.

Results: Between 2012 and 2018, requests for germplasm from outside IRRI were received from 63 countries in all regions of the world, mostly from Asia. IRRI distributed germplasm externally to requestors from universities (32%), national research programs (14%), private companies (9%), and individuals, including farmers (24%) as well as other CGIAR centers (3%). The traits sought most often were tolerances 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. The analytical model confirmed the significant positive relationship between PDCI values and the demand for those accessions. The results indicated that improving the availability of information at the accession level will enhance the use of those materials. To the best of our knowledge, this study is the first to show the empirical link between documentation and use of germplasm.

Conclusions: The findings demonstrate the crucial role of IRRI's genebank as a key germplasm source for global rice research and development, with important implications for the conservation and use of rice genetic diversity in the future. Public sector organizations and the scientific community in general benefit from the conservation and availability of rice genetic resources. We also show the importance of the availability of data on conserved accession to enhance their use. To sustain the benefits, continuous investment in genebanks is needed to allow them to adapt to changes in technology and agricultural context.

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Introduction

This study examined patterns of germplasm use for the largest rice diversity collection in the world, managed by the International Rice Genebank of the International Rice Research Institute (IRRI).[1] 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 (FAO 2021). Research, breeding, and other crop improvement efforts have focused on enhancing yield and addressing consumer preferences in quality and nutrition. As a result, global rice production has continued to increase over the last several decades. However, while productivity is still increasing overall, the rate of increase has been declining (Fig. 1). Long-term experiments at IRRI have confirmed yield stagnation due to several factors, including "soil-related factors and gradual depletion of key nutrients, a downward shift in nutrient response function, and changes in the climate" (Ladha et al. 2003). Hence, maintaining yield growth is crucial to meet future consumption because challenges continue to evolve with climate change and the emergence of new pests and pathogens in combination with a decrease in the land available for rice production.

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 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 132,000 accessions of cultivated rice and wild species. There are 24 species of rice belonging to the genus *Oryza,* and two species are the most important for global production: (1) *O. sativa*, cultivated worldwide, and (2) *O. glaberrima*, grown mainly in parts of Africa (Jacquemin et al. 2013). These genetic resources are the foundation for rice improvement, which is necessary to sustain growth and improve quality in food production.

Most accessions in the rice genebank are maintained in an active collection at 2–4 °C and − 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 safely

duplicated both in the Svalbard Global Seed Vault in Norway and in the United States National Plant Germplasm System (US NPGS). The ten countries providing the most germplasm to IRRI are presented in Table 1. The countries in the list are all in Asia, highlighting the importance of this region as a center of rice domestication and diversity.

Plant genetic resources (as seeds or other 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. There is ample evidence that the continuous release of improved varieties by public 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 best documented achievements in international agricultural research and development assistance (Herdt and Capule 1983; Khush 1984; Pingali and Hossain 1998).

Evenson and Gollin (1997) 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 US\$ 325 million. A study by Brennan and Malabayabas (2011) demonstrated that there had 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 US\$ 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 contributed 16.4% of genetic materials to rice varieties developed in China between 1982 and 2011. A recent study by Villanueva

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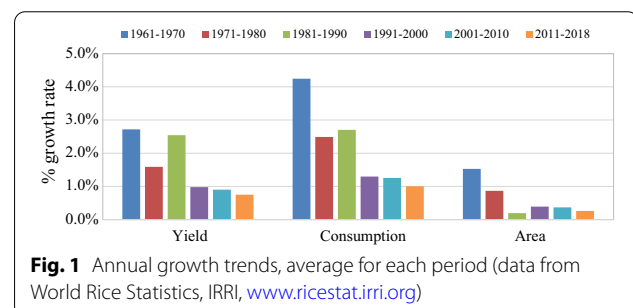
[1] We use the terms "International Rice Genebank" and "IRRI genebank" interchangeably throughout this paper. The International Rice Genebank is in the T.T. Chang Genetic Resources Center of IRRI.

Fig. 1 Annual growth trends, average for each period (data from World Rice Statistics, IRRI, www.ricestat.irri.org)

Table 1 Origin of rice accessions conserved at IRRI (data from Genesys; https://www.genesys-pgr.org/)

Country	Number of accessions
India	17,584
Laos	15,668
Indonesia	10,204
Philippines*	9486
China	9106
Bangladesh	7494
Thailand	6319
Cambodia	4958
Vietnam	4777
Malaysia	4683
Other	39,370
Not specified	2491
Total	132,140

* Includes materials sourced from IRRI research and breeding programs

et al. (2020) estimated the contribution of IRRI's genetic resources to varietal improvement and rice productivity of farmers in eastern India. The authors demonstrated that 45–77% of the genetic composition of improved rice varieties was derived from the genes of IRRI genebank accessions. Further, a 10% increase in the genetic contribution of IRRI's materials to an improved rice variety was associated with a yield increase of 27%.

Despite these high returns, questions about the value of germplasm and levels of genebank use continue. Wright (1997) identified four fundamental information gaps about genebanks: (1) who uses genebanks, (2) why users want germplasm, (3) what kind of germplasm is used, and (4) 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 addressed 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 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 justify why genebanks must be supported in the long term.

How are seeds distributed from the IRRI genebank?
IRRI[2] provides small quantities of rice germplasm from its International Rice Genebank in the Philippines to any individual or organization anywhere in the world for the purposes of research, breeding, or training for food and agriculture, under the Multi-Lateral System (MLS) of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA). IRRI's Standard Operating Procedure (SOP) for the distribution of rice germplasm lists 15 steps from request initiation to completion (IRRI 2021):

1. Initiation
2. Acknowledgements
3. Checking the seed availability
4. Checking of requestor's provided information and documents
5. Checking for possible charges
6. Sending short-list of accessions
7. Creating the request record
8. Generation of request number
9. Generating the distribution list for seed withdrawal
10. Seed withdrawal
11. Submission to Seed Health Unit (SHU)
12. SHU seed testing and document review
13. Preparation of shipment
14. Post consignment
15. Completion

The distribution procedure is initiated when the genebank receives a germplasm request submitted by a requestor via the online ordering system of Genesys (https://www.genesys-pgr.org/) or GRIN-Global (https://gringlobal.irri.org/gringlobal/search).

