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# A significantly enhanced role for plant genetic resource centres in linking *in situ* and *ex situ* conservation to aid user germplasm access

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**Abstract:** Plant genetic resources (PGR) serve as the cornerstone for global varietal enhancement and food security. However, these resources face significant threats, including diversity erosion and extinction, are often inadequately conserved, and frequently remain inaccessible for practical use. Traditionally, PGR have been primarily conserved through population seed samples stored *ex situ* in genebanks. In contrast, complementary *in situ* techniques – whether involving crop wild relatives (CWR) in genetic reserves or crop landraces (LR) on-farm – have largely remained experimental. The demand from breeders for a broader diversity is driving a more integrated approach that combines *ex situ* and *in situ* methods. This paper posits that such an integrated strategy would be mutually advantageous for PGR, biodiversity, and farmer-based conservation communities. As a foundation for future PGR science, we propose the three 'Principles of PGR Conservation and Use Congruence' and outline the practical processes involved in *in situ* and on-farm conservation. We also review the challenges associated with integrating *ex situ* and *in situ* conservation, specifically addressing how collaborative resource management can be established, how potential resource users can access *in situ* and on-farm conserved PGR, how to promote user access to *in situ* conserved populations, and the progress made thus far in integrating *in situ* and *ex situ* efforts. While it is acknowledged that full integration may be unrealistic without adequate resources for Genetic Resource Centres and the rectification of skill gaps, the potential to significantly enhance the long-term, sustainable conservation of PGR diversity holds profound existential benefits for humanity in the 21st century.

**Keywords:** crop wild relatives, *ex situ*, genebank, genetic reserves, *in situ*, landraces, on-farm conservation, integrated conservation

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## Introduction

Plant genetic resources (PGR) conservation is unique among conservation methods as it aims to preserve biodiversity while also utilizing conserved resources (Maxted *et al*, 1997a). This process involves several steps: identifying genetic diversity across plant species, prioritizing target taxa, planning and implementing conservation actions, and characterizing, evaluating and utilizing resources by farmers, breeders or researchers. Clarity and expediency in this model's application are essential for global, regional, national and local initiatives focused on food security, poverty reduction, and enhancing human well-being, thereby supporting many UN Sustainable Development Goals (UN, 2015).

PGR conservation employs two main strategies: *in situ*, where resources are conserved in their natural habitats, and *ex situ*, where resources are relocated to safer environments for conservation and accessibility (see definitions in Supplemental Table 1). It is widely accepted that *in situ* and *ex situ* actions should complement each other, enhancing overall conservation effectiveness (FAO, 1996). Historically, formal PGR conservation and germplasm application for orthodox-seeded species have relied heavily on *ex situ* seed storage in genebanks and, latterly, cryogenic preservation, with field genebanks and tissue culture techniques primarily used for recalcitrant-seeded species and clonally propagated crops. Genebanks can secure long-term viability at low cost and have successfully made this diversity available to plant breeders and researchers (FAO, 1998, 2011). However, *ex situ* approaches alone do not fully address the growing demand for broader diversity in a rapidly changing environment.

The science of *in situ* and on-farm PGR conservation has advanced significantly, with refined techniques and a solid evidence base (Maxted *et al*, 1997c, 2002, 2020; Brush, 2000; Eyzaguirre and Linares, 2004; Heywood and Dulloo, 2005; Jarvis *et al*, 2007, 2016; Iriondo *et al*, 2008, 2021; Veteläinen *et al*, 2009; Hunter and Heywood, 2011; Hunter *et al*, 2017). Initially, *in situ* and *ex situ* techniques were viewed as independent, even competitive (Ford-Lloyd and Maxted, 1993), but the case for their complementarity is now widely accepted, though their practical integration remains incomplete (Maxted *et al*, 1997a, 2020; van Hintum *et al*, 2021). Lack of integration limits conservation effectiveness, resulting in unconserved resources being unavailable to users and preventing their potential utilization. The challenge of increasing food production to feed a growing human population while mitigating climate change impacts on agriculture is escalating for the PGR and breeding communities FAO (2010, 2012). Lack of breadth and access to conserved genetic diversity is now a barrier to crop improvement (McCouch *et al*, 2013; IPCC, 2014; Dempewolf *et al*, 2017; Zhang *et al*, 2017).

There is an opportunity to better serve farmers and breeders by integrating *in situ* conservation, genebanks, and germplasm use into a cohesive continuum that could significantly enhance breadth and access to diversity for users (Maxted and Brehm, 2023). Failure to integrate these activities reduces the potential role of genebanks in leading PGR conservation and meeting user demands. Maxted *et al* (2016) suggested that expanding the role of genebanks to include both *ex situ* and *in situ* conservation was logical and required change to the PGR paradigm and would warrant their renaming as Genetic Resource Centres (GRC), as the term 'genebank' implies a more restrictive focus.

To explore this enhanced GRC role, a questionnaire was prepared in 2024 on European genebank activities for the Horizon Europe project 'Promoting a Plant Genetic Resource Community for Europe' (PRO-GRACE - https://www.grace-ri.eu/pro-grace). The results indicated that 76% of genebanks (13 of 17 respondents) were interested in adopting complementary *in situ*/on-farm roles alongside traditional *ex situ* activities. Genebanks have historically succeeded in supporting breeders and farmers while maintaining the PGR foundation for diverse crop varieties, but human population increase and climate change's impact on crop production and food security are forcing a change of practice. Although some GRC may face limitations in skills and resources, with appropriate support, their roles could evolve to become even more critical for humanity's future.

This discussion focuses on how to better integrate *in situ*, *ex situ*, and user access in PGR conservation to provide greater diversity. We highlight current opportunities to: (1) clarify PGR conservation aims through proposed Principles of PGR Conservation and Use Congruence; (2) summarize practical processes for *in situ* and on-farm conservation; (3) promote resource management collaboration; (4) enhance user access to *in situ* and on-farm conserved PGR populations; (5) facilitate access to *in situ* conserved populations via the European Search Catalogue for Plant Genetic Resources (EURISCO, http://eurisco.ecpgr.org); and (6) identify future ways to better integrate *in situ* and *ex situ* conservation. For PGR actors and germplasm users, the clear advantage lies in addressing current challenges and ensuring greater diversity availability, with an enhanced role for genebanks or GRC at the core, ultimately leading to increased sustainable food production and long-term food security.

