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ORIGINAL PAPER

Twenty-five years of international exchanges of plant genetic resources facilitated by the CGIAR genebanks: a case study on global interdependence

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Abstract This article analyses 25 years of data about international movements of plant genetic resources for food and agriculture (PGRFA), facilitated by the gene banks hosted by seven centres of the Consultative Group on International Agricultural Research. It identifies trends in the movements of PGRFA for use in research and development, and describes the diversity of those resources transferred over time. The paper also presents data on the number of countries involved in the global exchanges, analyses their development status and describes their role as providers and/or recipients, providing a picture of the breadth of these global exchanges. We highlight that it is primarily developing and transition economies that have participated in the flows, and that the transferred germplasm has been largely used within their public agricultural research and development programmes. We conclude that, when provided the opportunity of facilitated access, countries will use a wide diversity of germplasm from many other countries, sub-regions and continents as inputs into their agricultural research and development programmes. We highlight the importance of enabling the continuation of the non-monetary benefits from international access to germplasm. We discuss the implications for the process of development and reform of the multilateral system of access and benefit sharing under International Treaty on Plant Genetic Resources for Food and Agriculture.

Keywords Plant genetic resources · Interdependence · International Treaty on Plant Genetic Resources for Food and Agriculture · Multilateral system · Conservation · Breeding

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Introduction

Plant genetic resources for food and agriculture (PGRFA) are the basic building blocks of crop improvement and adaptation and, by extension, of food security. As a result of the history of crop domestication and global dispersal and adaptation, all countries are now highly dependent upon plant genetic resources located (or originally collected from) beyond their borders. Global interdependence on plant genetic resources has been previously discussed (Crosby 1972, 1986; Diamond 1997; Fowler et al. 2001; Halewood et al. 2014; Mann 2011; SGRP 2011), and predictions have been made of increased future interdependence as a result of challenges such as climate change (Lane and Jarvis 2007; Burke et al. 2009; Jarvis et al. 2010; Fujisaka et al. 2011; Ramirez-Villegas et al. 2013) and the evolution of food systems and diets (Khoury et al. 2014). Global recognition of the policy significance of interdependence on PGRFA arguably reached its zenith in 2001 when ‘interdependence’ was explicitly included in Article 11 of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) as one of two criteria—the other being relevance for food security—for including crops or forages in the multilateral system of access and benefit sharing (MLS).[1]

Through the MLS, ITPGRFA parties agree to create a global, virtual pool of genetic resources for 64 crops and forages (these are listed in the Treaty’s Annex 1). In addition to conservation, this germplasm is intended to be utilized for the purposes of training, breeding and research for food and agriculture. Member states agree to provide facilitated access to one another (including natural and legal persons within their borders) on the understanding that monetary benefits will be shared if the recipients incorporate materials in new, commercialized PGRFA products that are not available to others for research, training or breeding. The multilateral architecture of access and benefit sharing under the ITPGRFA was designed to reflect countries’ current and future interdependence on PGRFA. The system was meant to minimize transaction costs that could otherwise multiply beyond acceptable limits, given the magnitude of international exchanges of genetic resources that accompany agricultural research, development and plant breeding.

In recent years, ITPGRFA member states have expressed concerns that the MLS has not been functioning at the anticipated levels, either in terms of generating financial benefits by users to be shared through the international Benefit-Sharing Fund (BSF) or in terms of materials being made available to, and accessed through, the MLS. Based on this concern, the ITPGRFA’s Governing Body created the Ad Hoc Open Ended Working Group to Enhance the Functioning of the MLS. Its mandate is to develop a range of optional measures to both increase user-based payments and contributions to the BSF in a sustainable and predictable long-term manner and enhance the functioning of the Multilateral System by additional measures.

This article focuses on an issue at the heart of the MLS—the state of global interdependence on PGRFA. We hope that the data presented here will be useful within any process aimed at revising or reforming the terms and conditions of the MLS. It is critically important to keep interdependence in mind when developing policies concerning the conditions under which genetic resources can be accessed and used as well as the ways in which benefits derived from their use should be shared. Illustrating the volume, diversity and geographical spread of global flows of plant genetic resources mediated by Consultative Group on International Agricultural Research (CGIAR) centres, the findings

[1] International Treaty on Plant Genetic Resources for Food and Agriculture, 29 June 2004, http://www.planttreaty.org/content/texts-treaty-official-versions (accessed 15 December 2015).

highlight the benefits accrued by virtually all countries in the world—namely, being granted access to a rich variety of materials (and associated technology and information) otherwise unavailable within their own borders and difficult to access under bilateral conditions. The resulting conclusions highlight the importance of the system's non-monetary modalities for sharing benefits, most of which have involved users in developing countries. We hope that such evidence will encourage efforts to maintain and enhance these mechanisms, in addition to improving the mechanisms associated with monetary payments to the BSF.

Data sources and methods

Data on the holdings, acquisitions and distributions of nine CGIAR genebanks was retrieved from the CGIAR's System-wide Information Network on Genetic Resources (SINGER).[2] A system-wide database such as SINGER has never been established for the distribution of germplasm from the CGIAR's breeding programmes, and, therefore, our study focuses on genebank distributions only. We asked each of the genebank curators to validate the accuracy of the data stored in SINGER and/or to provide updates or integrations. In the end, we obtained validated or updated data for seven genebanks, which are those included in this study (Table 1). Given the magnitude of the distributions from the other centres whose data is not included in this research, i.e., CIMMYT, CIAT, IITA, the final conclusions regarding the extent of international interdependence would likely have been even stronger had their data been included.

Distribution data followed a standard format gathering information according to the fields shown in Table 2.

Distribution records were available beginning in 1973 for some of the genebanks included in the study, but there were large gaps in the records until 1985 (due to data storage and reporting systems not being fully in place in all centres). Thereafter, the data were more uniform, which led to the decision to consider only the data from 1985 onwards. Since our focus was the germplasm sent to countries and within-country recipients, intra- and inter-CGIAR centre distributions were removed as well as those from CGIAR genebanks to the Svalbard Global Seed Vault. The total number of distributed samples shown in Table 1 was the basis for our analysis. These centres' mandate crops (and their wild relatives) include key staples for worldwide food security, such as rice, tropical and dryland legumes and cereals, potatoes and other roots and tubers, bananas and plantains and tropical forages (see Appendix, Tables 6, 7 for details on the collections hosted at all CGIAR centres).

Various ways of measuring international PGRFA movements were explored. We considered the total number of samples distributed [a single sample consisting ideally of between 50 and 100 viable seeds or less vegetative propagules (CGKB 2014)], the number of accessions distributed (excluding the repeated distributions of the same accession) and the number of species distributed. The latter two statistics provide a picture of the diversity, rather than the sheer volume, of the flows.

Further analyses qualified the international germplasm flows facilitated by the genebanks using the number of countries from which the materials distributed were originally

[2] SINGER has been discontinued, with much of its data and functionality—minus distribution data—incorporated into GENESYS, http://www.genesys-pgr.org (accessed 20 November 2014).