If a request is received via email, letter, oral communication, or fax, instructions on how to request via Genesys or GRIN-Global are sent to the requestor. The requestor can also request support from genebank staff. A list of accessions is provided to the requestor based on the conditions indicated. The requestor then selects from the list and submits a request through Genesys or GRIN-Global. Requestors are encouraged to explore the search data on characterization and evaluation which are updated regularly.

All samples distributed are shared with "all available passport data and, subject to applicable law, any other associated available non-confidential descriptive information" as stipulated in the SMTA (FAO 2015).

The distribution procedure is completed and finalized when: (1) the genebank receives an official confirmation by the requestor that the shipment has been received, (2) all pertinent information has been entered into the genebank's information management system, and (3) the SMTA has been reported to the Governing Body of the ITPGRFA.

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[2] For details, visit https://www.irri.org/rice-seeds

Methods

Data presented here were compiled from three sources: (1) a summary of germplasm distributions from 2012 to 2018 provided by the IRRI Genetic Resources Center, (2) data from the IRRI genebank user survey carried out in 2019, and (3) accession-level data provided by the IRRI genebank to the Genesys data platform (https://www.genesys-pgr.org/, accessed 01 September 2019).

We implemented regression models to examine the relationship between the demand for specific accessions, measured by the number of requests for each unique accession, and the availability of germplasm data for each accession, measured by the passport data completeness index (PDCI), on the set of rice accessions that were requested at least once between 2012 and 2018. PDCI quantifies the level of completeness of passport data, taking into account the presence or absence of data points in the documentation of a genebank accession (van Hintum et al. 2011).

Passport data is the basic information associated with each accession. The availability of passport data is crucial during the request process: both for the user requesting germplasm and for genebank staff who responds to the request and other inquiries. An accession could be more likely recommended by the genebank staff if the information on that accession is available. Both the requestors and genebank staff could access Genesys and GRIMS and search the germplasm inventory using relevant data filters. Passport data is also shared with the requestor as noted in the SMTA and as agreed by the IRRI genebank with each user.

The values for PDCI could range from 0 to 10. The calculations and applicability of PDCI have been demonstrated using over 1 million records from the European Search Catalogue for Plant Genetic Resources (EURISCO) (van Hintum et al. 2011). The international genebanks of the CGIAR have also started monitoring the quality of germplasm data using PDCI since 2017 (CGIAR Genebank Platform Annual Report 2020). We tested the hypotheses that an increase in the PDCI is related to higher demand for accessions.

IRRI genebank user survey

The first user survey implemented by the IRRI genebank was conducted in 1995–27 years ago. In that pioneering work, Loresto et al. (2000) documented (1) how requested germplasm was used, (2) the traits identified and used in breeding or crop improvement, (3) any 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 from 1989 to 1994 and received responses from 48. The 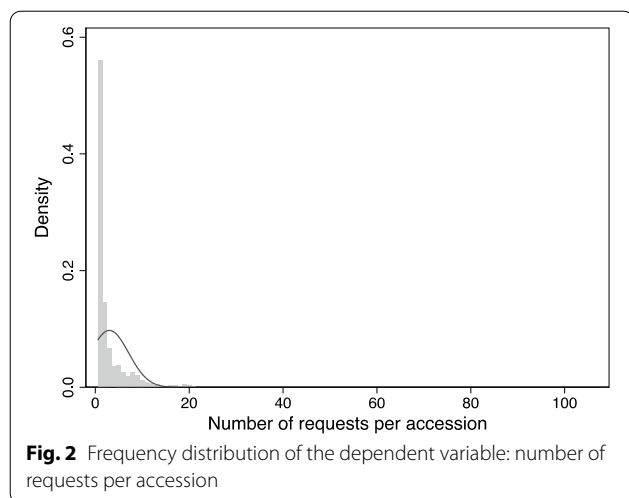results confirmed the importance of the IRRI rice collection in evaluating tolerance to biotic and abiotic stresses. To our knowledge, no follow-up study has been conducted since.

The 2019 IRRI genebank user survey, implemented between April and May 2019, is the most recent attempt to obtain structured feedback from genebank end-users in multiple countries on their use of rice germplasm since 1995. A genebank user is defined as either an individual or entity that requests and/or receives genetic material from the IRRI genebank. The survey was part of a broader initiative by the CGIAR Genebank Platform (www.genebanks.org) to evaluate the performance of the international genebanks. We developed a questionnaire based on the questions posed by Wright (1997), which allowed for comparison with the US NPGS study by Smale and Day-Rubenstein (2002).[3]

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 Bernal-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 online 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 the IRRI Genetic Resources Center. The first survey link was sent to the complete list of 694 respondents with valid email addresses (out of 1005 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. The use of an online survey was appropriate, considering that 82% of germplasm requests in the previous four years were sent by email. We received 244 valid responses (a 35% response rate), and respondents took, on average, 11 min to complete the survey.

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[3] 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).

Fig. 2 Frequency distribution of the dependent variable: number of requests per accession

Analytical model

The Poisson regression model is suitable for analyzing count data, where the dependent variable takes the form of a non-negative integer (Greene 2003). The model was suitable for this study since the dependent variable was measured as the number of requests for each accession, a positive integer. We focused our analysis on the set of accessions that were requested. Only about 19% of unique accessions in the genebank (24,792 out of 132,1404 accessions) were requested during our study period. Hence, the estimates were conditional on being requested.

Count data can be analyzed using the Ordinary Least Squares (OLS) method, but this can yield biased results due to several reasons, including the inability of OLS to account for the zero truncated data, heteroskedasticity, and non-normality (Greene 2003). The histogram of the dependent variable, number of requests for each accession, indicated a possible violation of underlying assumptions. The majority of accessions were requested only once (56%) (Fig. 2).