## The Principles of PGR Conservation and Use Congruence

The aim of PGR conservation may be summarized in three fundamental principles, to ensure: (1) long-term, sustainable maintenance of PGR[1] diversity, (2)

[1] The scope of PGR found outside of GRC, or breeding collections is commonly focused on crop wild relative (CWR) and landrace (LR) diversity both of which are highly threatened.

active[2] conservation and characterization of crop, varietal and related wild taxon diversity using complementary[3] techniques and (3) conserved resource documentation and availability for utilization within the applicable legislative context. The use of complementary techniques provides additional security by employing multiple, diverse approaches to conserve these resources, ensuring greater security as each technique backs up and supplements the others. There could as well be other subordinate objectives, such as maintaining seed viability, phenotypic and genotypic characterization and evaluation of conserved resources, and ensuring standard material transfer agreement (SMTA) enforcement, but the three fundamental objectives should hold true for whatever form of conservation strategy is applied. Together, these objectives may be referred to as the *Principles of PGR Conservation and Use Congruence*; overall, conservation should, in the long-term, maintain the full breadth of genetic diversity, employ multiple conservation techniques, and make the conserved resources available to actual or potential users.

These three objectives are met for most *ex situ* holdings (except for the requirement to link to complementary *in situ* conservation). *Ex situ* PGR conservation and use is well tested, and we know it already 'works', but there is now an urgent need to further develop *in situ* conservation approaches. Hawkes (1991) commented in the early 1990s that *in situ* techniques were in their "infancy", and although advances in this area have been made (Maxted *et al*, 2020), *in situ* and on-farm conservation is still largely experimental and not based on more than 60 years of practice and the associated extensive evidence-base available for *ex situ* conservation. Additionally, effective standardization of *in situ* conservation techniques is itself challenging, as their application occurs in natural or semi-natural environments, or in on-farm locations, where diverse environmental, socioeconomic and cultural factors impact the target taxa, and effective PGR population managers (e.g. farmers, foresters, estate managers, etc.), may not be professional conservationists or have the necessary skills to maintain intrinsic genetic diversity. This is not to devalue the efforts of farmers or other landrace (LR) maintainers, or landscape managers, who have retained crop wild relative (CWR) populations on the estates they manage for extended periods of time. However, if *in situ* PGR conservation is to function as intended and be appropriately resourced, it must meet all three principles and objectives, as do *ex situ* approaches. Populations and diversity of *in situ* resources must be maintained in the long term via the application of complementary techniques, and the conserved resources must be available to users. If *in situ* PGR conservation does not ensure availability of the conserved resource, it will not meet the Principles of PGR Conservation and Use Congruence and it is unlikely ever to be seen as truly complementary to *ex situ* conservation.

It should also be noted that the third principle, which conserved resources are available for use, may not always be achievable, for example, when the *in situ* conserved populations are rare or threatened, and few, or an *ex situ* conserved accession has limited seed numbers and low viability. In both cases, the sample may need to be multiplied or regenerated before it can be made available to users. The principle remains that resource availability is paramount, and any periods of unavailability should be temporary until germplasm can be offered.

## Practical processes of *in situ* and on-farm conservation

To identify potential opportunities for integration, we need first to summarize and understand how *in situ* and on-farm conservation operate. The conservation–utilization continuum for *in situ* conservation is divided into four component steps and summarized in Figure 1 (adapted from Maxted *et al* (2020)):

1. **Conservation planning.** This involves: (i) selection of target conservation units, either CWR or wild food plant (WFP) taxa or crop LR (Maxted *et al*, 1997c; Brehm *et al*, 2017); (ii) prioritization, usually based on potential use value, relative crop value and threat, identifying an easily implementable inventory of highest priority CWR, WFP or LR (Brehm *et al*, 2017; Nilsen *et al*, 2017; FAO, 2019b); (iii) ecogeographic and gap analyses to identify concentrations of the conservation units and predict which sites with target populations (Maxted and Kell, 2008; Maxted *et al*, 2012b; FAO, 2019b); and (iv) field exploration to check the validity of the previous prediction and establish where the target diversity will be conserved in genetic reserves, other effective area-based conservation measures (OECM), on-farm, or in home garden.
2. **Conservation technique implementation**. Conservation targets are actively managed either in nature for CWR or WFP or cultivated on-farm or in-garden for LR diversity. This involves: (i) selection of sites with targeted resource diversity (Hawkes *et al*, 2000; Maxted *et al*, 2002; Dulloo *et al*, 2008; Veteläinen *et al*, 2009; Iriondo *et al*, 2021); (ii) formulation of the management plan, a detailed plan for how the population(s) of the target taxa/crop are to be maintained and enhanced (Maxted *et al*, 2002, 2008; Dulloo *et al*, 2008; Veteläinen *et al*, 2009; Iriondo *et al*, 2021); (iii) implementation of the management plan, including the site interventions, implementation of which is likely to be experimental initially until tar-

[2] Active conservation implies targeted management and monitoring of conserved CWR or LR populations, as opposed to passive maintenance of CWR or LR populations, where there may be a conservation ethos but no targeted management and monitoring.
[3] Complementary conservation implies the use of both *ex situ* and *in situ* techniques to conserve CWR or LR populations.

get population retention is sustainable (Veteläinen *et al*, 2009; Iriondo *et al*, 2021); (iv) resource monitoring at set time intervals to check the success the management regime (Veteläinen *et al*, 2009; Iriondo *et al*, 2021); and (v) formation and upkeep of partnerships essential for *in situ* and on-farm conservation of the genetic resources to occur.

3. **Conserved resource description**. The pre-utilization stage will involve characterization and evaluation (Maxted *et al*, 2020). These data may be uploaded alongside passport data in EURISCO to facilitate germplasm selection.
4. **Conserved resource utilization.** The *in situ* conserved resource should be available for use by breeders, farmers, researchers and other potential bona fide users. Forms of traditional utilization should be encouraged, provided it is not detrimental to the target taxon or taxa, thus fostering local support for conservation actions.