Table 1 Total number of samples sent to national recipients from the seven CGIAR genebanks (1985–2009)

	AfricaRice	Bioversity	CIP	ICARDA	ICRISAT	ILRI	IRRI
Samples distributed	38,963	13,436	84,380	246,026	418,934	30,830	166,681

Table 2 Fields of information included in the distribution data from CGIAR genebanks

CGIAR centre	Transfer year
Accession number	Recipient country code
Genus	Recipient country name
Species	Recipient institute
Country of origin	Recipient last name
Biological status	Recipient first name
Recipient code	Recipient user type
Recipient region	Transfer date

collected or improved, the number of recipient countries and types of recipient institutions, the number of genera and species distributed, and the type of materials exchanged. Countries were classified based on their development status according to the United Nations classification system (UN 2012), which helped to analyse the germplasm contributions according to the economy of the donor or recipient country. All data handling and analyses were performed in R (R Development Core Team 2011).

Results and discussion

Global flows of PGRFA, 1985–2009: volumes and diversity

Between 1985 and 2009, germplasm conserved in the selected CGIAR genebanks was distributed to a broad range of users. According to the available data, 999,250 samples of 262,872 accessions belonging to 1470 different plant species were distributed during that period. The average number of samples distributed per year (39,970) is below that of the U.S. National Plant Germplasm System (NPGS), where total annual distributions have increased from around 120,000 (Bretting 2007) to more than 200,000 (Heisey and Day Rubenstein 2015) over the past few years. About 30 % of NPGS yearly distributions are typically to requestors from outside the U.S. However, in making this comparison, our lack of data from three important CGIAR genebanks should be kept in mind. Notwithstanding the missing data, the yearly volumes described are much higher than the average number of distributions of other important germplasm systems, such as the Russian Vavilov Institute (6400) (FAO 2009), the German Institute of Plant Genetics and Crop Plant Resources (4400 of barley only) (Ullrich 2011), the Centre for Genetic Resources in the Netherlands (2500) (Centre for Genetic Resources 2008), the Brazilian Empresa Brasileira de Pesquisa Agropecuária (1800) (Da Silva Mariante et al. 2009), the Institute of Crop Germpasm Resources in China (1550) (ICGR 2015), the Plant Genetic Resources Institute of Canada (1500) (Fowler and Hodgkin 2004). These numbers are useful for providing a general idea of the CGIAR's relative contribution on the international scene, but they should be considered with caution because of the differences in the reporting periods and the limitations of our data.

Virtually all countries in the world have been involved in the exchange of germplasm. The materials listed in Table 1 were originally collected in, or provided by, at least 189 countries and distributed to at least 191 countries. In addition to distributions from the various genebanks, large amounts of germplasm in different stages of improvement have been sent out by the centres' breeding programmes, although no system-wide mechanism has ever been set up to document these distributions over time. However, data provided by the centres[3] for the fourth session of the ITPGRFA's Governing Body indicate that from August 2008 to December 2009 these breeding programmes sent out over 500,000 samples (SGRP 2011). This amount points to the outstanding contribution that the CGIAR breeders make to international flows of germplasm, in addition to the centres' genebanks.

According to data available through the GENESYS portal, which gathers information on numerous national and international genebanks, the international ex situ collections hosted by the CGIAR centres currently include 712,834 accessions of their mandate crops and related gene pools, originally collected from a vast number of countries (Appendix, Tables 6, 7, 8). The genebanks that were analysed in this study, currently host 445,785 accessions of 2848 species.[4] Our data suggest that samples of roughly half the diversity held have been distributed at least once by these genebanks.

During the period analysed, there appears to be have been a slight downward trend in the overall number of samples distributed, as already highlighted elsewhere (Halewood et al. 2013). A similar decline was observed in the diversity of the materials distributed, which was measured according to the number of accessions distributed and the number of species represented (Table 3). This trend may be attributed to the fact that the requests became more targeted as more characterization and evaluation data became available, which led to breeders and researchers making requests for smaller sets of materials (Halewood et al. 2013; López Noriega et al. 2013a). For those CGIAR genebanks actively distributing sets of materials for international adaptation trials, the decline could also be due to decreases in the funding made available for these multi-location field operations. It could be that some of the requests that were traditionally made to the CGIAR are now being directed to other genebanks. In addition to institutions that have always been at the forefront of international distributions, alongside the CGIAR, such as the US Department of Agriculture (USDA), a number of national institutions in other countries have been increasing their collections and may be receiving more germplasm requests (FAO 2010). In addition, some private sector users—those most likely to apply some form of intellectual property rights to the final PGRFA products—may have refrained in recent years from requesting germplasm from the CGIAR because of their reluctance to accept the benefit-sharing clauses of the MLS (Halewood and Nnadozie 2008). It is important to note that traditionally these companies have been an extremely small portion of the users of CGIAR materials, as described later.

Types of materials and frequency of distribution

According to GENESYS, over 50 % of the total germplasm distributed by the CGIAR genebanks over the 25 years analysed are landraces or traditional cultivars, which are predominant within these collections (Fowler et al. 2001; Genesys 2014). Breeding and

[3] Except IITA, which did not provide information for this report.

[4] GENESYS, http://www.genesys-pgr.org (accessed 20 November 2014).

Table 3 Results of the models used for analysing trends in the overall flows over time (1979–2009)

Parameter/year	Estimate	*P* value	Method
Samples	−0.031	<2e−16	Generalized linear model with Poisson error distribution
Accessions	−0.065	<2e−16	Generalized linear model with Poisson error distribution
Species	−0.013	<2e−16	Generalized linear model with Poisson error distribution

research lines constitute less than 20 % of the materials distributed, while advanced or improved cultivars comprise only 7 % of the distributions. Wild and weedy relatives amount to 12 % of the samples sent out by the analysed genebanks, not only suggesting their importance as sources of useful traits but also reflecting the greater difficulty of using them in breeding compared to other materials (Fig. 1). The decision about which materials to conserve in the long term is made by each centre independently, often following the outcomes of economic analyses on the costs and benefits of conserving materials in genebanks or breeding programmes (Koo et al. 2004). The data in this study reveal that most centres give priority for long-term storage in their genebanks to materials that belong to the primary genepools – that is, the landraces and wild relatives of their mandate crops. This strategy also reflects the fact that all centres with genebanks also have breeding programmes that actively exchange research, breeding and improved lines with partners worldwide, making the conservation of these sets by the genebank neither necessary nor efficient. However, research, breeding and advanced lines are sometimes included in long-term collections, when the properties, or the use of the material, justify it. For instance, this may be the case with materials that have accumulated unique genetic properties (for example, allele combinations), those that are laborious to reproduce (for example, inter-specific hybrids) or those that are commonly used as benchmark varieties in evaluation trials.

