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REVIEW

Trends in *ex situ* conservation of plant genetic resources: a review of global crop and regional conservation strategies

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Abstract In 2005, the newly established Global Crop Diversity Trust initiated a consultation process leading to the development of over 30 global crop and regional strategies for the *ex situ* conservation and utilisation of crop diversity. These strategies represent a major undertaking the field of plant genetic resources, mobilizing experts to collaboratively plan for the more efficient and effective conservation and use of crop diversity. The strategies are reviewed for eight themes: regeneration, crop wild relatives, collecting, crop descriptors, information systems, user priorities, new technologies and research, and challenges to building a strategy for rational conservation. The themes shed light upon the status, constraints, and promising directions regarding *ex situ* conservation and utilization of plant genetic resources globally, and provide insight into the current challenges to planning for an efficient and effective global system. The primary constraints affecting conservation, use, and planning are the quality and availability of accession-level information, and availability of resources for regeneration, collecting, and research. A series of connected organizations working at the global level are addressing some of the major constraints in regeneration, collecting, information systems, descriptors, user involvement, and new technology development, although certain crops and regions will need additional support beyond the activities currently funded, particularly in collecting and in the development of specific conservation technologies. Achieving an efficient and effective global system will depend on active support by stakeholders, and will be aided by continuing to develop the strategies and by supporting the strategies' recommendations for efficient and effective practices in plant genetic resources.

Keywords Crop diversity · *Ex situ* conservation · Genebank · Plant genetic resources

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Introduction and methods

International agreements regarding plant genetic resources call for a more efficient and effective global system in order to ensure that genetically unique diversity is securely conserved and is available for utilization. The Global Plan of Action for the Conservation and Sustainable Use of Plant Genetic Resources for Food and Agriculture (GPA), adopted by 150 countries at the International Technical Conference on Plant Genetic Resources in 1996, and drawing upon the State of the World's Plant Genetic Resources for Food and Agriculture (1997), outlined the benefits of the global system:

> With a more rational system based on better planning and more coordination and cooperation, costs could be reduced and conservation work placed on a scientifically sound and financially sustainable foundation. This would lay the groundwork for expanded utilization of plant genetic resources for food and agriculture, in the context of more effective conservation (FAO 1996).

The development of a global system within existing international agreements necessitated that the International Undertaking on Plant Genetic Resources (1983) be revised in accordance with the Convention on Biological Diversity (1992). This eventually led to the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), which has the specific objective of the conservation and sustainable use of plant genetic resources for food and agriculture and the fair and equitable sharing of the benefits arising out of their use (FAO 2002).

In recognition that sustainable funding would be necessary to address the financial resource gaps that have continued to plague *ex situ* conservation efforts, and to aid in the development and the maintenance of the rational global system outlined in the ITPGRFA and the GPA, the Global Crop Diversity Trust (the Trust) was founded by the United Nations Food and Agriculture Organisation (FAO) and by Bioversity International, acting on behalf of the Consultative Group on International Agricultural Research (CGIAR). A conceptual framework regarding the role of the Trust in conserving and making available crop diversity is presented in "The Role of the Global Crop Diversity Trust in Helping Ensure the Long-Term Conservation and Availability of PGRFA" (Global Crop Diversity Trust 2007c), and the current programs and activities are described on the Trust website (www.croptrust.org).

The evolution toward a rational global system necessitates the identification of the location and status of unique genetic diversity, and the outlining of the processes by which this diversity can be most efficiently and effectively conserved and utilized for the benefit of the global community. Toward this end, from 2005 the Trust has supported the development of *ex situ* conservation and utilization strategies with two complementary and mutually reinforcing approaches: one is to identify key crop diversity collections and conservation/utilization needs on a region-by-region basis (regional conservation strategies) and the other is on a crop-by-crop basis at the global level (global crop conservation strategies). The strategies are roadmaps toward an efficient and effective global system. They are also important guiding documents for the Trust and other donors by contributing to the identification of funding priorities that ensure the conservation and availability of crop diversity for food security worldwide, specifically the diversity of crops listed in Annex 1 of the ITPGRFA.

The strategies are created through a collaborative process involving crop and regional experts such as genebank curators and managers, researchers, breeders, and national programme coordinators as well as the international Centres of the CGIAR with the global mandate for conservation and use of the specific crop. The global crop strategy development process generally involves the identification of a leading expert in conservation and use of the crop, who is responsible for the task of contacting crop collections worldwide in order to obtain information regarding: contents; storage conditions; regeneration status; safety duplication status; status and accessibility of collection passport, characterization, and other data; and utilization information, and other related data. Results of these surveys are collated, and then reviewed and discussed during meetings of crop experts. Aside from identification of the most important collections, gaps in collections are identified, status and needs for partnerships, training, utilization, and networks debated, and policy opportunities and constraints discussed. After peer review, a strategy is published which outlines priority collections, identifies collections in need of support in order to conserve and distribute resources more effectively, and highlights gaps in collections as well as needs for partnering, training, policy, etc. Even though the strategies become 'final', they are working documents, meant to evolve as new information becomes available and projects and activities progress as the global system is developed. The regional conservation strategies follow a similar process, but draw upon a series of meetings of scientists and national program managers via regional networks to identify the regional priorities. Since 2005 many hundreds of scientists and experts have contributed to the strategies.