## Proposed resource management collaboration

It is important to clarify not only how the target populations are managed, but also (1) who should provide oversight of the networks of *in situ* or on-farm sites and populations, and (2) who should practically implement the management interventions of individual *in situ* or on-farm sites and populations. There are several potential communities that might fulfil these roles: existing population managers, national GRC staff and other diverse PGR stakeholders (including allied non-governmental organizations (NGOs), research centres and universities). As noted above, given that often the conserved *in situ* or on-farm genetic resources have been managed by the reserve/protected area (PA) manager, landowner, farmer or gardener for extended periods, one might assume they are the most appropriate to play both roles. While existing *in situ* and on-farm site managers should continue their successful management of individual *in situ* or on-farm sites and populations, the question is: do they have the necessary skills, tools and resources to provide oversight of the network(s) of *in situ* or on-farm sites and populations established?

It can be argued that it would be impractical for individual *in situ* and on-farm site managers to provide oversight of the network(s) of *in situ* or on-farm sites and populations given they: (1) are unlikely themselves to use trait diversity from the conserved CWR or WFP populations; (2) lack skills and expertise in international and national policy and legislation; (3) lack skills and expertise in field trials or genomic analysis; (4) lack access to a PGR information system to aid *in situ* population management and transfer of germplasm to the end user; and (5) already have an existing heavy core load of activities in managing biodiversity populations or producing food and their scope to adding a significant additional activity is limited. Therefore, it would seem appropriate that national GRC staff (or other appropriate national PGR agency or PGR-focused NGOs) would be better placed with the necessary skills, tools, resources and long-term experience from *ex situ* PGR applications, to provide multi-site PGR governance and overall oversight of the networks of *in situ* or on-farm sites and populations, including overall monitoring of natural reserves, other effective area-based conservation measures (OECM) sites or on-farm systems to prevent population losses (Maxted *et al*, 2016).

However, it is important to stress that national GRC staff cannot work in isolation. The PGR conservation goal of maximum PGR diversity conservation and availability can only be achieved by the three communities working in integrated collaboration, with national GRC staff providing national PGR leadership and oversight, individual PGR field population maintainers (i.e. reserve/PA manager, landowner, farmer or gardener) managing the genetic resources under their responsibility, and other PGR stakeholders (allied NGOs, research centres and universities) providing the necessary additional support. Furthermore, as the *in situ* or on-farm resource is maintained outside of a controlled unit, like a GRC, the local community within the vicinity of the *in situ*/on-farm resource site should also be involved in the conservation project management and associated decisions. Individual roles will vary depending on multiple factors (e.g. taxa included, whether wild or cultivated, resources available, value of resource conserved, etc.), therefore stakeholder discussions and negotiations will form part and parcel of the process of defining the roles of each actor, however it can be safely stated that the key expertise and areas of responsibility are likely to include those presented in Table 1 . To aid clarity, Figure 2 highlights those components managed by GRC staff, and *in situ* site maintainers alone, and which may be managed jointly. Collaboration between the three communities would be critical and involve periodic meetings of a PGR *In Situ* Population Management Committee.

Such an integrated approach to *in situ* and *ex situ* collaboration would extend each communities roles and responsibilities. However, for those maintaining PGR populations (PA, OECM or on-farm field maintainers) and given the target populations were selected because of their ‘health’, the additional workload is not foreseen as being significant, at least initially, as it would primarily involve monitoring target populations, while the provision of additional ecosystem and food services from the site would underpin the public good value of maintaining PGR populations. Furthermore, in some countries, additional targeted PGR conservation could generate additional subsidies or added income for the site maintainers/owners through government funding (such as payments for ecosystem services, subsidies for farmers who cultivate and conserve landraces that suffer from genetic erosion), so the benefit to PGR field population maintainer could be substantial. The proposed changes outlined for the national GRC would also be significant, possibly requiring additional staff with *in situ* expertise and