Based on the number of samples per accession sent to recipients, there appears to be enormous variation in the popularity of any single accession. Almost 60 % of the accessions in the dataset have been distributed between two and ten times, while only 5.7 % (150 accessions) have been distributed more than 100 times. Most of the latter come from ILRI, CIP and ICRISAT and have been distributed to an average of over 38 countries (SD 20.5) (see Appendix, Table 9 for details on the top 50 most 'popular' accessions of our dataset).

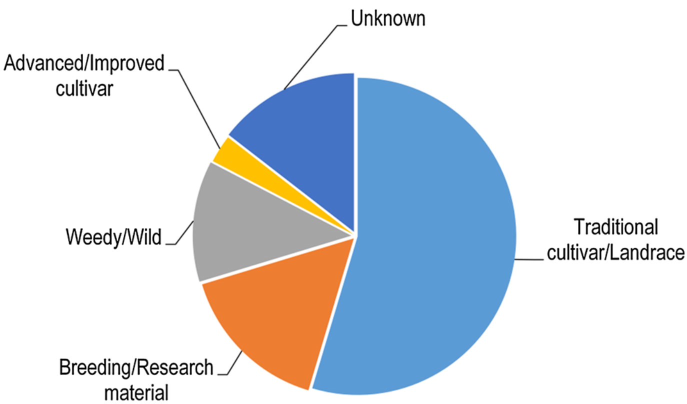

Fig. 1 Proportion of the different types of germplasm distributed by the selected CGIAR genebanks based on accession data (1985–2009)

More than half of these frequently distributed materials are improved lines, whereas landraces, wild relatives and, to a lesser extent, breeding materials constitute the bulk of the accessions transferred less frequently. Among the possible reasons for the 'popular' materials to be more frequently requested (that is, by many institutions worldwide) is the fact that the characterization and/or evaluation data already accumulated on them increases their value for breeding and research. This information, in turn, facilitates their use including in institutions and countries with limited capacity or infrastructure for conducting lengthy and costly pre-breeding research using non-adapted populations and wild relatives (FAO 2010).

Providers and recipients

Of the total 189 countries from which material distributed by the seven CGIAR genebanks was obtained, 112 are developing countries, 54 are developed countries and 23 have economies in transition. Of the total 191 recipients, 116 are developing countries, 19 are economies in transition and 56 are developed countries. Data for developing countries and countries with economies in transition has been combined in our analyses. Both developed and developing countries are net recipients—that is, they receive more diversity than they contribute to international gene banks. While this 'sink' behaviour is more evident for developed countries, which tend to harbour comparatively less indigenous genetic diversity in their territories, the majority of global exchanges of germplasm mediated by the CGIAR genebanks is distributed South to South—that is, between developing countries (Fig. 2).

In their analysis of the flows from six of the CGIAR genebanks and from the USDA's National Plant Germplasm System (NPGS) between 1990 and 1999, Smale and Kelly Day Rubenstein (2002) also observed that a predominance of developing countries and transition economies were providers and recipients. So too did the CGIAR's System-wide Genetic Resources Programme (2011) in its biannual reports to the Governing Body of the ITPGRFA. Tables 4a, b provide more detail on the amount, diversity and geographical coverage of the distributions facilitated by the international genebanks for the top 25 provider countries and the top 25 recipient countries.

Almost all of the top providers listed in Table 4 are developing countries. Many of them are important centres of origin, domestication or diversification of the crops curated by the

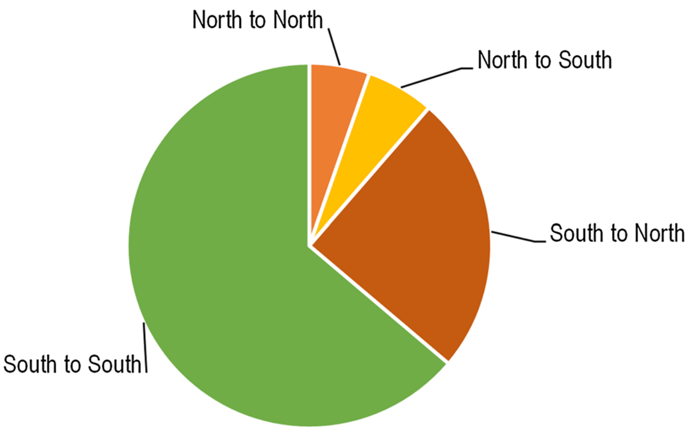

Fig. 2 Number of accessions exchanged between developed (the 'North') and developing and transition countries (the 'South')

Table 4 Top 25 provider countries (including total number of samples, genera and accessions originally sourced in these countries and circulated by the CGIAR genebanks analysed in this study as well as the number of recipient countries) and top 25 recipient countries (total number of samples, genera and accessions received as well as the number of countries where these materials were originally sourced) (1985–2009)

Provider country	Total samples provided	Accessions provided	Genera provided	Recipient countries	Recipient country	Total samples received	Accessions received	Genera received	Provider countries
India	188,911	48,635	35	144	India	284,454	115,849	70	181
Peru	67,899	16,216	23	158	United States	45,992	39,963	97	178
Ethiopia	40,143	13,683	94	120	China	33,690	18,664	48	151
United States	36,652	6294	30	156	Ethiopia	28,863	17,572	175	150
Iran	29,829	9779	26	87	Australia	20,218	17,566	63	150
Turkey	29,579	9634	29	83	Japan	17,628	12,022	32	141
Syrian Arab Republic	26,029	7487	27	78	United Kingdom	17,231	14,283	89	144
Sudan	24,262	3457	17	61	Morocco	16,362	14,618	38	97
The Philippines	21,626	4016	7	109	The Philippines	16,332	8798	50	107
Côte d'Ivoire	20,494	3037	4	78	Tunisia	13,399	9706	18	70
China	18,559	7225	21	125	Iran	13,083	12,301	18	135
Nigeria	16,060	3462	27	126	Austria	12,703	12,657	24	92
Zimbabwe	15,477	4500	19	62	Italy	12,345	10,003	36	116
Cameroon	15,216	2942	13	67	Syrian Arab Republic	10,598	8610	19	92
Jordan	12,328	3319	20	66	South Korea	10,195	8423	26	137
Morocco	12,257	4106	34	69	Russia	9614	8636	12	92
Bangladesh	12,092	3839	14	94	Pakistan	9512	7901	64	139
Indonesia	11,696	3774	12	93	Turkey	9295	7221	25	96
Uganda	11,172	2565	13	103	Canada	9160	7709	38	121
Tunisia	10,799	3523	22	74	Indonesia	8965	8395	32	110
Pakistan	10,587	2950	23	99	Peru	7953	4053	33	75
Kenya	10,509	2205	38	104	Egypt	7921	6685	54	126