The coefficient estimates of a Poisson model were interpreted as semi-elasticities, while the marginal effects were interpreted as the change in the number of requests when the explanatory variable changed by one unit. Our main explanatory variable of interest was the PDCI. We controlled for other accession-level factors, such as (1) number of years in storage, (2) Multi-lateral System (MLS) status, and (3) biological status. We controlled for the years of storage because accessions that were acquired earlier could be requested more because they have been available for a longer period of time. Accessions that were available in the MLS of the ITPGRFA were also assumed to be widely distributed across international borders because there are fewer restrictions in the exchange of these materials for research and breeding

purposes (FAO 2009). The biological status of accession could potentially affect the demand for certain materials.[4] Van Hintum et al. (2011) showed that for crop collections maintained in Europe, cultivars were best documented, whereas research materials exhibited the poorest data quality in the European Search Catalogue for Plant Genetic Resources.

An important assumption for the use of Poisson models is equidispersion, meaning the conditional variance equals the conditional mean. If the variance value is greater than the mean value, it is called overdispersion. The Negative Binomial regression model deals with this problem by allowing the variance to exceed the mean (Greene 2003). We tested for overdispersion and presented the results for the OLS, Poisson, and Negative Binomial models. We obtained robust standard errors for the parameter estimates, as recommended by Cameron and Trivedi (2005), to control for mild violation of underlying assumptions.

Results

Here, we have organized the results from the user survey and the analysis of germplasm distribution starting with the four fundamental information gaps about genebanks posited by Wright (1997): (1) who uses genebanks, (2) why users want germplasm, (3) what kind of germplasm is used, and (4) what characteristics users are seeking. We added a fifth information gap following Loresto et al. (2000): contributions made to rice science. In addition, we present responses of the 2019 IRRI genebank user survey respondents to questions regarding their likely future demand for germplasm and alternate sources of germplasm. These questions are relevant for the management of crop collections at IRRI and elsewhere. Finally, we present the results from the regression analysis to establish the importance of germplasm data in promoting the use of genetic resources.

Who uses genebanks?

Between 2012 and 2018, there were a total of 2174 requests for rice germplasm from 1005 unique requestors, with an average of 247 annual requests in the last three years (Table 2). Most users (71%) requested only once in the past seven years, but some made multiple requests, ranging from 2 (14%) to more than 20 (0.9%). Approximately half of the requests came from IRRI

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[4] The categories for the biological status are 100 wild, 200 weedy, 300 traditional cultivar/landrace, 400 breeding/research material, 420 genetic stock, 500 advance or improved cultivars, or 999 others, based on the Multi-Crop Passport Descriptors (MCPD). The MCPD is a widely used international standard to facilitate germplasm passport information exchange (see https://www.genesys-pgr.org/descriptorlists/0cd31350-234b-4ebf-80bc-fc65f14f7541).

Table 2 Number and breakdown of germplasm requests from 2012 to 2018 (data from IRRI Genetic Resources Center)

Year	Internal requests from IRRI staff	External requests from outside IRRI	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	**1101**	**1073**	**2174**	**51%**
Annual average, 2012–2018	157	153	311	51%

internal users, which confirmed the integrative service provided by the genebank to IRRI's research and breeding platforms.

Externally, IRRI distributed germplasm to requestors from universities (32%), national research 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, mostly from Asia (71%), followed by Europe (16%). The top ten countries with the most requests for rice germplasm are presented in Table 3. After the Philippines, 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 (World Rice Statistics, IRRI, www.ricestat.irri.org).

While there were only 2174 requests, the total number of accessions requested between 2012 and 2018 was 230,136. This is because each requestor could request multiple number of accessions. On average, a request include 106 accessions, but the distribution was highly skewed. The mode was 1, and 81% of requests made between 2012 and 2018 include less than 100 accessions (Fig. 3).

Responses to the 2019 survey 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 was easier to get responses from recent users and demonstrating the importance of regularly seeking feedback.

Why do users want germplasm?

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:

1. Research
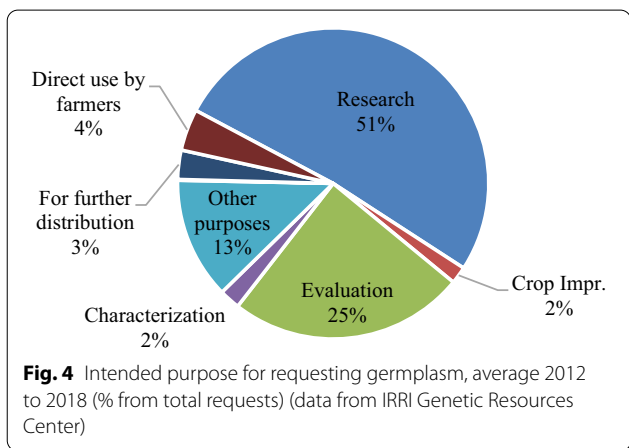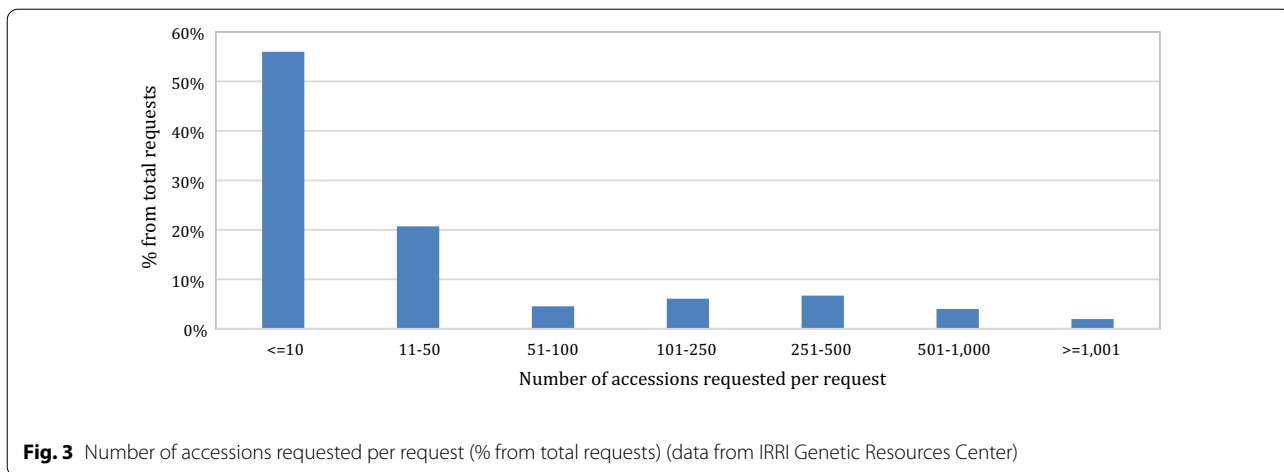2. Crop improvement
3. Evaluation
4. Characterization