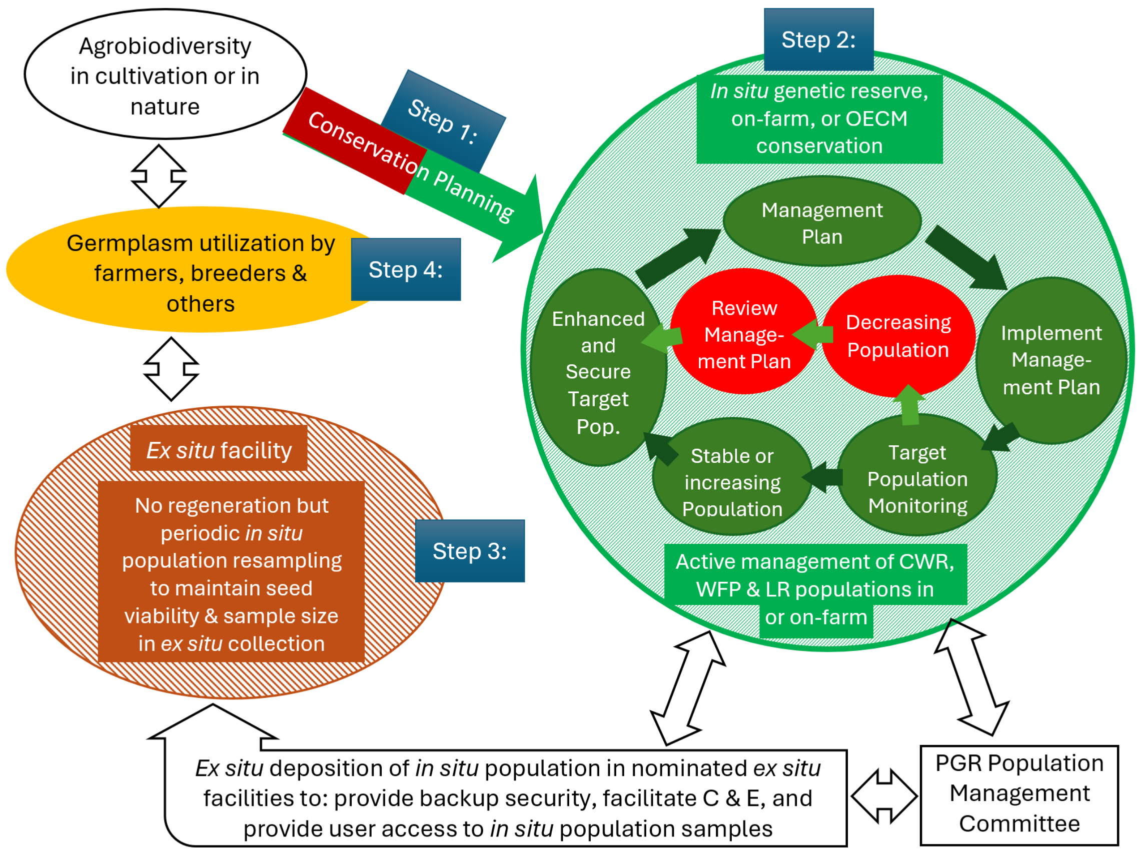


**Figure 1.** Schematic description of key elements of *in situ* conservation to utilization pathway. Green, *in situ*; brown, *ex situ*; red, threatened populations; gold, utilized PGR; blue, conservation steps; CWR, crop wild relatives; LR, landraces; OECM, other effective area-based conservation measures; WFP, wild food plants.

additional resources, but the additional role would fall within the existing genebank's remit – Genebank Managers Network (https://www.ecpgr.org/about/genebank-managers-network) and AEGIS initiative (https://www.ecpgr.org/aegis) of the European Cooperative Programme for Plant Genetic Resources (ECPGR) – and would substantially boost the genebank's role in national biodiversity conservation.

For all three collaborating communities, increased collaboration will involve additional time and resource commitments, incurring additional costs. Therefore, it is crucial to identify sustainable funding mechanisms to cover these costs, even if they are anticipated to be minor. However, any additional costs incurred due to collaboration and changes in roles would be far outweighed by the potential benefits of increased diversity available for breeders and other stakeholder's use (Maxted and Brehm, 2023). Access to and conservation of additional germplasm significantly enhances the diversity of collections, a core GRC and genebank objective, thereby better fulfilling their professional mandate.

As a final point, the collaboration as outlined in this document, involves the transfer of *in situ* or on-farm samples from their original locality to a nominated *ex situ* GRC for backup and to facilitate access for germplasm users. This means that the provisions emanating from the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) (FAO, 2001) and the Convention of Biological Diversity (CBD) Nagoya Protocol (CBD, 1992, 2011) are triggered and there is the need for an SMTA or Internationally Recognized Certificate of Compliance (IRCC) respectively, between the *in situ* maintainer and the recipient nominated GRC. This would need enacting even if the GRC had no intention to utilize the germplasm itself, but simply to conserve the *in situ* or on-farm sample and make it in turn available to more active users. By virtue of the relationship between the *in situ*/on-farm source, the GRC and the end user, the involved actors would be required to address the requirements to ensure fair and equitable sharing of benefits arising from the sample's potential final utilization, depending on the terms established under national regulations. The actual scope of the three-way (source, GRC and end user) relationship would require expert deconstruction and is therefore beyond the scope of this document but must be resolved before any germplasm transfer occurs.

**Table 1.** Collaborative activities of national Genetic Resource Centre (GRC) staff, plant genetic resource (PGR) population maintainers and other stakeholders. CWR, crop wild relatives; LR, landraces; WFP, wild food plants

| | **CWR, WFP or LR *in situ* population conservation** | |
|---|---|---|
| **National GRC staff's role** | **PGR population maintainer's role** | **Other stakeholder's role** |
| Lead preparation and periodic revision of National PGR Strategy and Action Plan, including *in situ* site selection and management plan production. | Contribute to preparation and periodic revision of National PGR Strategy and Action Plan, lead *in situ* site selection and management plan production. | Contribute to preparation and periodic revision of National PGR Strategy and Action Plan, and *in situ* site selection and management plan production. |
| Lead national PGR *in situ* conservation site network management. | Contribute to PGR *in situ* conservation site network management. | Contribute to PGR *in situ* conservation site network management. |
| Assist with implementing the site's individual management plan. | Lead implementation of individual site management plan. | Assist with implementing of individual site management plan. |
| Assist with periodic monitoring of target populations and analysis of demographic and genetic trends. | Lead periodic monitoring of target populations and analysis of demographic and genetic trends. | Assist with periodic monitoring of target populations and analysis of demographic and genetic trends. |
| Assist with periodic revision of individual site management plan and building evidence base. | Lead periodic revision of individual site management plan and building evidence base. | Assist with periodic revision of individual site management plan and building evidence base. |
| Target population characterization and evaluation. Ensuring user access to *in situ* conserved resources (via *ex situ* backup samples). | Periodic collection of target populations for *ex situ* representative backup samples. | Diverse research projects focused on aiding effective PGR diversity conservation and use. |
| Ensure integration of *in situ* and *ex situ* conservation activities and support tools and applications to aid *in situ* conservation site network management, e.g. national inventories, management and monitoring, germplasm access, characterization and evaluation databases and information management. | Collation of site and PGR population data, and integration with national PGR databases, activities assisted by network tools and applications. | Diverse research projects supporting national PGR population management and use, and associated tool and application development. |
| Promotion of national integration into international PGR community. | Promotion of PGR integration into the broader biodiversity community. | Participation in national and international research actions. |
| Lead and participate in the National PGR *In Situ* Population Management Committee. | Participate in the National PGR *In Situ* Population Management Committee. | Participate in the National PGR *In Situ* Population Management Committee. |