Table 4 continued

Provider country	Total samples provided	Accessions provided	Genera provided	Recipient countries	Recipient country	Total samples received	Accessions received	Genera received	Provider countries
Algeria	9743	3522	24	65	Germany	7276	6253	63	130
Tanzania	8438	2132	37	96	Brazil	6903	6030	34	129
Nepal	7725	2745	19	73	Thailand	6821	4899	27	103

genebanks considered in this study, including India (rice, millet), Peru (potatoes), Syria and Turkey (wheat and barley), China (rice) and a number of African countries (particularly for tropical forages). Many of the top recipients are also developing countries, and, again, many of them are centres of origin or diversity of crops or forages that they have requested, underscoring the fact that even diversity-rich countries are not self-sufficient in terms of their PGRFA needs. As an example, the difference in the amount of germplasm flowing in and out of India, compared to other countries, stands out as very significant. India has provided and received massive quantities of germplasm. Interestingly, a significant percentage of the materials originally collected in, or obtained from, India ends up going back to Indian recipients (59 % of the samples and over 70 % of the accessions), which makes it the largest recipient of CGIAR-hosted materials originally obtained from within its own borders. A high percentage of 'reabsorption' of their own materials through CGIAR-mediated flows are also recorded for Tunisia and Morocco (48 and 42 % respectively), the Philippines (37 %), Iran and Jordan (30 and 25 %) and others to lesser extents. These observations highlight the additional benefit of germplasm deposited in international collections since it provides long-term secure conservation and availability of quality material (and often value-added characterization and evaluation data) originating from one's own territory, in addition to access to diversity from hundreds of other countries. The latter benefit is particularly relevant for those countries with limited capacity to establish and maintain national conservation programmes for their own local materials.

Differences exist not only in the amount, but also in the type of materials provided by developed and developing countries. While developed countries provide an overall lower quantity of materials compared to developing countries, they contribute a proportionally higher share of materials for which some formal research, pre-breeding or other form of improvement has been conducted. In total, 27 % of the samples 'distributed' by our seven CGIAR genebanks from developed countries were research materials and improved/elite lines (with the United States supplying as much as 80 % of this category); only 14 % of the samples distributed from developing and transition countries belonged to these categories. On the recipient side, the share of germplasm that carried some degree of research and improvement flowing into developing countries and transition economies is 30 % of the overall incoming samples, while it is 14 % for developed countries.

In both developed and developing nations, public institutions (including the National Agricultural Research System (NARS), universities and genebanks) are by far the predominant recipients of CGIAR materials (Table 5; Fig. 3). These public sector recipients are located in developing countries in over 75 % of the cases. The share of samples sent to commercial companies is only around 3 % of the total, and the recipients are primarily (77 %) in developing countries.

These findings are also consistent with those of Smale and Day Rubenstein (2002) who found that most recipients of germplasm from the US NPGS, another important worldwide facilitator of PGRFA for research and breeding, were in the public sector. The volume and diversity of the PGRFA flows described in this study, albeit only a small sample of worldwide exchanges, demonstrate the extent of countries' interdependence on PGRFA for crop improvement and, ultimately, food security. While acknowledging the limits of our dataset, we believe that the conclusions regarding the extent of international interdependence would likely have been even stronger had the data from important genebanks such as those at CIMMYT, CIAT and IITA been included. The emerging picture confirms an established description of modern agriculture as an interdependent network of seed and germplasm sources, in which very few countries or farming systems in the world do not

Table 5 Type of recipients, samples and accessions and percentages over the total

Recipient type	Samples received	Percentage	Accessions received	Percentage
NARS	573,456	57.39	374,714	61.87
University	297,034	29.73	161,845	26.72
Genebank	53,198	5.32	33,967	5.61
Commercial company	32,020	3.20	10,985	1.81
Other	24,739	2.48	13,650	2.25
Non-governmental organization	14,821	1.48	7905	1.31
Regional organization	2727	0.27	2054	0.34
Farmer	1255	0.13	528	0.09

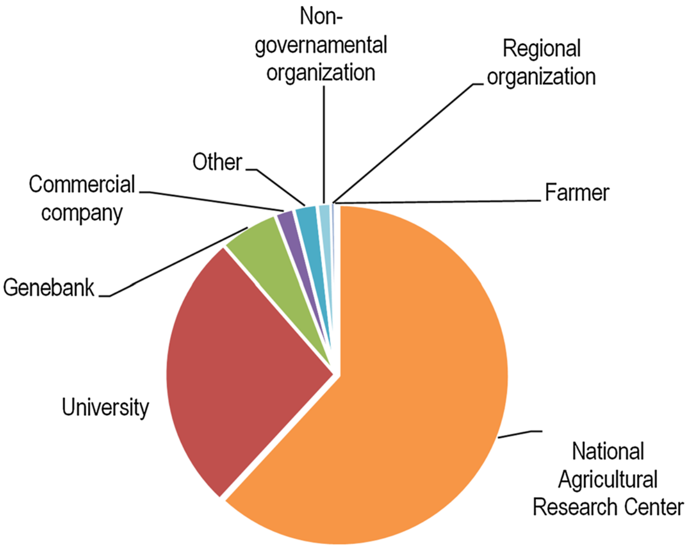

Fig. 3 Share of accessions received by different recipient categories (1985–2009)

rely to some degree on the international system that moves crop germplasm, breeding lines and improved varieties across international borders (Duvick 1984).

Analyses by other authors confirm these patterns, describing how crop improvement has benefited from access to a wide range of materials with different origins. Fowler, Smale and Gaiji (2001) undertook an analysis of CGIAR data focusing on a different time frame and different measures than those presented here. Smale et al. (2002) used the case of spring bread wheat released by national programmes in developing countries. Warburton et al. (2006) and Dreisigacker et al. (2005) looked at synthetic hexaploids to illustrate the significance of access to wild relatives from centres of diversity in wheat improvement. Voysest et al. (2003) took the case of beans in Latin America (Fowler et al. 2001; Smale et al. 2002; Voysest et al. 2003; Dreisigacker et al. 2005; Warburton et al. 2006). Additional studies have focused on those countries that are the centres of crop diversity. Rejesus et al. (1996) reported that 45.6 % of the germplasm used by wheat breeders in Western Asia, the Vavilov centre for the species, comes from international sources. Evenson and Gollin (1997) documented the dependence of Asian countries, including the Vavilov-centre countries such as India, Burma, Bangladesh, Nepal and Vietnam, on IRRI for rice germplasm of different provenance (65.0 % in India and 98.1 % in Vietnam) (Rejesus et al. 1996; Evenson and Gollin 1997). All of this evidence points to the 'international public good' nature of the materials held and made available by the CGIAR as well as by other actors who make such materials available. It highlights the importance of supporting the continuation and enhancement of conservation as well as the internationally facilitated sharing of germplasm within the framework of the ITPGRFA.