Table 3 Top countries with the most requests from 2012 to 2018 (data from IRRI Genetic Resources Center)

Rank	Country	Region	Number of requests	Number of accessions
1	Philippines*	Asia	416	8508
2	China	Asia	91	18,301
3	India	Asia	83	8549
4	United States	Americas	65	3687
5	United Kingdom	Europe	47	947
6	Japan	Asia	35	2158
7	Netherlands	Europe	31	615
8	Korea, Rep	Asia	23	2689
9	Bangladesh	Asia	19	748
10	Germany	Europe	18	1257
Sub-total, top ten external			828	47,459
Others, external			245	30,180
Total external			1073	77,369
Total internal[+]			1101	152,497
Grand total			**2174**	**230,136**

*Excludes internal distribution to IRRI's breeding and research programs

[+] Internal distribution to IRRI's breeding and research programs

Fig. 3 Number of accessions requested per request (% from total requests) (data from IRRI Genetic Resources Center)

Fig. 4 Intended purpose for requesting germplasm, average 2012 to 2018 (% from total requests) (data from IRRI Genetic Resources Center)

5. Multiplication/rejuvenation
6. Other purposes
7. Restoration
8. Rejuvenation with characterization
9. For further distribution
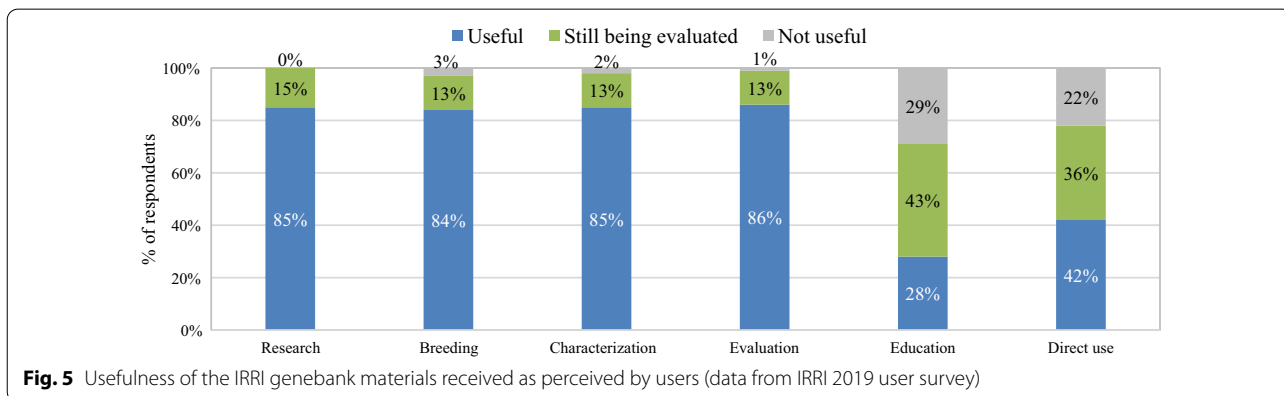10. Direct use by farmers

Figure 4 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%). Both activities are indicative of active rice improvement programs worldwide.
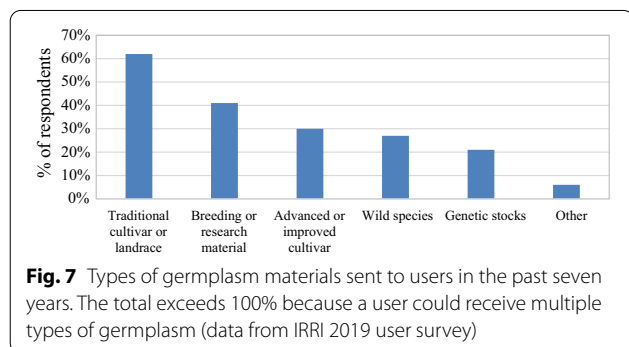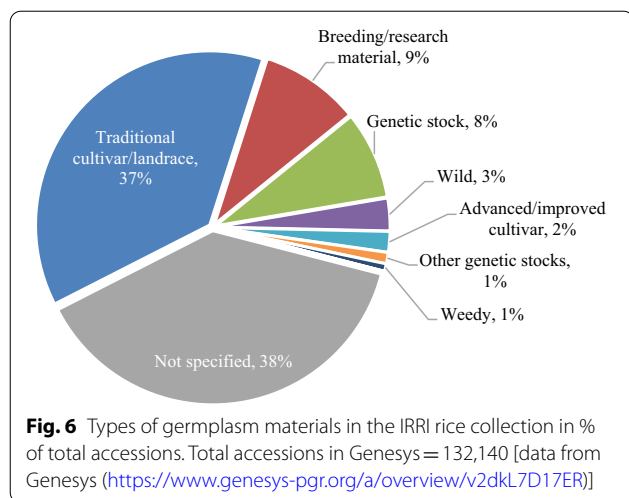
Survey respondents confirmed the usefulness of IRRI germplasm for various purposes. More than 80% of respondents found the germplasm to be useful for their research, breeding, characterization, and evaluation work, and some materials were still being evaluated at the time of the survey (Fig. 5). The 2019 survey confirmed that rice germplasm received from IRRI was less frequently used for direct planting or educational purposes.

What kind of germplasm is used?