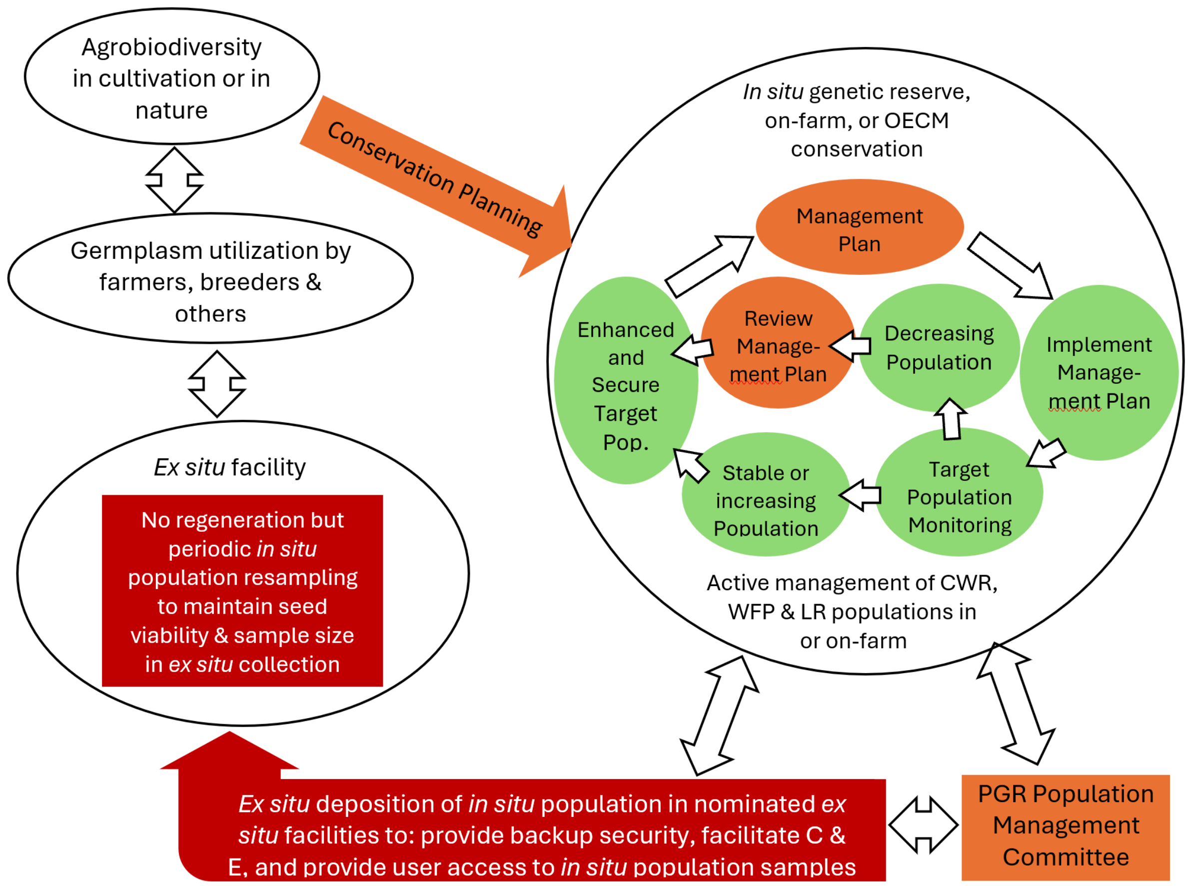


**Figure 2.** Schematic description of key elements of *in situ* conservation, highlighting Genetic Resource Centre (GRC) staff (dark red), *in situ* populations manager (green) and joint (orange) responsibilities. CWR, crop wild relatives; LR, landraces; OECM, other effective area-based conservation measures; WFP, wild food plants.

## User access to *in situ* and on-farm conserved PGR populations

The endpoint of PGR conservation is not conservation itself but ensuring that conserved germplasm is available for present or potential future utilization (Maxted *et al*, 1997a). The pathway of use for *ex situ* conserved PGR is tried and tested, but, apart from the positive activities of farmers and farming NGOs focusing on PGR diversity and farming systems, the *in situ* pathway to utilization has yet to be established. Without effective *in situ* conservation-to-use linkage, it is doubtful whether in situ conservation sites and site networks will ever be established (Maxted, 2019). Therefore, establishing links between *in situ* resources and use is fundamental to ensure additional germplasm access and the promotion of *in situ* conservation itself (Maxted and Brehm, 2023).

Maxted and Kell (2008); Maxted and Palmé (2016) and Maxted (2019) each reviewed potential models for how *in situ* conserved resources might be linked to user access, either accessed for use directly from the *in situ* population or indirectly via an *ex situ* conservation facility (Figure 3). Five potential options have thus far been proposed for promoting user access to *in situ* and on-farm conserved PGR and are elaborated in Table 2. Except for Option 3, users request an *in situ* PGR population sample and ≈(20-) 40–50 viable seeds are dispatched to the end user, fulfilling the *in situ* to-use prerequisite outlined in the Principles of PGR Conservation and Use Congruence. The chosen option may vary based on GRC facilities, available resources, conservation practices, and constraints from PGR maintainers or national authorities. However, assuming resources are adequate and constraints do not limit distribution, Option 5 achieves the Principles of PGR Conservation and Use Congruence, making the *in situ* resource-to-user link via the GRC, while placing the minimum additional burden on the GRC staff and their resources.

However, such an approach has not been practically implemented in any country. The reason is not thought to be that Option 5 or the other options are not conceptually sound, but due to funding limitations, risk aversion, lack of formal incentives, or the necessary skills and tools to promote *in situ* utilization. It could also simply be that active CWR, WFP *in situ* or LR on-farm conservation itself is only now being tentatively initiated, *in situ* conserved resources are uncharacterized and evaluated, the potential of *in situ* or on-farm germplasm access is unflagged so potential users are unaware such resources are accessible or how to access them.