In combination, the strategies provide a global perspective on the current issues regarding the conservation and use of plant genetic resources, and the viewpoints on better arrangements for their management in the future. In order to identify some major common trends in *ex situ* needs worldwide, this paper examines eight themes arising from the global crop and regional conservation strategies:

1. regeneration,
2. crop wild relatives,
3. collecting,
4. crop descriptors,
5. information systems,
6. user priorities,
7. new technologies and/or research,
8. challenges to building a robust strategy for rational conservation.

Twenty-six strategies were examined in total, including 18 global crop (aroid; banana; barley; breadfruit; cassava; chickpea, coconut; grasspea; lentil; maize; oat; pigeonpea; potato; rice; sorghum; strawberry; sweetpotato; and wheat, rye and triticale) and 8 regional strategies (Americas; Central Asia and the Caucasus; Eastern Africa; Pacific Islands; South, Southeast, and East Asia; Southern Africa; West Asia and North Africa; and West and Central Africa).

The completed crop and regional strategies and supporting guidelines are published and available for download from the Trust website (Global Crop Diversity Trust 2006, 2007a, b). The aroids, cassava, pigeonpea, and rice strategies are drafts in varying states of completion, but in general are fairly advanced. Major changes to the themes examined in this analysis are therefore unlikely to change significantly during finalization stages. One exception is the first draft rice strategy, whose gaps include areas covered by the themes. Strategies in planning for future development include *Phaseolus* beans, cowpea, finger millet, pearl millet, and yam.

Results and discussion

Regeneration

The periodic regeneration of seed accessions stored in genebanks is necessary in order to maintain optimal seed viability and to replenish seed stocks for distribution. Vegetative accessions likewise require rejuvenation via field cultivation or subculturing of tissue stored in laboratory conditions (in vitro). Among genebank activities, regeneration is a relatively costly procedure requiring land, labour, material resources and complex planning (Sackville Hamilton and Chorlton 1997; Koo et al. 2004).

Every strategy that assesses current regeneration needs identifies significant concerns regarding regeneration backlogs and the subsequent loss of unique genetic diversity held *ex situ*, concerns echoed in research and assessments of the status of plant genetic resources conservation (FAO 2009b; Dulloo et al. 2008; Imperial College Wye 2002; Engels and Rao 1998; Hammer et al. 2003; Fowler and Hodgkin 2004; Schoen et al. 1998; Qualset and Shands 2005; Hammer 2004). As highlighted in the Wheat Strategy, regeneration backlog is a critical problem in *ex situ* conservation: “regeneration is probably the single greatest threat to the safety of wheat accessions held in globally important genebanks” (Global Strategy for the *ex situ* Conservation with Enhanced Access to Wheat, Rye, and Triticale Genetic Resources 2007).

Lack of adequate funds is the greatest impediment to successful regeneration of genebank collections, leading to deficiencies in labour, infrastructure, and materials, and to postponement of regeneration activities beyond the ideal interval. Lack of skilled staff is a constraint especially evident in more difficult or poorly researched species and genotypes.

Regeneration backlogs are noted in all types of germplasm (seed crops- both cross-pollinating and self-pollinating, vegetatively propagated species, tree crops, wild species, etc.) and in all regions. The field regeneration of vegetatively propagated species such as sweet potatoes, cassava, bananas, aroids, and strawberries is particularly constrained by the challenge and cost of controlling plant disease. Due in part to the need to continually ensure disease-free conditions for these crops, slow-growth storage of vegetative material in vitro has become increasingly prominent.

Cross-pollinating (allogamous) species present greater management difficulties during regeneration, as their ability to easily cross with neighbouring accessions requires additional planning, care, and special techniques in order to ensure isolation of accessions (Richards 2001). Common regeneration techniques for allogamous species include spatial or temporal isolation, caging, and hand pollination. Wind pollinated, allogamous crops with very small flowers and self-incompatibility, such as rye, represent the extreme of difficulty in managing the regeneration of such crops.

Crop wild relatives (CWR) present a series of additional regeneration challenges (Brown et al. 1997; Engels and Rao 1998). Many wild species, including those with self-pollinating (autogamous) domesticated relatives, are cross-pollinating, as in wheat (*Aegilops speltoides* Tausch) (Zaharieva and Monneveux 2006), barley (*Hordeum bulbosum* L.) (von Bothmer et al. 1995), and oat (*Avena macrostachya* Balensa ex Coss. et Durieu) (Global Strategy for the *ex situ* Conservation of Oats (*Avena* spp.) 2008). Along with the challenges of regenerating cross-pollinating related species (Chen et al. 2004), CWR of rice typically produce low seed yields and exhibit high degrees of shattering, such that large accession plots must be planted to produce adequate seed. Certain CWR, such as wild oat (*Avena fatua* L.), have the potential to become noxious weeds and therefore require special containment measures during regeneration.