Conclusions

It is clear that access to globally pooled genetic resources is a fundamentally important benefit that all countries have historically exploited when systems were set up to facilitate such access. Any effort to improve the MLS must be guided by the necessity of supporting and improving countries' ability to further capitalize on this benefit. This is particularly true considering the contemporary challenges associated with climate change (Fujisaka et al. 2011), population growth and the harmonization of diets across the world (Khoury et al. 2014). While acknowledging the importance of improving the monetary benefit-sharing mechanisms, we believe that one should not lose sight of the need to maintain the non-monetary benefit-sharing mechanisms when evaluating the effectiveness of the MLS and considering options for its reform. Significant knowledge and opportunities for crop improvement accompany the materials distributed by the CGIAR genebanks, so focusing exclusively on the monetary benefits that can potentially result from germplasm flows represent too narrow a view of its overall impact. Indeed, it has been argued that non-monetary benefits from the MLS (as outlined in Articles 13.1 and 13.2(a)–(c) of the ITPGRFA) can generate much greater economic return than developing countries would ever gain through the BSF.

With respect to monetary benefit sharing, it is important to underscore the fact that the primary users of germplasm from the CGIAR and the MLS have been public sector organizations (in developing countries) rather than private sector entities. Indeed, it has been pointed out that a crucial factor that determines the demand for genetic resources in the seed and crop protection industries is the effort required to turn them into usable materials. Genetic resources that widen a company's gene pool, but without the identified properties of interest, are typically considered to have little commercial value since they require considerable investment and the return on investment is often risky (Smolders 2005). Although new technology can assist in the search for a specific trait, the expense of doing so is generally prohibitive, particularly for smaller companies (Laird and Wynberg 2006). Larger companies that would most likely trigger the mandatory financial benefit-sharing provisions associated with the MLS tend to opt out of receiving materials from the system (Halewood and Nnadozie 2008). These kinds of reasons likely underlie the failure of efforts to 'privatize' monetary benefit sharing through the adoption of mechanisms for mandatory payments from companies based on sales of products that incorporate materials from the MLS.

We believe that some other approach to monetary benefit sharing, linked to the operation of the MLS, is necessary. Such an approach should more closely reflect the public goods nature of PGRFA as well as the historical development of the international and national collections that host most of the materials that do, and will, constitute the MLS. It should also be as simple as possible, and less administratively burdensome on both the providers and users of PGRFA, to encourage, rather than discourage, participation. In particular, it could be useful not to link the collection of financial benefits to the privatization of products incorporating materials from the MLS. Rather, it could be governments or public authorities which devise means to assume the costs of the MLS' proper functioning, in a more familiar form of state assumed responsibility on publically valuable assets. Governments could then decide if and how they would need to recoup some of those costs; one option, which was actually discussed in early Treaty days, could be some sort of contribution from the commercial sector based on their annual seed sales. This approach would also be in line with the way public organizations have historically supported the collections.

Of course, there are other ways to improve and enhance the functioning of the MLS and to acknowledge countries' increasing interdependence on PGRFA, beyond adopting a new approach to monetary benefit sharing. No matter how well the system is designed or reformulated, there are practical, institutional and capacity limitations for all countries and all potential beneficiaries (from farmers to breeders and researchers) to take advantage of the MLS, even once their legal ability to do so has been established. This may be particularly true in some developing countries. Capacities and strong partnerships need to be established among the broadest possible range of stakeholders, enabling them to recognize specific trait-based needs, identify where the potentially useful materials could be within the MLS, and request, receive and use the materials concerned. A more proactive and widespread participation would contribute to a greater willingness to voluntarily introduce materials into the MLS, increasing the diversity available to agricultural research and development and giving rise to additional monetary and non-monetary benefits to be shared.

It has been argued that capacity building, technology transfer and information exchange in the context of the MLS should take place in close relation to other ITPGRFA objectives, particularly the recognition and protection of farmers' rights (Article 9). Indeed, a number of countries have flagged their concern about the MLS having too narrow a focus to the detriment of issues that are more closely related to farmers and their role in on-farm conservation (López Noriega et al. 2013b). After all, most of the ex situ materials that are being, or will be, circulated globally thanks to the MLS are landraces or naturally adapted resources developed and conserved by small farmers, often from developing countries. Their role today is ever more crucial for allowing the continued conservation, evolution and development of genetic resources with the potential to adapt to changing climates. Greater synergy between the architecture of the MLS and the implementation of farmers' rights would also contribute to moving the ITPGRFA forward as a package of integrated measures, building confidence among a wider range of key stakeholders and truly reflecting global interdependence.

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Appendix

See Tables 6, 7, 8 and 9.

Table 6 Current numbers of accessions of plant germplasm held by the genebanks of the CGIAR system Data from Genesys, http://www.genesys-pgr.org (accessed on 20 November 2014)

Centre	Number of accessions held
Africa Rice	26,098
Bioversity International	1516
CIAT	64,721
CIMMYT	164,320
CIP	16,061
ICARDA	147,076
ICRAF	2005
ICRISAT	119,524
IITA	27,232
ILRI	20,229
IRRI	124,052

Table 7 Plant genera represented in the genebank collections of all CGIAR centres (genera represented by less than 50 accessions are grouped as "other"; numbers of accessions refer to those received and reported by centres over time and may overestimate the current living material available for distribution in each genebank) Data from Genesys, http://www.genesys-pgr.org (accessed on 20 November 2014)

Collection	Genus	Number of accessions
Africa Rice	*Oryza*	131,840
	Other	22
Bioversity	*Musa*	1525
	Ensete	4
CIAT	*Phaseolus*	36,124
	Manihot	5458
	Stylosanthes	4276
	Desmodium	3561
	Centrosema	2874
	Aeschynomene	1209
	Macroptilium	1052
	Vigna	1050
	Zornia	967
	Brachiaria	601
	Panicum	563
	Galactia	561
	Calopogonium	553
	Rhynchosia	389
	Teramnus	372
	Chamaecrista	339
	Desmanthus	325
	Crotalaria	274
	Alysicarpus	259
	Pueraria	255
	Canavalia	215
	Dioclea	199
	Leucaena	198
	Indigofera	184

Table 7 continued

Collection	Genus	Number of accessions
	Flemingia	179
	Uraria	176
	Arachis	171
	Clitoria	157
	Lablab	155
	Paspalum	155
	Tephrosia	153
	Phyllodium	139
	Cajanus	135
	Tadehagi	108
	Andropogon	93
	Pseudarthria	72
	Neonotonia	68
	Dendrolobium	62
	Sesbania	62
	Cratylia	52
	Other	926
CIMMYT	*Triticum*	103,780
	Zea	27,279
	Triticosecale	16,004
	Hordeum	14,221
	Aegilops	1316
	X Triticoaegilops	991
	Secale	438
	Tripsacum	156
	X Aegilotriticum	128
	Other	7
CIP	*Ipomoea*	7783
	Solanum	7112
	Oxalis	520
	Ullucus	435
	Tropaeolum	54
	Other	157
ICARDA	*Triticum*	37,214
	Hordeum	31,619
	Vicia	16,151
	Cicer	14,906
	Lens	12,463
	Medicago	9418
	Pisum	6110
	Trifolium	5010
	Aegilops	4257
	Lathyrus	4184