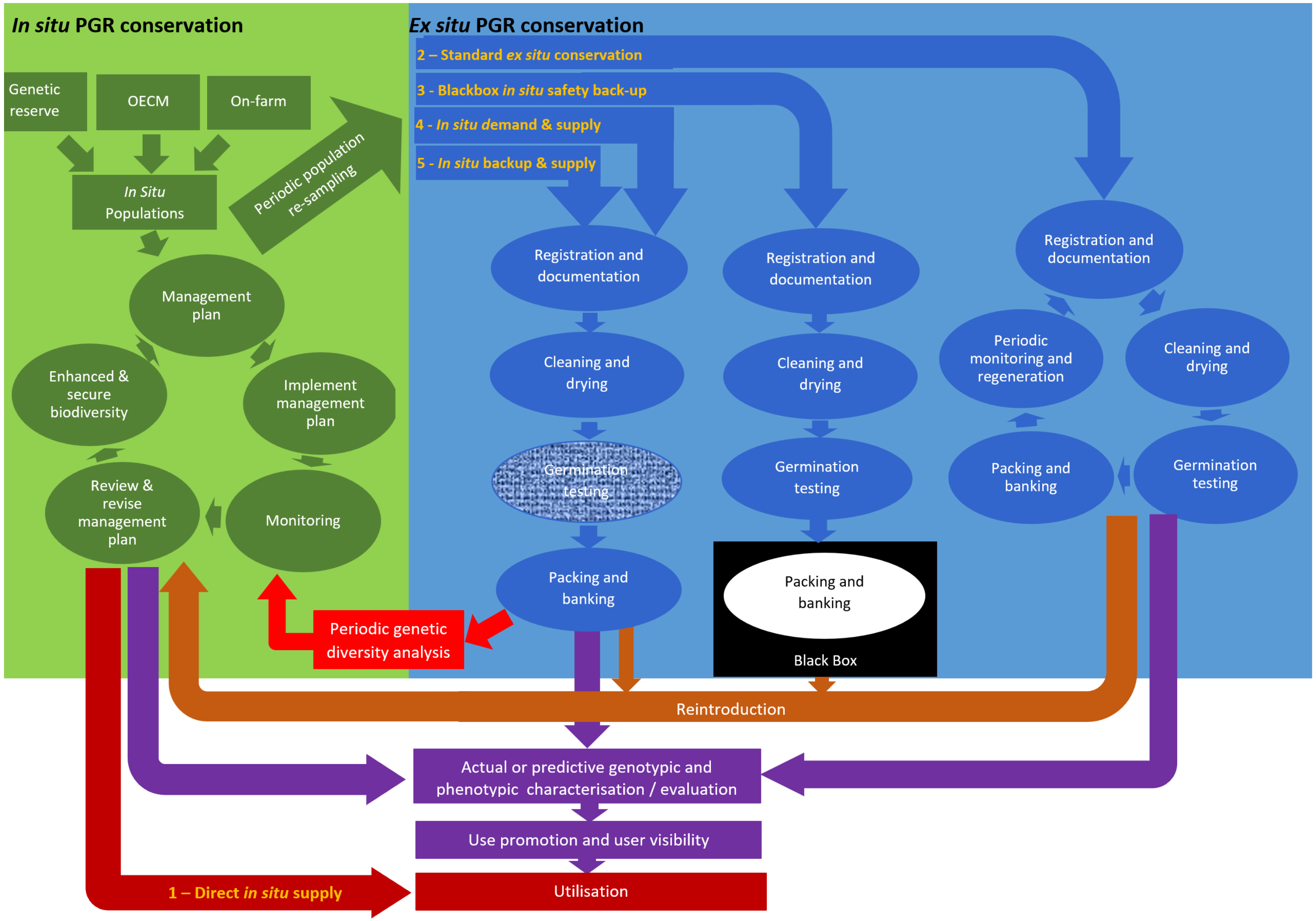


**Figure 3.** Five options to linkplant genetic resource (PGR) *in situ* conserved resources to user access: 1. Direct *in situ* supply, 2. Standard *ex situ* conservation, 3. Blackbox *in situ* safety backup, 4. *In situ* demand and supply, and 5. *In situ* backup & supply. OECM, other effective area-based conservation measures.

**Table 2.** Options proposed for promoting user access to *in situ* and on-farm conserved plant genetic resources (PGR). The addition of an asterisk to option number means the option meets the Principles of PGR Conservation and Use Congruence. ABS, Access and benefit sharing; CBD, Convention on Biological Diversity; CWR, crop wild relatives; GRC, Genetic Resource Centre; ITPGRFA, International Treaty on Plant Genetic Resources for Food and Agriculture; LR, landraces; WFP, wild food plants.

| Option | Option description | Advantages | Disadvantages |
|---|---|---|---|
| 1 | **Direct *in situ* supply:** involves the user being made aware of the availability of particular *in situ* PGR populations and their characteristics, the user contacts the PGR *in situ* maintainer and the maintainer sends a sample directly to end user. | A simple procedure agreed and organized by the *in situ* or on-farm maintainer and the user, which would not necessarily imply GRC involvement. In some cases, users may be granted permission to autonomously collect by the appropriate national authority. | (a) In general, *in situ* population maintainers (protected area managers, farmers, land agents, gardeners, etc.) do not see germplasm supply as one of their core activities, have no experience with such activities and are unable to engage in direct user supply. Further, they rarely have legislative knowledge of CBD (2011) and ITPGRFA-related legislation or its national application and/or international ABS statutes (FAO (2001); Art. 12.3(h) and Art. 15.1(b)), therefore cannot enact the legislation. (b) Germplasm supply outside of the country of origin requires phytosanitary certification and testing to ensure seeds are free from specific pests/pathogens and the *in situ* population maintainers would not have the required processing skills. While it might be feasible to supply such knowledge to some maintainers, such as protected areas managers, extending it to all potential farmers, land agents and gardeners, is unrealistic. (c) Training *in situ* population maintainers in germplasm supplier skills would be almost meaningless as the chances of each individual supplier supplying conserved germplasm would be limited given their large number and the limited number of seed requests. (d) *In situ* population maintainers could only supply germplasm during the PGR fruiting season, so there would be significant delays between request and user supply. |
| 2* | **Standard *ex situ* conservation:** describes the typical route by which germplasm enters the GRC: populations are sampled from the wild or on-farm location, transferred to the GRC, registered and documented, processed following the standard guidelines (FAO, 2014) and supplied to users. | A tried and tested route applied widely for *ex situ* conservation that effectively meets users' needs, but here is applied to an *in situ* conserved population. It meets the Principles of PGR Conservation and Use Congruence. | (a) If each country maintains a substantial number of *in situ* conservation sites for CWR, WFP or LR population conservation and these all *ex situ* backup accessions in the GRC, the processing of additional *in situ* samples and making them available to users would require significant additional resources. |