For vegetative crops such as potatoes, cassava, and sweet potatoes, some CWR can be conserved as true seeds, facilitating conservation by extending the interval between regenerations and lowering storage maintenance costs. At the time of regeneration, though, species present various challenges to cultivate, isolate, produce adequate seed quantities, and maintain genetic diversity within accessions. Research is needed to address these constraints in order to improve regeneration practices.

Photoperiod requirements may limit the success of regenerating certain accessions in standard regeneration facilities. Accessions whose ecological requirements for successful regeneration are not easily replicable by curators must be regenerated with additional effort and this may necessitate international collaboration.

Regeneration activities complement a range of other genebank functions, including multiplication, gathering of characterization data, and ridding accessions of disease. Characterization of accessions not only produces valuable agronomic and breeding data, but also is useful for the identification of duplicates within and between collections, contributing to the potential for rationalization (i.e. elimination of unnecessary duplication) of collections, which in turn can help ensure that the limited resources available for regeneration are used most efficiently and effectively.

Adequate funding for regeneration is necessary in order to support labour, grow-out costs, materials and infrastructure purchases, replanting of field collections, the transfer of field collections to in vitro and cryopreservation storage, production of disease-free vegetative material, and related activities. New research and technologies are needed in order to develop or refine successful regeneration techniques, especially for vegetative crops and for wild species, in order to regenerate difficult germplasm, extend the time interval between regenerations, and lower maintenance requirements.

Crop wild relatives

Wild species related to crops have proved useful to crop improvement as sources of a variety of valuable traits, particularly pest and disease resistance, and tolerance to abiotic stress (Hajjar and Hodgkin 2007; Tanksley and McCouch 1997; FAO 2009b; Meilleur and Hodgkin 2004; Maxted and Kell 2009; Hoisington et al. 1999; McCouch et al. 2007; Gur and Zamir 2004; Damiana 2008). The wild portion of a crop genepool generally contains much greater genetic variation than that contained in the cultivated taxa, as domestication and improvement have created genetic bottlenecks that have limited the diversity available in the crop (Vollbrecht and Sigmon 2005; Petersen et al. 1994; Tanksley and McCouch 1997; Damiana 2008).

The majority of the strategies that remark on CWR relate that valuable traits for crop production have been derived from wild genetic resources, with statements such as "the wild relatives of wheat have proved to be highly useful sources of resistance to biotic and abiotic stresses in wheat breeding over the last two decades and this trend is expected to accelerate in the future" (Global Strategy for the *ex situ* Conservation with Enhanced Access to Wheat, Rye, and Triticale Genetic Resources 2007). The remaining strategies appreciate the potential value of wild relatives to crop improvement and food security, and identify ongoing research programs working with wild resources. The breadfruit and aroids strategies also recognize the economic value of wild related species in their own right for food production. Thus, all of the strategies that include a discussion on CWR identify current or potential value to crops and regions, as encapsulated by the WANA regional strategy statement:

> The wild relatives of crop plants…constitute an increasingly important resource for improving agricultural production and for maintaining sustainable agro-ecosystems. They have contributed many useful genes to crop plants, and modern varieties of most crops now contain genes from their wild relatives. The wise conservation and use of crop wild relatives are essential elements for increasing food security, eliminating poverty, and maintaining the environment (Towards a regional strategy for the conservation of plant genetic resources in: West Asia and North Africa [WANA] 2006).

Resistance to pests and diseases, and tolerance to abiotic stresses, are the major focus of research with wild resources identified in the strategies. Wild species have also contributed to breeding techniques. For hexaploid domesticated oat, a wild species representing a genetic intermediate in terms of ploidy has facilitated hybridization with tetraploid wild relatives. Wild species containing cytoplasmic male sterility and restorer traits have been utilized in rice, pigeonpea, and rye, permitting efficient hybrid variety production.

The conservation of CWR is increasingly widely recognized as a high priority (Maxted and Kell 2009; Heywood 2008; Meilleur and Hodgkin 2004; Hammer et al. 2003; Maxted 2003; Jarvis et al. 2003; Maxted et al. 2008a, b; Damiana 2008), and a number of global and regional initiatives focus on conservation and information sharing regarding CWR (Bioversity International 2009a; IUCN/SSC 2008; Bioversity International 2008; European Crop Wild Relative Diversity Assessment and Conservation Forum 2008). Estimates of the percent of *ex situ* holdings worldwide comprised of wild or CWR accessions range from 2% (Astley 1991), 2–6% (Maxted and Kell 2009), 15% (Hammer et al. 2003), and 18% (FAO 2009b). Very large gaps in species coverage remain to be filled; Maxted and Kell (2009) estimated that 94% of European crop wild relative species are entirely missing from *ex situ* collections. The strategies depict current conservation of wild relatives as varying greatly by crop, from a poor representation in wheat, lentil, chickpea, and cassava, to dominance in terms of the overall number of accessions globally in potato. The high representation of CWR in some vegetative crops is likely due more to the relative ease of conservation of wild species as true seed, compared to the challenge of vegetative maintenance of cultivated varieties, than to a greater prioritization of CWR in conservation or breeding programs for these crops.