Table 7 continued

Collection	Genus	Number of accessions
	Astragalus	956
	Onobrychis	733
	Avena	593
	Scorpiurus	500
	Hippocrepis	319
	Trigonella	280
	Coronilla	251
	Lotus	246
	Hymenocarpos	223
	Melilotus	219
	Lupinus	134
	Elymus	81
	Hedysarum	81
	Brachypodium	78
	Secale	73
	Other	977
ICRAF	*Prosopis*	929
	Calycophyllum	390
	Guazuma	390
	Leucaena	80
	Gliricidia	55
	Desmodium	52
	Other	109
ICRISAT	*Sorghum*	37,901
	Pennisetum	22,200
	Cicer	20,140
	Arachis	15,440
	Cajanus	13,289
	Eleusine	5957
	Setaria	1542
	Panicum	1306
	Echinochloa	749
	Paspalum	665
	Rhynchosia	290
	Other	45
IITA	*Vigna*	18,237
	Dioscorea	3169
	Manihot	2984
	Glycine	1749
	Zea	798
	Musa	150
	Sphenostylis	145
	Other	0

Table 7 continued

Collection	Genus	Number of accessions
ILRI	*Trifolium*	1649
	Vigna	1161
	Stylosanthes	1160
	Leucaena	801
	Sesbania	674
	Indigofera	669
	Brachiaria	663
	Alysicarpus	516
	Neonotonia	508
	Rhynchosia	501
	X Triticale	459
	Macroptilium	431
	Panicum	423
	Tephrosia	395
	Lablab	374
	Centrosema	323
	Teramnus	322
	Cenchrus	294
	Zornia	283
	Phaseolus	282
	Vicia	258
	Digitaria	255
	Medicago	252
	Acacia	248
	Pennisetum	245
	Crotalaria	237
	Paspalum	223
	Cytisus	220
	Chloris	194
	Glycine	192
	Galactia	188
	Desmodium	177
	Lathyrus	166
	Cajanus	164
	Urochloa	162
	Chamaecrista	160
	Aeschynomene	158
	Calopogonium	152
	Avena	147
	Gliricidia	141
	Eragrostis	136
	Cynodon	130
	Lotononis	130

Table 7 continued

Collection	Genus	Number of accessions
	Setaria	130
	Pisum	126
	Clitoria	122
	Andropogon	109
	Desmanthus	107
	Echinochloa	93
	Pseudarthria	93
	Bothriochloa	89
	Senna	89
	Uraria	89
	Pueraria	76
	Lolium	75
	Sorghum	72
	Cassia	71
	Hordeum	71
	Festuca	64
	Argyrolobium	57
	Erythrina	57
	Lupinus	53
	Amaranthus	51
	Cymbopogon	51
	Hyparrhenia	51
	Dolichos	50
	Other	2160
IRRI	*Oryza*	124,052
	Other	22

Table 8 Countries from which accessions held by CGIAR genebanks were originally collected or improved Data from Genesys, http://www.genesys-pgr.org (accessed on 20 November 2014)

Country code in Genesys	Country	Number of accessions in the CGIAR genebanks
AFG	Afghanistan	4962
ALB	Albania	75
DZA	Algeria	3828
AGO	Angola	110
ATG	Antigua and Barbuda	116
ANT	Antilles	9
ARG	Argentina	3991
ARM	Armenia	1304
AUT	Austria	564
AZE	Azerbaijan	1723
BHS	Bahamas	4

Table 8 continued

Country code in Genesys	Country	Number of accessions in the CGIAR genebanks
BHR	Bahrain	2
BRN	Baker Island	215
BGD	Bangladesh	8009
BRB	Barbados	57
BLR	Belarus	324
BEL	Belgium	347
BLZ	Belize	376
BEN	Benin	1455
BTN	Bhutan	507
BOL	Bolivia	3289
BIH	Bosnia and Herzegovina	59
BWA	Botswana	1078
BRA	Brazil	14,765
IOT	British Indian Ocean Territory	1
VGB	British Virgin Islands	55
BGR	Bulgaria	1570
BFA	Burkina Faso	2995
MMR	Burma	3550
BDI	Burundi	867
KHM	Cambodia	4885
CMR	Cameroon	5320
CAN	Canada	914
CPV	Cape Verde	22
CAF	Central African Republic	849
TCD	Chad	909
CHL	Chile	2431
CHN	China	15,294
COL	Colombia	12,829
COM	Comoros	8
COG	Congo	334
COD	Congo (Democratic Republic of)	687
COK	Cook Islands	7
AUS	Coral Sea Islands	2172
CRI	Costa Rica	1543
CIV	Cote d'Ivoire	10,018
HRV	Croatia	63
CUB	Cuba	980
CYP	Cyprus	1103
CZE	Czech Republic	556
DNK	Denmark	206
DJI	Djibouti	6
DOM	Dominican Republic	497
ECU	Ecuador	3934

Table 8 continued

Country code in Genesys	Country	Number of accessions in the CGIAR genebanks
EGY	Egypt	1831
SLV	El Salvador	562
GNQ	Equatorial Guinea	28
ERI	Eritrea	97
EST	Estonia	10
ETH	Ethiopia	22,113
FLK	Falkland Islands (Islas Malvinas)	2
FSM	Federated States of Micronesia	7
FJI	Fiji	53
FIN	Finland	91
YUG	Former Yugoslavia	222
FRA	France	1136
GUF	French Guiana	20
PYF	French Polynesia	2
GAB	Gabon	100
GMB	Gambia	695
PSE	Gaza Strip	129
GEO	Georgia	1230
DEU	Germany	2357
GHA	Ghana	2006
GRC	Greece	3921
GRD	Grenada	50
GLP	Guadeloupe	62
GUM	Guam	9
GTM	Guatemala	4447
GIN	Guinea	1678
GNB	Guinea-Bissau	151
GUY	Guyana	156
HTI	Haiti	233
HND	Honduras	1476
HKG	Hong Kong	21
HUN	Hungary	1625
IND	India	44,216
IDN	Indonesia	12,087
IRN	Iran	21,347
IRQ	Iraq	1652
IRL	Ireland	3
ISR	Israel	1663
ITA	Italy	2720
JAM	Jamaica	189
JPN	Japan	2555
JOR	Jordan	5023
KAZ	Kazakhstan	613

Table 8 continued

Country code in Genesys	Country	Number of accessions in the CGIAR genebanks
KEN	Kenya	4048
KIR	Kiribati	1
KGZ	Kyrgyzstan	226
LAO	Laos	15,642
LVA	Latvia	32
LBN	Lebanon	2208
LSO	Lesotho	587
LBR	Liberia	3616
LBY	Libya	762
LTU	Lithuania	38
MAC	Macau	1
MKD	Macedonia	766
MDG	Madagascar	4296
MWI	Malawi	3214
MYS	Malaysia	4832
MDV	Maldives	23
MLI	Mali	4850
MLT	Malta	35
MTQ	Martinique	17
MRT	Mauritania	162
MUS	Mauritius	31
MEX	Mexico	77,448
MDA	Moldova	94
MNG	Mongolia	232
MNE	Montenegro	43
MSR	Montserrat	11
MAR	Morocco	4989
MOZ	Mozambique	413
BUR	Myanmar	323
NAM	Namibia	1546
NPL	Nepal	5858
NLD	Netherlands	780
NCL	New Caledonia	11
NZL	New Zealand	117
NIC	Nicaragua	646
NER	Niger	4983
NGA	Nigeria	14,636
NIU	Niue	4
PRK	North Korea	2592
NOR	Norway	29
OMN	Oman	324
PAK	Pakistan	5604
PLW	Palau	2