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

Fig. 5 Usefulness of the IRRI genebank materials received as perceived by users (data from IRRI 2019 user survey)

Fig. 6 Types of germplasm materials in the IRRI rice collection in % of total accessions. Total accessions in Genesys = 132,140 [data from Genesys (https://www.genesys-pgr.org/a/overview/v2dkL7D17ER)]

Fig. 7 Types of germplasm materials sent to users in the past seven years. The total exceeds 100% because a user could receive multiple types of germplasm (data from IRRI 2019 user survey)

landraces, 9% are breeding or research materials, and 8% are genetic stock (Fig. 6).

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

What characteristics are users seeking?
The types of traits sought by the recipients provide insight into the demand for germplasm held at genebanks. IRRI identifies eight traits in its current germplasm request form:

1. Morpho-agronomic
2. Environmental and abiotic stresses
3. Rice Tungro Disease (RTD)
4. Rice Grassy Stunt Virus (RGSV)
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, RGSV, RRSV, and BB. The 1995 IRRI user survey had a higher proportion of respondents seeking certain morpho-agronomic traits, but most of the samples were used to evaluate for tolerance to environmental stresses, such as shade, cold, drought, and salinity. Tolerance to RRSV and RGSV was also important. RRSV and RGSV, transmitted between plants by insect vectors, have resulted in severe yield losses in several tropical Asian countries (Morales 2008).[5]

Survey respondents in 2019 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.
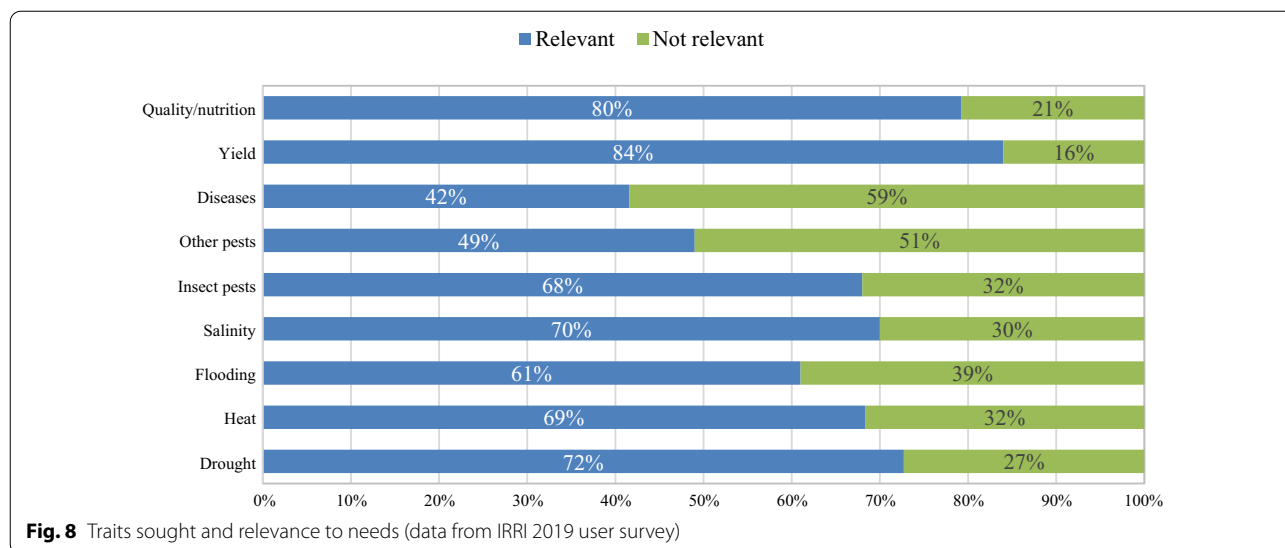
Eighty-four percent of respondents confirmed they used IRRI rice germplasm for improving yield (Fig. 8). Many germplasm samples were also intended for improvements in nutrition and/or quality. Other important traits were resistance to drought and salinity. The total percentage of respondents and samples exceeded 100% because germplasm are often evaluated for multiple traits.

The findings were 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 trait (Smale and Day-Rubenstein 2002). Tolerance to insects, other pests, and diseases was also more important to respondents from the 1995 IRRI survey than those from our 2019 survey.

More respondents to the 2019 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

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[5] See   http://www.knowledgebank.irri.org/training/fact-sheets/pest-management/diseases for information on rice diseases.

Fig. 8 Traits sought and relevance to needs (data from IRRI 2019 user survey)

decades. The global discourse on climate change, the United Nations Sustainable Development Goals, and the impact of increased occurrences of extreme weather events have likely contributed to this shift.

What are the contributions of the genebank to rice science?

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, the option value from ensuring the long-term availability of rice diversity was not taken into account. Second, recent users were most likely to respond, meaning that we were unable to capture some future uses of the germplasm. Indeed, some respondents were still evaluating the germplasm materials received from IRRI. Received materials are perceived useful when incorporated into research activities many years later. Nevertheless, the survey confirmed the usefulness of the germplasm to respondents within the seven years covered.

We validated the usefulness of germplasm by asking respondents to confirm key outputs that resulted from the IRRI samples they received (Table 4). While many respondents were still evaluating the seeds for other possible uses, 95 respondents reported that they had published scientific publications using the IRRI materials as a basis for their research. Tracing this output could be easier in the future with the adoption of germplasm-level Digital Object Identifiers (DOIs). DOIs provide a globally unique and permanent mechanism for identifying germplasm (Alercia et al. 2018). Ninety-six percent of IRRI's germplasm are registered with the Global Information

**Table 4** Key outputs from the germplasm received from IRRI (data from IRRI 2019 user survey)

	Key outputs	Number of responses
1	*The germplasm is still being evaluated*	103
2	Scientific publication	95
3	Characterization and evaluation data	78
4	Identification of traits	77
5	Genes/markers generated	51
6	Expanded germplasm options	43
7	Advanced breeding lines	40
8	Improved variety or new cultivar	38
9	Digital sequence information generated	23
10	Direct planting material	18

System on plant genetic resources for food and agriculture, which is managed by the ITPGRFA (CGIAR Genebank Platform 2020).