The collection of CWR from important regions of diversity has been constrained in some crops by limited cooperation and exchange at the international level, as well as limited resources devoted to collection at the national level. Collection of CWR may also have been neglected compared to domesticated resources because the conservation of wild relatives tends to fall between the ecological conservation movement and the agricultural conservation sector (Maxted 2003), or due to a viewpoint that wild species are less threatened *in situ* in comparison to other types of germplasm, such as landraces (Global Strategy for the *ex situ* Conservation with Enhanced Access to Wheat, Rye, and Triticale Genetic Resources 2007). This viewpoint is likely to change in regions with increased impacts on CWR from climate change (Brooks et al. 2006; Thuiller et al. 2005; FAO 2008; Maxted and Kell 2009).

Even in crops with large collections of wild germplasm, the diversity within the accessions themselves may be limited. Although sizeable collections of teosinte are conserved in four institutes, these accessions were largely collected for research rather than conservation, with few seeds collected per accession. Sampling for long-term conservation of most in situ populations of wild maize (*Zea* L.) is therefore a priority.

Priority actions for conservation of CWR repeated in the strategies include further collecting, regeneration, safety duplication, and *in situ* conservation. Threats to CWR of maize, wheat, oat, cassava, and banana include habitat destruction, deforestation, urbanization, climate change, grazing, expansion of modern agriculture, and the abandonment of traditional agriculture (this last case for wild maize, which is adapted to traditional farming agroecosystems (Wilkes 2007).

Among the most significant means to expand use of CWR identified in the strategies is improving accession-level data of wild material through evaluation, ploidy determination, molecular characterization, and by correcting taxonomic misidentifications. Development of CWR through pre-breeding, and application of technologies such as somatic hybridization, gene transformation, and better regeneration techniques are also prioritized in order to enhance the availability of accessions for use.

Collecting

The urgency for collection of plant genetic resources in order to fill gaps in collections and to conserve unique diversity before it is extirpated *in situ* has been recognized for decades (Frankel and Bennett 1970; Hawkes 1971; Harlan 1972; Wilkes 1977) and continues to be emphasized (Zedan 1995; Vetelainen et al. 2009; Hammer et al. 2003; Kiambi et al. 2005; Wilkes 2007; Maxted and Kell 2009; Johnson 2008; Burke et al. 2009; Damiana 2008). FAO (2009b) highlights the need for collection particularly for neglected and underutilized crop diversity, and for CWR. Many of the international genebanks in the CGIAR are currently emphasizing the need to collect CWR (Halewood and Sood 2006), and U.S. germplasm experts ranked acquiring additional materials as the number one funding priority for the U.S. germplasm system (Zohrabian et al. 2003). Despite these efforts, the number of accessions collected per annum has on average decreased since the mid-1980's (FAO 2009b; Fowler et al. 2001).

The strategies collectively prioritize collecting as an important activity for the present and future, both for wild relatives and landraces. Collection priorities for CWR follow the estimated value of the resources for use: closely related species are prioritized for collection and conservation over more distantly related taxa. For the more distant relatives, or in the case of difficult or expensive collecting, "there should probably be a combined weight given to environmental threats to populations in the wild, along with expected potential use in (crop) genetic improvement" (A Global Conservation Strategy for Cassava (*Manihot esculenta*) and Wild *Manihot* Species 2008 Draft).

The primary reason given for the prioritization of collecting is to fill taxonomic, geographic, or trait gaps in current collections, or even to re-establish entire collections, as in the West and Central Africa strategy. Collection is also prioritized in order to conserve species subjected to habitat destruction and climate change, e.g. for oat genetic resources in North Africa, and coconut genetic resources in the South Pacific and Indian Ocean regions.

A number of the strategies prioritize research on existing collections through geo-referencing and spatial analysis prior to collecting, and promote collaboration between genebanks and breeders, in order to make future collecting more efficient and effective. The East Africa strategy recognizes that collaborative collecting involving a number of nations would be helpful for the conservation of cross-border weedy and wild species.

Crop descriptors

The usefulness of samples held in genebanks is dependent upon the degree and quality of information connected to the samples (Rubenstein et al. 2006; Damiana 2008). Since 1976, Bioversity International (formerly IBPGR 1974–1991; IPGRI 1991–2006) has supported the production of descriptor lists by relevant expert groups providing an internationally agreed format for passport, characterization, and evaluation data collection on accessions in genebanks. Ninety-five individual crop descriptors have been published, as well as multi-crop lists [List of Multicrop Passport Descriptors (2001); List of Descriptors for Genetic Marker Technologies (2004)], and lists have been published in at least 8 languages. Over the years these lists have become more comprehensive in scope and many have come to include sub-set lists of the most important discriminating descriptors. Gotor et al. (2008) found Bioversity descriptors to be the best known of crop descriptors worldwide, generally rated as essential by the plant genetic resources community, particularly for developing databases, increasing uniformity in documentation, increasing collaboration with partners, making collections more efficient through aiding in identifying and reducing duplication, and improving use of collections.