Table 8 continued

Country code in Genesys	Country	Number of accessions in the CGIAR genebanks
VUT	Palestine	3
PAN	Panama	1000
PNG	Papua New Guinea	991
PRY	Paraguay	1375
PER	Peru	14,412
PHL	Philippines	9224
POL	Poland	426
PRT	Portugal	2381
PRI	Puerto Rico	364
REU	Reunion	1
ROU	Romania	572
RUS	Russia	3529
SUN	Russia	1259
RWA	Rwanda	874
KNA	Saint Kitts and Nevis	33
LCA	Saint Lucia	37
VCT	Saint Vincent and the Grenadines	54
WSM	Samoa	2
SMR	San Marino	3
SAU	Saudi Arabia	84
SEN	Senegal	3540
SRB	Serbia	99
SYC	Seychelles	3
SLE	Sierra Leone	1997
SGP	Singapore	6
SVK	Slovakia	105
SVN	Slovenia	8
SLB	Solomon Islands	56
SOM	Somalia	562
ZAF	South Africa	2138
KOR	South Korea	2153
ESP	Spain	3567
LKA	Sri Lanka	2740
SDN	Sudan	3528
SUR	Suriname	188
SWZ	Swaziland	276
SWE	Sweden	554
CHE	Switzerland	1102
SYR	Syria	10,776
TWN	Taiwan	3075
TJK	Tajikistan	2275
TZA	Tanzania	4094
THA	Thailand	7870

Table 8 continued

Country code in Genesys	Country	Number of accessions in the CGIAR genebanks
TGO	Togo	2817
TON	Tonga	15
TTO	Trinidad and Tobago	201
TUN	Tunisia	4382
TUR	Turkey	16,775
TKM	Turkmenistan	587
TUV	Tuvalu	1
UGA	Uganda	3532
UKR	Ukraine	1610
ARE	United Arab Emirates	4
GBR	United Kingdom	801
USA	United States	12,969
UNK	Unknown	6870
URY	Uruguay	1229
UZB	Uzbekistan	987
VEN	Venezuela	4075
VNM	Vietnam	3787
VIR	Virgin Islands	17
YEM	Yemen	2816
ZMB	Zambia	2733
ZWE	Zimbabwe	5717

Table 9 Top 50 most popular accessions of our distribution dataset (based on how many samples of each accession have been distributed), with information on the distributing centre, genus, frequency of distribution, number of recipient countries, biological status and country of origin. Data elaborated from SINGER

Accession number	Centre	Genus	Frequency of distribution	Number of recipients	Biological status	Country of origin
328	IRRI	*Oryza*	321	42	Landrace	Philippines
CIP 985003	CIP	*Solanum*	312	76	Improved	Peru
10865	ILRI	*Sesbania*	268	66	Weedy/ wild	Unknown
104	ILRI	*Desmodium*	253	51	Improved	Australia
CIP 720088	CIP	*Solanum*	252	101	Improved	Argentina
4	ILRI	*Stylosanthes*	247	53	Improved	Colombia
69	ILRI	*Macroptilium*	247	59	Improved	Unknown
4918	ICRISAT	*Cicer*	246	13	Improved	India
5159	IRRI	*Oryza*	246	21	Landrace	Philippines
30333	IRRI	*Oryza*	245	23	Landrace	Philippines
6765	ILRI	*Desmodium*	240	50	Improved	Unknown
140	ILRI	*Stylosanthes*	232	49	Improved	Brazil

Table 9 continued

Accession number	Centre	Genus	Frequency of distribution	Number of recipients	Biological status	Country of origin
CIP 379706.27	CIP	*Solanum*	220	88	Improved	Peru
70	ILRI	*Leucaena*	219	55	Improved	Unknown
30416	IRRI	*Oryza*	213	41	Improved	Philippines
ITC0249	Bioversity	*Musa*	213	50	Weedy/wild	Unknown
75	ILRI	*Stylosanthes*	212	50	Improved	Venezuela
ITC0504	Bioversity	*Musa*	212	77	Improved	Unknown
ITC1123	Bioversity	*Musa*	212	67	Landrace	Unknown
599	IRRI	*Oryza*	210	18	Breeding/research	Philippines
CIP 378017.2	CIP	*Solanum*	210	88	Breeding/research	Peru
CIP 720087	CIP	*Solanum*	209	91	Improved	Argentina
6756	ILRI	*Macrotyloma*	208	51	Improved	Unknown
7035	ICRISAT	*Cajanus*	207	16	Improved	India
CIP 374080.5	CIP	*Solanum*	203	67	Improved	Peru
CIP 800827	CIP	*Solanum*	199	70	Improved	United States
CIP 978001	CIP	*Solanum*	195	54	Breeding/research	Peru
4973	ICRISAT	*Cicer*	194	14	Improved	India
6984	ILRI	*Medicago*	179	37	Improved	Unknown
10320	IRRI	*Oryza*	178	30	Improved	Philippines
12048	IRRI	*Oryza*	178	38	Other	Guinea
ITC0506	Bioversity	*Musa*	178	74	Improved	Unknown
27748	IRRI	*Oryza*	177	29	Landrace	Thailand
71	ILRI	*Leucaena*	176	43	Improved	Unknown
CIP 978004	CIP	*Solanum*	176	64	Breeding/research	Peru
66970	IRRI	*Oryza*	175	38	Improved	Philippines
CIP 984001	CIP	*Solanum*	174	60	Breeding/research	Peru
167	ILRI	*Stylosanthes*	173	51	Weedy/wild	Venezuela
147	ILRI	*Lablab*	169	42	Improved	Unknown
17159	ICRISAT	*Cicer*	169	7	Weedy/wild	Turkey
5003	ICRISAT	*Cicer*	169	12	Improved	India
15036	ILRI	*Sesbania*	167	54	Improved	Uganda
6633	ILRI	*Chloris*	167	40	Improved	Unknown
11575	ILRI	*Cajanus*	163	50	Weedy/wild	Unknown
15019	ILRI	*Sesbania*	163	53	Weedy/wild	DR Congo

Table 9 continued

Accession number	Centre	Genus	Frequency of distribution	Number of recipients	Biological status	Country of origin
23364	IRRI	*Oryza*	163	29	Landrace	Philippines
ITC0505	Bioversity	*Musa*	163	68	Improved	Unknown
CIP 980003	CIP	*Solanum*	159	54	Breeding/ research	Peru
15632	ICRISAT	*Cajanus*	158	5	Weedy/ wild	India
312	ILRI	*Desmanthus*	157	42	Weedy/ wild	Belize