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.

What is the demand outlook for rice germplasm?

About half of the respondents (52%) expected an increase in their demand for IRRI rice germplasm in the next ten years (Fig. 9). A third (34%) anticipated about the same level of demand, and 4% expected a decrease in their
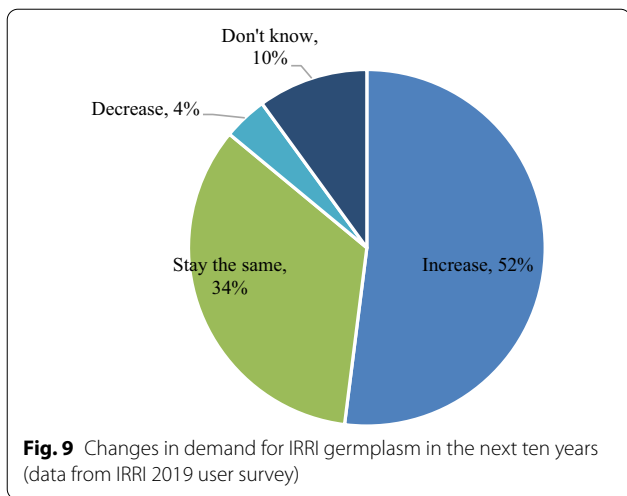
Fig. 9 Changes in demand for IRRI germplasm in the next ten years (data from IRRI 2019 user survey)

Table 5 Traits that are relevant for future work (data from IRRI 2019 user survey)

	Traits	Number of responses
1	Drought resistance	97
2	Nutrition/quality enhancing	94
3	Resistance to other diseases	92
4	Yield enhancing	91
5	Salinity tolerance	73
6	Resistance to insect pests	67
7	Heat tolerance	65
8	Tolerance to waterlogging	44
9	Resistance to other pests	28
10	Other traits	30

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 (Fig. 10). Respondents anticipated greater demand for specific traits, such as drought tolerance and resistance to rice plant diseases, in the next ten years (Table 5).

What are alternate sources of rice germplasm?

Many respondents sourced rice genetic materials from IRRI exclusively or also from national genebanks (Table 6). Some others indicated that they had multiple sources of rice germplasm. We examined germplasm sources according to the institutional affiliation of the

respondent and confirmed that respondents employed at CGIAR centers sourced more than 90% of rice seeds from the IRRI genebank (Fig. 11). Respondents from universities and other learning institutions also received more seed samples from IRRI than from other sources, confirming the important role of the IRRI genebank in rice research and breeding programs around the world.

Linking the demand for accessions to germplasm data

A total of 2174 requests for 24,792 unique accessions of rice germplasm were received from more than 1000 unique requestors between 2012 and 2018. Summary statistics for the variables included in the analysis are presented in Table 7. The first variable, the number of
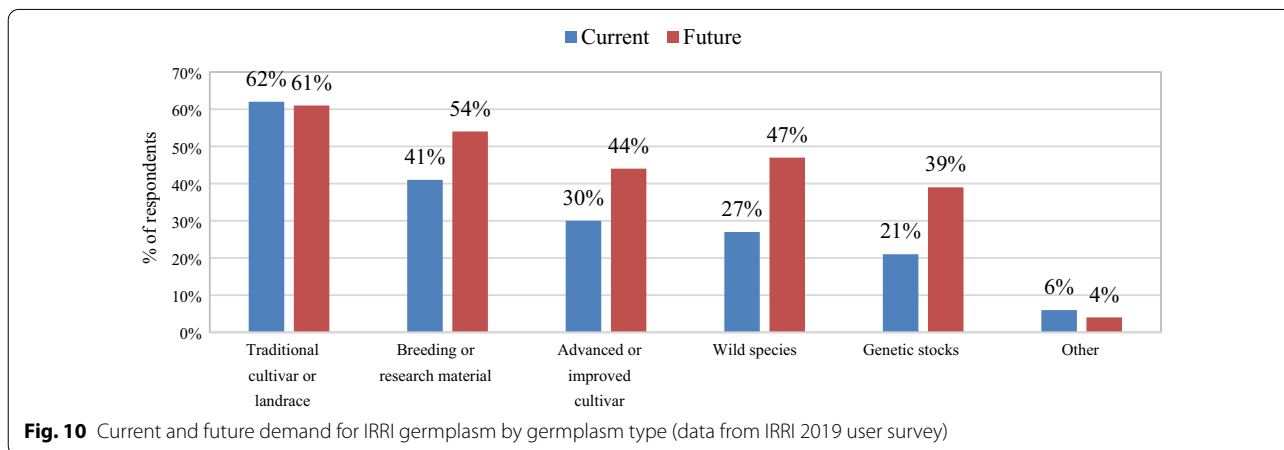
Fig. 10 Current and future demand for IRRI germplasm by germplasm type (data from IRRI 2019 user survey)

Table 6 Germplasm sources (data from IRRI 2019 user survey)

	Traits	Number of responses
1	*I source my germplasm from IRRI exclusively*	73
2	National genebank	71
3	University/learning institution	47
4	National Agricultural Research System	32
5	Collecting from in situ conditions (farms or the wild)	30
6	Farmers/farmer org	29
7	Individual/private collection	25
8	Other CGIAR genebank	23
9	Regional genebank	16
10	Company/private sector	15

Table 7 Descriptive statistics of requested accessions

Variable	Mean	Std dev	Min	Max
Number of requests per accession	3.0036	4.0919	1	107
PDCI	5.2199	1.2327	2.95	8.1
Years in storage	29.9510	29.9510	1	57
Biological status				
100 Wild	0.0916	0.2885	0	1
200 Weedy	0.0185	0.1347	0	1
300 Traditional cultivar/landrace	0.2541	0.4354	0	1
400 Breeding/research material	0.1122	0.3156	0	1
420 Genetic stock	0.2003	0.3156	0	1
423 Other genetic stock	0.0112	0.1055	0	1
500 Advanced or improved cultivar	0.0366	0.1878	0	1
999 Other	0.0002	0.0156	0	1
MLS status (= 1 if available in the MLS)	0.9999	0.0110	0	1

requests per accession, showed that each accession was requested three times, on average, between 2012 and 2018. The mean PDCI value across the requested accessions was 5.2199, with a standard deviation of 1.2327, a minimum value of 2.95, and a maximum of 8.1.[6]

IRRI has regularly acquired new accessions for conservation since 1961. On average, requested accessions have been stored in the genebank for 30 years. The frequency distribution shows peaks in the years 1977/78 and 2010/11. Correspondingly, this indicates that accessions collected from over 40 years ago are still requested frequently. Twenty-five percent of the accessions requested are traditional cultivars/landraces, followed by genetic stocks (20%). Almost all accessions requested are available under the MLS.