The Bioversity crop descriptors are the standard accepted descriptors currently used, as stated in every crop strategy for which a Bioversity descriptor list has been published. Gotor et al. (2008) found that the majority of users of the Bioversity descriptors adapted them, with only 20% using them without modifications. Additional descriptors (e.g. USDA-GRIN, UPOV) may be used separately, or in supplement to Bioversity descriptors for specific material, and a minority of collections use their own descriptors instead of Bioversity descriptors. In the absence of Bioversity descriptors, as in the case of breadfruit, the sole major collection described in the breadfruit strategy (the National Tropical Botanical Garden [NTBG]) uses its own descriptor system (Ragone and Wiseman 2007). Traditional vegetables and other crops without descriptors have been characterized in Southern Africa in collaboration with the International Centre for Underutilized Crops.

Degree of completion of passport, characterization, and evaluation data is inconsistent across different institutions for all crops and regions examined, and the data itself also varies in quality. In general, the completion of passport data is at a high level, with lower amounts of characterization and especially evaluation data, and very little molecular characterization data to date. Despite rapid advances in molecular techniques and an increasing call for characterization of germplasm based on these tools (Gepts 2006), much still remains to be done in order to complete characterization of collections. The maize strategy relates degree of completion of morphological descriptor data to date of regeneration; the more recent the regeneration, the more descriptor data available.

Future needs in relation to descriptors fall into three categories. The majority of strategies evaluate existing descriptors as more or less adequate, and recognize the importance of adoption and standardization of use of a common descriptor across all collections. With standardization and adequate training, accessions may be more easily compared across collections, facilitating greater utilization and rationalization of collections.

Secondly, the barley, oat, and sorghum strategies prioritize the review and updating of existing Bioversity descriptors. For the latter two strategies, as well as for the chickpea and the lentil strategies, the development of a list of a minimum number of characters of highest priority within the descriptors is also envisioned as an important step in providing greater standardization between collections as well as improved utilization of accessions. Thirdly, the strategies for crops that do not currently have a standard published descriptor call for the development and publication of such a list. These strategies include the aroid strategy, for giant swamp taro (*Cyrtosperma merkusii* (Hassk.) Schott); the breadfruit strategy, based on the NTBG collection descriptors; the cassava strategy; and the Southern Africa regional strategy, in regard to regional underutilized crops.

Information systems

Data management systems in genebanks are vital to tracking accessions for management purposes and for adding value to accessions for efficient utilisation. The strategies agree with assessments that the establishment and quality of genebank management information systems varies between institutes, from poorly completed, non-computerized lists to online databases incorporating descriptors, molecular data, photos, geo-reference data, and more (FAO 2009b; van Hintum et al. 2008; Qualset and Shands 2005; Imperial College Wye 2002).

A number of global or regional information databases exist for crops, gathering some degree of accession-level data from many collections into a centralized source. Examples include the Global Inventory of Barley Genetic Resources (GIBGR), which holds data on 190,000 accessions from 62 institutes; the Coconut Genetic Resources Database (CGRD); The *Musa* Germplasm Information System (MGIS); the SADC Plant Genetic Resources Centre (SPGRC) Documentation and Information System; the EURISCO and crop specific databases of the European Cooperative Program for Plant Genetic resources (ECPGR); and the System-wide Information Network for Genetic Resources (SINGER) of the CGIAR.

The strategies highlight the need for the creation or improvement of an information system that links at least the most important collections together, so as to create a single searchable database of crop or regional genetic resources. Most of the strategies place a very high priority on acting to build better information systems:

> any such (global conservation system) is ineffective without an effective information resource on which to base decisions and strategies. Indeed the lack of coordinated information is the major

hindrance to the development of an efficient and rational global strategy…therefore at the heart of the network there must be a global information system documenting, as far as possible, the relevant data of all accessions conserved in all participating genebanks (A Global Strategy for the effective and efficient conservation of rice 2008 First Draft).

Lack of accession-level information and robust systems for managing and sharing data is a major constraint to greater efficiency of conservation and use of crop diversity (FAO 2009b; Fowler and Hodgkin 2004; Heywood 2008; Qualset and Shands 2005). Better information management systems within genebanks as well as integrated information systems linking collections, serve a variety of needs. Regarding conservation, improved information systems aid in identifying unique germplasm versus duplications, a prerequisite to the building of a rational global conservation system. Information such as geo-reference data contributes to gap analyses that identify collecting priorities. Regarding utilization, integrated information systems make more easily available the data that interests breeders and researchers, and will aid in the reporting requirements for benefit sharing regarding transfers required by the ITPGRFA. Analysis of germplasm transfers through robust information systems should also reinforce the need for and the benefits of an effective global system, illuminating the global interdependence of agricultural research (Fowler et al. 2001; Rubenstein et al. 2006).

Constraints to the construction of robust information systems for genebanks are three-fold. First, the technology, infrastructure, and knowledge base supporting information systems must be present. A number of strategies, particularly the sweetpotato and the Southern Africa strategies, identify constraints regarding equipment and technology. Some of these constraints are easily addressed through the acquisition of better equipment. Others, such as the lack of development of Internet infrastructure in the regions where rural genebanks are located, are more difficult to resolve.

Second, the construction of a valuable integrated information system is limited by the paucity of accession level information, including passport, characterization, evaluation, geo-reference, and other data. Finally, the stakeholders involved in conservation of the plant genetic resources must support the continued maintenance of information systems. Lack of motivation or capacity to update an integrated information system lowers the overall quality of the system, as has been noted in the *Musa* Germplasm Information System (Global Conservation Strategy for *Musa* [Banana and Plantain] 2006).