References

Bretting PK (2007) The U.S. National Plant Germplasm System in an Era of Shifting International Norms for Germplasm Exchange. In: Acta horticulturae. International Society for Horticultural Science (ISHS), Leuven, Belgium, pp 55–60

Burke MB, Lobell DB, Guarino L (2009) Shifts in African crop climates by 2050 and the implications for crop improvement and genetic resources conservation. Glob Environ Chang 19:317–325

Centre for Genetic Resources (2008) Collections. http://www.cgn.wur.nl/UK/CGN+Plant+Genetic+Resources/Approach/Safety+duplicates/. Accessed 1 Aug 2015

CGKB (2014) Procedures for in-country seed plant material distribution

Crosby A (1972) The Columbian exchange: biological and cultural consequences of 1492. Greenwood Publishing, Westport

Crosby A (1986) Ecological imperialism: the biological expansion of Europe, 900–1900. Cambridge University Press, Cambridge

Da Silva Mariante A, Amstalden Sampaio MJ, Valadares Inglis MC (2009) State of the Brazil's plant genetic resources. Second rep, Brazilia, DF

Diamond J (1997) Guns, germs and steel: the fate of human societies. Norton & Co., New York

Dreisigacker S, Zhang P, Warburton ML et al (2005) Genetic diversity among and within CIMMYT wheat landrace accessions investigated with SSRs and implications for plant genetic resources management. Crop Sci 45:653–661

Duvick DN (1984) Genetic diversity in major farm crops on the farm and in reserve. Econ Bot 38:161–178

Evenson RE, Gollin D (1997) Genetic resources, international organisations, and improvement in rice varieties. Econ Dev Cult Change 45:471–500

FAO (2009) Russia: country report to the FAO International Technical Conference on Plant Genetic Resources. Moscow, Russian Federation

FAO (2010) Report on the state of the world's plant genetic resources for food and agriculture. Food and Agriculture Organization of the United Nations, Rome

Fowler C, Hodgkin T (2004) Plant genetic resources for food and agriculture: assessing global availability. Annu Rev Environ Resour 29:10.1–10.37

Fowler C, Smale M, Gaiji S (2001) Unequal exchange? Recent transfers of agricultural resources and their implications for developing countries. Dev Policy Rev 19:181–204

Fujisaka S, Halewood M, Williams D (2011) Background study paper no. 48

Genesys (2014) A gateway to genetic resources. www.genesys-pgr.org. Accessed 17 Nov 2014

Halewood M, Nnadozie K (2008) Giving priority to the commons: the international treaty on plant genetic resources for food and agriculture. In: Tansey G, Rojotte T (eds) The future control of food: a guide to international negotiations and rules on intellectual property, biodiversity and food security. Earthscan, London

Halewood M, López Noriega I, Louafi S (2013) Crop genetic resources as a global commons: challenges in international governance and law. Routledge, Abingdon

Halewood M, Baidu-Forson JJ, Clancy E, Vodouhe RS (2014) Cooperating to make the best use of plant genetic resources in West and Central Africa: a regional imperative. Rome, Italy and Dakar, Senegal

Heisey P, Day Rubenstein K (2015) Using crop genetic resources to help agriculture adapt to climate change: economics and policy. U.S. Department of Agriculture, Economic Research Service, Washington

ICGR (2015) Utilization of Plant Genetic Resources in China. http://icgr.caas.net.cn/China/chinesutilization.htm. Accessed 12 Aug 2015

Jarvis A, Upadhyaya H, Gowda CLL, et al (2010) Climate change and its effect on conservation and use of plant genetic resources for food and agriculture and associated biodiversity for food security. In: Second state of the world plant genetic resources for food and agriculture. Food and Agriculture Organization of the United Nations, Rome, Italy, p 26

Khoury CK, Bjorkman AD, Dempewolf H et al (2014) Increasing homogeneity in global food supplies and the implications for food security. Proc Natl Acad Sci USA 111:4001–4006. doi:10.1073/pnas.1313490111

Koo DB, Pardey PG, Wrigh B (2004) Saving seeds: the economics of conserving crop genetic resources ex situ. Wallingford, UK and Cambridge, MA, USA

Laird SA, Wynberg R (2006) The commercial use of biodiversity: an update on current trends in demand for access to genetic resources and benefit-sharing, and industry perspectives on ABS policy and implementation. Montreal, Canada

Lane A, Jarvis A (2007) Changes in climate will modify the geography of crop suitability: agricultural biodiversity can help with adaptation

López Noriega I, Halewood M, Galluzzi G et al (2013a) How policies affect the use of plant genetic resources: the experience of the CGIAR. Resources 2:231–269

López Noriega I, Wambugu P, Mejías A (2013b) Assessment of progress to make the multilateral system functional: incentives and challenges at the country level. Crop genetic resources as a global commons: challenges in international governance and law. Routledge, Abingdon, pp 199–225

Mann CC (2011) 1493: uncovering the new world Columbus created. Knopf, New York

R Development Core Team (2011) R: A language and environment for statistical computing

Ramirez-Villegas J, Jarvis A, Fujisaka S et al (2013) Crop and forage genetic resources: international interdependence in the face of climate change. In: Halewood M, López Noriega I, Louafi S (eds) Crop genetic resources as a global commons: challenges in international law and governance. Earthscan, London, pp 78–98

Rejesus RM, Smale M, Van Ginkel M (1996) Wheat breeders' perspectives on genetic diversity and germplasm use: findings from an international survey. Plant Var Seeds 9:129–147

SGRP (2011) CGIAR Centers' Experience with the Implementation of Their Agreements with the Treaty's Governing Body, with Particular Reference to the Use of the SMTA for Annex 1 and Non-Annex 1 Materials

Smale M, Day Rubenstein K (2002) The demand for crop genetic resources: international use of the US national plant germplasm system. World Dev 30:1639–1655

Smale M, Reynolds MP, Wharburton M et al (2002) Dimensions of diversity in modern spring bread wheat in developing countries from 1965. Crop Sci 42:1766–1779

Smolders W (2005) Commercial practice in the use of plant genetic resources for food and agriculture. Background study paper prepared for the Commission on Genetic Resources for Food and Agriculture, Food and Agriculture Organisation of the United Nations, Rome, Italy, 18 pp

Ullrich SE (2011) Barley: Production, improvement, and uses. Wiley-Blackwell, Chichester

UN (2012) Statistical annex - Data sources, country classifications and aggregation methodology. In: World Economic Situation and Prospects. United Nations, p 9

Voysest O, Johnson N, Pachico D (2003) The distribution of benefits from public international germplasm banks: the case of beans in Latin America. Agric Econ 29:277–286

Warburton ML, Crossa J, Franco J et al (2006) Bringing wild relatives back into the family: recovering genetic diversity in CIMMYT improved wheat germplasm. Euphytica 149:289–301