*Continued on next page*

*Table 2 continued*

| Option | Option description | Advantages | Disadvantages |
|---|---|---|---|
| 3 | **Blackbox in situ safety back-up**: a sample is either collected by the *in situ* maintainer or collected by GRC staff and stored in the nominated *ex situ* facility and is only available to the donor for their use, or *in situ* population reinforcement or reintroduction. | A simple, inexpensive procedure agreed and organized by the *in situ* or on-farm maintainer and the GRC. | (a) This option does not meet one of the imperatives of the Principles of PGR Conservation and Use Congruence which mandates that conserved PGR should be available for utilization, therefore this cannot be considered effective as a primary PGR conservation measure. (b) If the *in situ* population is rare, highly threatened or has known unique, adaptive allelic diversity, then it should be conserved *in situ* and backed up *ex situ*[4]. |
| 4* | ***In situ* demand and supply**: proposed by van Hintum *et al* (2021) to minimize the GRC additional workload. It involves users identifying the *in situ* population they wish to obtain, requesting a sample from the appropriate GRC, and a staff member travelling to the site, collecting and processing a sample and distributing it to the end user. | This option does minimize the additional GRC workload and ensures the *in situ* or on-farm maintained population is provided to the user. | (a) This option would involve additional work for the GRC staff in sampling and processing *in situ* samples, though GRC sampling costs could potentially be shared with the user. Costs could be reduced by providing guidance to *in situ* maintainer so that they collect and forward the sample either directly to the user or via the GRC. However, any additional costs of *in situ* supply might act as a disincentive to potential users, especially if no such cost is associated with *ex situ* GRC holdings. (b) User supply would involve one-off population sampling and would not be as cost-effective as expedient sampling while undertaking a routine GRC collection mission. (c) Seasonality would mean seed, cuttings or tissue samples would not be available year-round and this might significantly delay *in situ* sample supply to the user, which would add a further disincentive to potential users (Maxted, 2019), while *ex situ* conserved GRC samples are available for distribution year-round. (d) For CWR and WFP taxa natural seed dispersal mechanisms make it difficult for collectors to gather the required target number of seed at the optimal time for conservation and supply during a brief one-off visit to a natural population. (e) Also, *in situ* populations are less likely to be characterized and evaluated for adaptive traits, although users could apply predictive characterization techniques to aid *in situ* population selection (Thormann *et al*, 2014). |

*Continued on next page*

[4] The assumption is that availability would be granted by the *in situ* maintainer in the future when target population levels have risen, and black box *in situ* back-up would not be a long-term preferred option.

*Table 2 continued*

| Option | Option description | Advantages | Disadvantages |
|---|---|---|---|
| 5* | ***In situ* backup and supply**: Iriondo *et al* (2012) proposed as a standard that *in situ* conserved populations should be backed up in nominated *ex situ* facilities. It involves users identifying the *in situ* population they wish to obtain, requesting a sample from the appropriate GRC, and a staff member supplying a sample from the *in situ* backup material to the end user. | Each *in situ* population should be backed up *ex situ* to facilitate reintroduction of the original material, if necessary. The sample could be collected by the *in situ* maintainer and sent by them to the nominated GRC. The backup sample could be maintained using a partial *ex situ* protocol and used for characterization and evaluation to promote user application. | (a) Backing up each *in situ* conserved population in the GRC would be costly, especially if all samples were collected and processed using standard *ex situ* models (FAO, 2014). To minimize the GRC costs of *in situ* sample processing: (i) the sample and associated data could be collected by the *in situ* population manager and sent to the GRC, rather than collected by GRC staff; (ii) on arrival in the GRC, the *in situ* sample would be processed using *ex situ* protocols, except regeneration[5] and germination monitoring would be omitted (Maxted, 2019), regeneration being replaced by regular *in situ* population resampling[6], which would also reduce the requirement for periodic germination testing; (iii) periodically resampling will also ensure that the genetic diversity captured in the *ex situ* backup sample accurately reflects the ongoing evolutionary trajectory of the *in situ* population. (b) The *in situ* backup sample needs to sufficiently large for the GRC to supply the end user. |

[5] Note for CWR samples, it may be difficult to collect recommended standard sample sizes quantities (FAO, 2014) and therefore, initial sample seed bulking may be required before formal seed storage, especially if the sample is to be used subsequently for characterization and evaluation, and user provision.
[6] Although germination testing as a relatively inexpensive task might be retained to confirm the initial quality of the sampled seeds and as an indicator to trigger *in situ* population resampling.

It is also true that there has been some initial resistance to changes in roles and responsibilities from both current *in situ* population maintainers and GRC staff; true *in situ* and *ex situ* GRC integration will add additional roles and responsibilities, especially when many staff are already over-committed and additional resources are limited.

Although *in situ* and *ex situ* GRC integration will add additional roles and responsibilities for both GRC staff and *in situ* population maintainer communities, it is likely to be mutually beneficial. For GRC staff it would extend the range of diversity they are able to provide to users, whereas for *in situ* maintainers, it presents a good example of applied additional ecosystem services from the PGR resources they manage, graphically demonstrating the fundamental value of area-based conservation and diversity-based farming systems to the public.

By providing access to *in situ* population samples, GRC extend their expertise in user seed supply — an area in which *in situ* population managers lack experience and have no institutional mandate. This aligns with the GRC's existing key role in effectively addressing user demand for genetic diversity. Furthermore, adoption of this option could be expanded if the additional commitment remained minimal for site managers and GRC staff, and if it were adequately resourced.

Such integration would also likely facilitate more coherent PGR policy development and implementation, rather than PGR policy being the responsibility of each discrete site managers and GRC communities, plus those from the third research community. It is appropriate that the GRC takes a lead role in PGR conservation and user provision because it: (1) has experience in PGR long-, medium- and short-term genetic conservation, collection management and meeting user requests for germplasm effectively, as well as promoting a supportive policy environment over the past 60 years globally; (2) possesses practical expertise in national and international germplasm transfer, as well as meeting associated phytosanitary and legislative requirements; (3) is already known as the germplasm source for diverse users and are accustomed to germplasm access procedures; and (4) has the potential to extend their role to supply samples from *in situ* conservation sites. It should be stressed that even if the GRC provides the overall PGR national lead they must ensure collective decision-making and implementation among the three communities involved, site managers and GRC communities, plus those from the third research community, site manager, PGR researcher and GRC communities, potentially plus more peripheral communities (e.g. biodiversity, informatics, systematics, etc.). How such managerial cooperation is achieved is likely to vary from country to country based on local contexts, species biology, resource constraints and broader socio-political factors, but it is likely to involve the establishment of a PGR conservation committee to promote collection management, user access promotion research direction and policy development discussion, chaired by GRC staff.