User priorities

Genebanks conserve diversity for present and future utilisation. Parallel with the need to collect and securely maintain plant genetic resources is the effort to promote use of these resources for agricultural development, production, education and research. With increasing pressures from climate change, the drive for a more ecologically-sensitive agriculture globally, the need to maintain or increase food production, and the continuing rapid evolution of new research technologies, the sustainable use of crop genetic diversity is critically important and has an increasing potential for greater use (FAO 2009b).

Utilization of plant genetic resources conserved in genebanks is limited by a range of factors, some related to the genebanks and related policy arrangements, some to the users themselves. Among users, FAO (2009b) found human resource capacity, funding, facilities and infrastructure to present the major constraints to greater use of genetic resources. The decline in public breeding programs evident in the last decade has further weakened the use of genetic diversity held in many national genebanks (FAO 2009b). Constraints connected to the genebanks include accession-level data existence and accessibility, quality and status of the material, policy and legal obstacles, and awareness/education/outreach (Weidong et al. 2000; Fowler and Hodgkin 2004; FAO 2009b).

The greatest constraint on utilization of plant genetic resources by researchers, taxonomists, breeders, farmers, and other users of germplasm presented in the strategies is the lack of accession level information, including passport, characterization (morphological and molecular), and evaluation data, especially for 'useful' traits. Even when data exists, low quality or reliability of characterization data, lack of use of standard descriptors, and constraints on access to information limit the usefulness of the data.

Constraints in germplasm availability also limit use, especially in vegetative crops, but also in orthodox seed crops such as sorghum and wheat. These constraints are often due to lack of adequate financial support in genebanks, leading to an under-investment of resources in multiplication and regeneration, or disease eradication (Fowler and Hodgkin 2004). In the case of breadfruit, the planned duplication of the NTBG collection in in vitro storage is predicted to help overcome availability limitations. Other constraints due to the collections themselves include difficulties in using CWR, gaps in desired traits in collections, genetic pollution in collections, and infection of accessions with diseases. Other constraints include lack of access to germplasm, and overly restrictive or unwieldy phytosanitary restrictions between countries/regions.

Genetic resources of most interest to breeders include advanced material (e.g. pre-bred material, breeding lines, adapted varieties, elite material) and research material (e.g. advanced core collections, mapping populations, mutant and genetic stocks mutants, and CWR). In general, breeders are interested in genebank material that has already been subjected to some degree of refinement or evaluation. In order to serve these users, "interesting genes must be introgressed into a context more attractive to breeders" (Global Strategy for the *ex situ* Conservation of Oats [*Avena* spp.] 2008). Researchers and other users, on the other hand, may be interested in a wider range of more diverse materials, and the goals of conservation of genetic diversity in genebanks broaden the spectrum of materials targeted for storage. Thus, priorities for the sort of work needed to attract breeders to collections may not always coincide with priorities asserted by collection managers: "genebank curators…took the…view that their focus should be on landraces and the near relatives…(breeders) are expecting collections to increase the range of materials they hold and distribute, in line with advances in the science of genetics and breeding, while curators maintain a more traditional view of the role of genebanks" (Global Strategy for the *ex situ* Conservation with Enhanced Access to Wheat, Rye, and Triticale Genetic Resources 2007).

Priorities outlined in the strategies to enhance user relationships with collections include refinement of collections for breeders (such as with marker-assisted selection technologies, creation of advanced core and mini-core collections, pre-breeding, further work on identifying diseases and resistance, and use and testing of elite material), and strengthening or creating new relationships with other users (e.g. creating international exchange networks, promoting plant genetic resources use through research and publication, building plant breeding capacity, developing innovative distribution relationships with organizations, and use of farmer-first and participatory plant breeding strategies).

The effect of the ITPGRFA on use of plant genetic resources is just beginning to be seen. The Multilateral System of access and benefit sharing of the Treaty is intended to directly increase use through facilitating access to the genetic materials held in public genebanks in member countries. Although the majority of countries have ratified the ITPGRFA (FAO 2009c), a number of countries holding major and important crop collections have not yet ratified, and in some member countries further policy work is necessary to clarify which collections are under the Treaty and to establish protocols for distribution under the Treaty. In order to increase use, there is a continuing need for the creation of greater awareness among policy makers and the general public of the value of crop diversity collections and the global interdependence on those collections for agricultural research, and action to strengthen and expand the Multilateral System in order to provide greater access to the global community.

New technologies and/or research

The techniques and protocols for the maintenance of orthodox seed crop species in cold, dry conditions in genebanks are well developed, but with underutilized or under-researched species, particularly tropical vegetative crops, CWR, and unusual genotypes, gaps remain in order to establish methods that ensure secure long-term conservation.