Table 8 presents the most requested accessions in the past seven years. All were sourced in the Philippines, except for the two genetic stocks from China and India. The top requested rice accessions were Dinorado and Jasmine, acquired in the Philippines in 1962 and 1976, respectively. Between 2012 and 2018, 107 requests were made for the two accessions, about 15 requests per year.

We present the estimation results in Table 9 for the three regression models: OLS, Poisson, and Negative Binomial. The likelihood-ratio (LR) test of alpha (estimate of the dispersion parameter) in the Negative Binomial model indicated that the outcome variable was overdispersed, which was not sufficiently captured in the
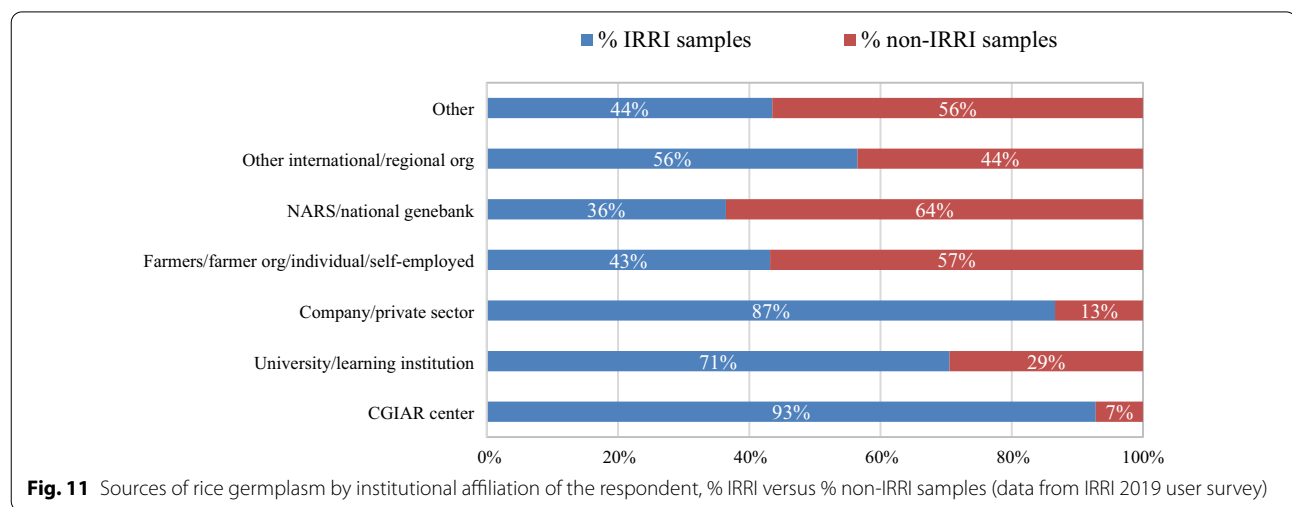
Fig. 11 Sources of rice germplasm by institutional affiliation of the respondent, % IRRI versus % non-IRRI samples (data from IRRI 2019 user survey)

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[6] Considering the full sample, the mean PDCI value across all accessions (both requested and not requested) is 5.3521, with a standard deviation of 1.1974, minimum value of 1.35, and a maximum of 8.1.

Table 8 Most requested accessions, 2012–2018

Rank	Accession number	Local name • Biological Status • Country of origin	Acquisition year	PDCI	Total requests 2012–2018	Average request per year
1	IRGC 30333	DINORADO • Traditional cultivar/landrace • Philippines	1962	5.6	107	15.3
1	IRGC 32591	JASMINE 85 • Advanced/improved cultivar • Philippines	1976	4.4	107	15.3
2	IRGC 599	MALAGKIT SONGSONG • Breeding/research material • Philippines	1962	4.9	69	9.9
3	IRGC 78627	SINANDOMENG • Traditional cultivar/landrace • Philippines	1990	4.3	67	9.6
4	IRGC 566	PERURUTONG NB • Breeding/research material • Philippines	1962	4.4	61	8.7
5	IRGC 66970	IR 64 • Advanced/improved cultivar • Philippines	1986	4.9	60	8.6
6	IRGC 328	AZUCENA • Traditional cultivar/landrace • Philippines	1962	6.1	59	8.4
7	IRGC 117268	IR 64–21 • Genetic stock • Philippines	2006	4.4	52	7.4
8	IRGC 117271	MINGHUI 63 • Genetic stock • China	2006	4.4	50	7.1
9	IRGC 44297	BALLATINAO • Traditional cultivar/landrace • Philippines	1978	6.55	48	6.9
9	IRGC 3809	BINIRHEN • Traditional cultivar/landrace • Philippines	1962	6.1	48	6.9
9	IRGC 117617	KASALATH • Genetic stock • India	2008	4.9	48	6.9
10	IRGC 5159	MILAGROSA • Traditional cultivar/landrace • Philippines	1962	5.6	45	6.4

Ranked by the total number of requests, 2012–2018. Country of origin is the country where the material was collected or bred, not the country of the source genebank