The greatest need identified in the strategies for research or new technologies involves the development or further refining of conservation techniques for in vitro storage and cryopreservation for vegetative crops (e.g. aroids, bananas, breadfruit, cassava, coconut, and sweetpotato). Various levels of infrastructure, protocols, and capacity exist in different collections in different regions. In many cases, protocols and infrastructure for these vegetative crops are already partially in place, but need to be extended to more institutions through capacity building, or refined to the needs of specific genotypes. Complementary to the conservation of vegetative germplasm, a number of strategies for these crops also identify research needs for seed conservation (e.g. induction of flowering for taro in the aroid strategy, seed conservation research in the breadfruit strategy, and flowering, germination, and maintenance of variability of seeds research in the cassava strategy). Other research areas identified in these strategies include the development of better techniques to facilitate movement of germplasm, generally involving tissue culturing, and also improving disease indexing and cleaning, both for vegetative propagules and true seeds.

Of the orthodox crops, research priorities include improving the techniques for molecular characterization (wheat), creating alternative, more efficient means of distribution to researchers (i.e. DNA distribution instead of seed distribution to appropriate researchers for maize), and further research on regeneration and storage protocols for wild relatives (chickpea) and non-orthodox germplasm (e.g. for glutinous rice accessions that do not conserve well at conventional temperature/moisture levels).

Challenges to building a robust strategy for rational conservation

The global crop and regional conservation strategies are a step in the process of converting the goals outlined in the ITPGRFA and the GPA for a rational global system of conservation and use into concrete roadmaps with specific actions for *ex situ* activities. Analysis of the strategies illuminates the difficulty of the task at hand, as the relative progress achieved in the planning effort is dependent upon the degree of available information and active collaboration by the plant genetic resources community, as well as political goodwill toward a global system.

The dominant constraint to mapping a strategy for efficient and effective conservation identified in the strategies is a lack of sufficient accession- and collection-level information to be able to confidently order collections by importance, identify duplicates, and complete other tasks vital to creating an ideal strategy. The cassava strategy expresses the challenge involved with interpreting existing data on collections:

> There are two principal issues that confound the interpretation of most registers of cassava genebanks, and probably for the genebanks of other species as well: in general it is not possible to distinguish what part of the accessions are landrace varieties, as opposed to bred varieties, or some other form or origin of material. And often it is also not possible to distinguish local landraces from landraces introduced from another country (A Global Conservation Strategy for Cassava (*Manihot esculenta*) and Wild *Manihot* Species 2008).

A number of strategies identify constraints based on the use of different taxonomic systems and identification numbers between collections, as well as misidentification of wild species in some collections. These inhibit the ability to compare collections efficiently. In addition, for most crops, some institutes did not respond to the survey or did not participate in the planning meetings, resulting in gaps in data regarding their collections.

A number of policy and legal constraints that affect planning are raised in the global crop strategies, echoing concerns raised by researchers regarding political limitations on access and use, and calling for greater collaboration (Gepts 2006; Fowler and Hodgkin 2004; Hammer et al. 2003; Fowler et al. 2001). Countries holding important collections but not currently Party to the ITPGRFA present potential constraints regarding access to germplasm. It is unclear in some of these cases whether the germplasm will be available to the global community in the future, and therefore whether institutes within these countries will be able and willing to serve key roles in the global system. The rice strategy identifies difficulties with the creation of safety duplication arrangements, even between countries that have ratified the Treaty. It is evident that political will and consensus regarding the obligations of the Treaty must be present at all levels (i.e. at the national programme and/or collection level as well as governmental levels) in order to achieve compliance toward the goals of facilitated exchange of germplasm.

Global activities to achieve the goals of the strategies

The genetic diversity conserved in *ex situ* collections is due to the work of countless dedicated individuals and institutions worldwide, and the current work to improve the global system builds upon their efforts. We briefly discuss here major global-level initiatives related to the themes presented in the strategies.

The ITPGRFA has opened a new era in conservation and use of crop diversity, and in 2009 announced its first distribution of grants in support of a variety of projects regarding the conservation and use of plant genetic resources, including characterization and evaluation, research, breeding, and on-farm conservation.

FAO, host of the Commission on Genetic Resources for Food and Agriculture, provides the major political forum, and offers coordination, outreach, and information services pertinent to information and user needs (FAO 2009a), including the production of the *State of the World's Plant Genetic Resources for Food and Agriculture* (FAO 1997), with the second edition in publication; the World Information and Early Warning System on Plant Genetic Resources (WIEWS) (FAO 2009d); and the Global Partnership Initiative for Plant Breeding Capacity Building (GIPB) (FAO 2009e).

Much of the global-level work of conservation and utilization of plant genetic resources is conducted within or connected to the international Centres of the CGIAR, including the institutions safeguarding, researching, breeding with, and distributing the global in-trust collections of mandate crops. These Centres maintain many diverse connections with national, regional and international programs, networks, and alliances, contributing to addressing technical backstopping and safety duplication constraints presented in the strategies. Bioversity International supports numerous activities related to information systems and technical backstopping of *ex situ* conservation work globally, and with other CGIAR Centres coordinates the production of a series of publications related to establishing robust standards for genebank activities including regeneration (CGIAR-SGRP 2009), genebank management, conservation techniques, and the descriptor lists (Bioversity International 2009b).

Within the CGIAR, regeneration backlogs, improvements in accession-level data generation, storage and availability, facility improvements, and distribution protocol standardization have been addressed since 2003 by two World Bank-funded projects coordinated by the System-wide Genetic Resources Programme (SGRP) of the CGIAR- "Global Public Goods" (GPG), and its second phase, "Global Public Goods 2" (GPG2) (CGIAR-SGRP 2006). The CGIAR crop collection managers are working together to develop a sustainability plan as part of the GPG2 Project in order to ensure improvements in genebank operations, methods and standards. The plan describes where the genebanks in the CGIAR system aim to be by ca. 2020, serving many more users, and being a major player in a global system of germplasm conservation and use, including covering more in-trust crops, including underutilised and CWR germplasm.

The Trust is partnering with institutions worldwide in order to evolve and secure an efficient and effective global system. Contributions to the endowment have allowed the Trust to provide sustainable, long-term funding support for storage, maintenance and distribution, starting with a variety of the global in-trust and other globally important collections, including aroids, banana, barley, bean, cassava, faba bean, forages, grasspea, lentil, pearl millet, rice, sorghum, wheat, and yam. With grants from the United Nations Foundation, supported by the Bill & Melinda Gates Foundation, and from the Grains Research and Development Corporation (GRDC), the Trust is supporting work to overcome some of the major constraints in *ex situ* conservation presented in the strategies, including in regeneration of threatened accessions of many Annex 1 crops held in national institutes, safety duplication of these accessions, targeted collecting, accession-level data generation (characterization and evaluation), data management and sharing, research, cryopreservation of vegetative crops, and training. Of particular note regarding information constraints, a state of the art genebank data management software system (GRIN-Global), to be freely available for use in genebanks worldwide, is under development in partnership with the USDA National Genetic Resources Program and Bioversity International. Bioversity International, the secretariat of the ITPGRFA, and the Trust are partnering on developing an integrated global information resource linking genebank databases and existing crop and regional databases together in order to create an information source useful for the identification, analysis and requesting of accessions worldwide, with the aim of holding passport, characterization, and other data on the majority of the *ex situ* diversity available for agricultural crops. These projects have the potential to tremendously enhance the quality, availability, and accessibility of accession-level data, contributing both to more efficient and effective conservation, and to greater use.

The Svalbard Global Seed Vault opened in 2008, and has received accessions from the majority of the CGIAR Centres, and from a number of national genebanks. Built by the government of Norway, and maintained by Norway and by the Trust, the Vault stores safety-duplicate copies of accessions deep below the arctic permafrost in order to ensure that in the case of loss of accessions in genebanks due to the constraints presented in the strategies, natural disasters, and other causes, these unique genetic resources will continue to be conserved, and can be retrieved by the donor genebank for further use.

Conclusions

The global crop and regional strategies represent a major undertaking in the field of plant genetic resources, mobilizing experts to collaboratively design plans for the more efficient and effective conservation and utilization of crop diversity *ex situ*. The strategies are now being used by scientists, researchers, curators, genebank managers, and donors to guide conservation decisions and inform funding priorities. With continued improvements as new information becomes available and the rational global system evolves, the strategies have the potential to serve the field into the future. This will be dependent upon a strong sense of ownership and coordination for the strategies by stakeholders.

Together the global crop and regional strategies demonstrate a number of major trends and needs in *ex situ* conservation of plant genetic resources. Regeneration backlog presents a serious constraint to the success of *ex situ* conservation. Robust genebank management systems, and complete global information databases, are of extreme importance to the conservation and use of collections and to the development of a rational global conservation system. Existing passport and characterization descriptors provide a good foundation, and their use should be standardized across collections. Some descriptors are in need of further development.

Future collecting of germplasm is a high priority in many crops and regions worldwide. Crop wild relatives are increasingly valued, and the consciousness of the need for more extensive collecting, conservation and use of these resources is growing. User involvement in *ex situ* conservation is important, and there are many ways to improve collaboration and connections with researchers, breeders and other user communities.

For many crops, but particularly the vegetatively propagated species, the development of new technologies, or extension of technologies to more genotypes, is needed for better conservation systems. The creation of global crop and regional strategies is primarily constrained by a lack of sufficient accession- and collection-level information and by access uncertainties related to policy.

A series of connected organizations working at the global level are addressing some of the major constraints in regeneration, collecting, information systems, descriptors, increased involvement with users, and the development of new technologies for better conservation, although in most of these areas certain crops and/or regions will need additional funding beyond the activities currently funded.

Stakeholders in the plant genetic resources community should consider enhancing coverage of funding and support for crops and regions outlined in the strategies that are not currently being addressed, such as for a more extensive global collecting program, the production of needed crop descriptors, the development of specific new technologies and protocols, and overcoming the challenges to building complete strategies for conservation and use. The community should also ensure that the information systems, regeneration, collecting, and other major activities currently in progress are actively supported so as to be successful in securing germplasm and contributing to building a global system. The development of conservation strategies for a number of additional Annex 1 and other globally important crops is also needed. The community should promote the benefits of the Multilateral System provided for under the ITPGRFA at the institutional and national level. Through these activities the plant genetic resources community may support the strategies in addressing the major constraints in conservation of *ex situ* germplasm, and move forward toward a more efficient and useful global system of conservation and use of these invaluable resources.

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