Table 9 Estimation results

Model	OLS	Poisson		Negative Binomial	
Dependent: Number of requests per accession	Coefficients	Coefficients	IRR	Coefficients	IRR
PDCI	0.3754***	0.1743***	1.1904	0.0778***	1.0809
Years in storage	0.0304***	0.0174***	1.0175	0.0123***	1.0124
MLS status	6.5148***	1.6848***	5.3913	1.7194***	5.5810
Biological status					
100 Wild	0.6562***	0.3500***	1.4191	0.5449***	1.7244
200 Weedy	− 0.4917***	− 0.1878***	0.8287	− 0.0290	0.9714
300 Traditional cultivar/landrace	− 0.7273***	− 0.3134***	0.7310	− 0.1087***	0.8970
400 Breeding/research material	− 0.2103***	− 0.0925***	0.9116	− 0.0245	0.9758
420 Genetic stock	7.7553***	2.3643***	10.6363	2.1294***	8.4102
423 Other genetic stock	− 0.0078	− 0.0698**	0.9325	− 0.1301*	0.8780
500 Advanced or improved cultivar	1.1637***	0.5846***	1.7943	0.6395***	1.8956
999 Other	0.6460	0.3701	1.4479	0.4714	1.6023
R-squared/Pseudo R-squared	0.4203	0.3252		0.1742	

Number of observations = 23,210

***, ** and * denote statistical significance at the 1%, 5%, and 10% level, respectively

Poisson model.[7] We, therefore, focused on the results of the Negative Binomial model, but we present the others here for reference. Nevertheless, the sign of the coefficients and the statistical significance of estimates were consistent across models. To facilitate the interpretation of coefficients, we included the estimates for the incident rate ratios (IRR).

Conditional on being requested, the IRR for PDCI showed that the incident rate of number of requests for an accession increased by 8% for every unit increase in PDCI. We also observed an increase of 1% on the incident rate of number of requests for an accession for every year's increase in storage. While the majority of materials from the IRRI genebank are available in the MLS, the estimate provided evidence that making genetic resources in the MLS indeed promotes the use and exchange of those materials. The results also showed positive effects from genetic stocks, wild relatives, and advance improved cultivars.

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[7] Test of dispersion: Alpha = 0.1889; /lnalpha = -1.6668; LR test of alpha = 0: chibar2(01) = 6306.67; Prob > = chibar2 = 0.000.

For robustness check, we ran the regression model on the full sample of accessions available at the IRRI genebank. However, as we noted earlier, this dataset has excess zeroes since only 24,792 (19%) unique accessions were requested between 2012 and 2018. We used Zero-Inflated Poisson and Negative Binomial models to account for the excess zeroes in the dependent variable, as recommended in Long and Freese (2006). The coefficients for our variables of interest remained consistent. The relationship between PDCI and the number of requests for that accession was positive and statistically significant (see Additional file 1: Table S1).

While there are recognizable limitations to our initial analyses, this study could motivate future work to explore the impact of different types of germplasm data on the demand for specific accessions. We focused on passport data, which are readily available in Genesys. There is, in addition, a wealth of accession-level information from phenotyping and genotyping activities that were not considered in our analyses. Users of the IRRI genebank could presumably select accessions more efficiently and effectively if they have better access to more information on certain morphological characteristics and genomic traits. The international resequencing effort of 3000 rice genomes, for example, offers opportunities for large-scale discovery of novel alleles for future rice improvement (The 3000 rice genomes project 2014). Key characteristics of genebank users could also be incorporated in future analyses to better capture the factors that could affect the demand for germplasm.

Conclusion

Our findings demonstrate the crucial role of IRRI's international rice genebank as a key germplasm source for agricultural research and development. 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, benefitted from the availability of rice genetic resources and 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.

The findings presented here have important implications for the conservation and use of rice genetic diversity in the future. First, improving the availability of data on conserved germplasm, including economic studies to better understand the changing demand of users, must be a priority for enhancing the use of rice germplasm at IRRI. The increased availability of genomic data, for example, could allow users of germplasm to select materials much faster and more cheaply based on genotype rather than on phenotype (Gollin 2020). The growing demand for rice genetic stocks at the IRRI genebank confirms this emerging trend. Innovations in technology, however, require complementary and continuous investment in genebanks to allow them to evolve and make full use of new knowledge (Smale et al. 2021).

Second, the feedback from the user survey demonstrated the extent of the use of rice germplasm and the magnitude and range of benefits generated by the IRRI genebank. The conservation and management of genetic resources benefit not only the requesters but also the multitude of indirect users of germplasm in research and breeding programs from a range of institutions in both low- and high-income countries. However, political uncertainties concerning the enhancement of the MLS and the regulation of access to genetic resources outside the MLS may restrict the acquisition of new materials to include in the international crop collections and the distribution of germplasm to recipients around the world (Halewood et al. 2020). The role of IRRI's genebank in ensuring that the benefits from the use of rice diversity will continue to be accessible to future generations cannot be overestimated nor undermined. It is vital not to endanger the raw materials that will provide us with the options to address food and nutrition security challenges in a changing climate and agricultural context.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43170-022-00095-6.

> **Additional file 1: Table S1.** Estimation results for the full sample.

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Author contributions
The first author contributed to research design and analysis, survey implementation, writing, and editing. The second author contributed to research design, data provision, and editing. Both authors have read and approved the final manuscript.

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Venuprasad Ramaiah is currently the head of the genebank at the International Rice Research Institute (IRRI), Philippines. Prior to this, he was a rice breeder at AfricaRice and contributed to the development of a number of rice varieties released in Sub-Saharan Africa. He has a PhD in Genetics and Plant Breeding from the University of Agricultural Sciences in Bangalore, India and has over 40 peer-reviewed publications.

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Availability of data and materials
The accession-level dataset used in the analysis is available and can be accessed at Genesys, https://www.genesys-pgr.org/. More information about the analyses and the result files are available from the corresponding author upon request.

Declarations

Ethics approval and consent to participate
Prior informed consent from respondents was secured during the conduct of the online survey. The survey instrument was reviewed and approved by the Management Team of CGIAR Genebank Platform.

Consent for publication
All authors have consented to the publication of the manuscript.

Competing interests
The first author works at the Crop Trust. The second author is the current genebank manager at IRRI.

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