It should be noted that the partnership between the *in situ* population maintainer and the *ex situ* component of the GRC is critical to facilitating *in situ* germplasm user access. To ensure this relationship is effective, it is preferable that each *in situ* population be partnered with a nominated *ex situ* GRC, this will be the national or a national GRC. However, in countries with a decentralized GRC network, matching specific crop group CWR, WFP or LR with their corresponding specialist GRC would be appropriate and beneficial.

The preceding discussion has focused on professional roles in PGR conservation and use, but locally, community biodiversity management is increasingly shown to be effective in facilitating local conservation management of PGR; a role that seems particularly pertinent in the *in situ* context linking local PGR conservation effort to local PGR use. It seems unlikely many local communities would be interested in CWR use because of the potential need for advanced techniques to overcome interspecific breeding barriers and problems associated with linkage drag of unwanted additional traits, though even here local communities have shown interest in CWR population surveying. However, WFP and LR could be conserved and used more directly via community seedbanks initiated by local communities. Local community seedbanks could also function as a conduit to the more formal GRC community (Bocci *et al*, 2025), aiding *in situ* characterization, adaptive trait recognition, *in situ* population sampling for *ex situ* duplication and backup, and even CWR prebred-varietal introductions, as well as provision of associated datasets. This could encourage greater recognition of the informal conservation sector, provision of resources and skills training, and inclusion of community seedbank holdings in national PGR inventories and EURISCO. Community seedbanks could take the role of LR population maintainers working in collaboration with GRC staff to maximize diversity maintenance. Improving integration between the PGR formal and informal systems will surely prove mutually beneficial and help secure existentially important food security resources.

## Aiding user selection of *in situ* conserved populations via EURISCO

Significant progress has recently been achieved in advancing *in situ* PGR conservation documentation through the incorporation of information on active *in situ* population conservation into EURISCO (https://www.ecpgr.org/working-groups/crop-wild-relatives/cwr-in-eurisco). This was accomplished through a project funded by the German Federal Ministry of Food and Agriculture (referred to as EURISCO project below), commenced in November 2021 and focused on country-based case study incorporation of CWR *in situ* population data in EURISCO. Although this initiative was developed for CWR populations, a similar approach could, in the future, be implemented for WFP and LR population data, marking a significant step forward in PGR science.

The extension of EURISCO is endowing the European region with a centralized, public and web-searchable inventory of priority *in situ* CWR populations' passport data, along with a fine-tuned data flow mechanism that uses an internationally agreed data exchange standard (Van Hintum and Iriondo, 2022). The new *in situ* module of the EURISCO catalogue was built in compliance with the 'FAIR principles': Findable, Accessible, Interoperable and Reusable data (Wilkinson *et al*, 2016). The online central catalogue of *in situ* CWR population data has been available since the beginning of 2024, and more European countries are being trained and encouraged to add their country data. This provides easy-to-access information to potential users seeking novel sources of diversity for breeding and pre-breeding programmes and other uses. The implementation of these international commitments prioritized by the CBD, Global Plan of Action (GPA) and ITPGRFA, as well as by the *European Plant Genetic Resources Strategy* (ECPGR, 2021), will prove beneficial to PGR conservationists and users alike, ultimately promoting food security and well-being.

A proposal, including principles and requirements for data inclusion, the definition of a data flow mechanism and the proposed data exchange standard (CWR passport descriptors), was developed and published on the ECPGR website (Van Hintum and Iriondo, 2022). It includes recommendations for identifying the most relevant CWR populations to be recorded in EURISCO. It also outlines a set of descriptors for *in situ* conserved populations, including their current location, precise coordinates, and where samples are being actively conserved to guarantee their long-term persistence. It addresses how samples from these populations can be accessed, potentially based on the terms and conditions of the ITPGRFA Multilateral System. Furthermore, it describes the structure of information shared between the CWR-National Inventory (CWR-NI) and EURISCO, the necessary steps to upload CWR-NI elements into EURISCO and the modifications to EURISCO to accommodate such type of data. Two annexes containing 'Descriptors recommended for the generation of a National Inventory of *in situ* Crop Wild Relatives' and 'Descriptors for uploading passport data of *in situ* CWR to EURISCO' complete the document. As of January 2025, eleven countries (Albania, Bulgaria, Cyprus, Germany, Italy, Lithuania, the Netherlands, Poland, Romania, Spain and the United Kingdom) have provided *in situ* CWR data to EURISCO, with data from a total of 5,764 populations.

Incorporating *in situ* data into EURISCO is a key step toward addressing some of the accessibility issues related to *in situ* material that have been discussed in this review. The EURISCO project has already played a key role in establishing *in situ* PGR conservation and documentation as being truly complementary to *ex situ* efforts in Europe and in helping ensure that *in situ* conservation meets the Principles of PGR Conservation and Use Congruence. Without this initial step, the establishment of *in situ* genetic reserves would have progressed more slowly. Further initiatives are likely to be agreed between the PGR *in situ* site and population maintainers, researchers and GRC to ensure a future fully integrated and effective complementary *in situ*– *ex situ* conservation–use continuum. Some first thoughts include:

- While a periodic update of *in situ* data to EURISCO, such as every five years, may be suitable long-term, more frequent updates might be necessary during the initial establishment of *in situ* genetic reserves.
- Recently, EURISCO has begun to support the linkage of characterization and evaluation data with the germplasm passport data held in EURISCO as a means of aiding user selection of germplasm and promoting further utilization of conserved resources. There is significant opportunity for further extending utilization by building Tools to Aid Germplasm Selection (TAGS) and links to additional data sets. One obvious TAGS would be a predicted characterization tool, where the crop and the desired trait required are selected and the tool suggests a subset of CWR and LR accessions that might have the trait for the crop. Another tool is a LR repatriation tool that allows the user to choose LR from certain localities to aid repatriation of LR lost from those locations.
- Just as CWR and WFP diversity is actively conserved in other non-PGR contexts, e.g. as a rare or threatened taxa by biodiversity specialists or as wild species by botanic gardens, so biodiversity specialists and botanic gardens are interested in CWR and WFP diversity, and organic crop producers and diversity-based farmer specialists, for example, are interested in PGR germplasm for their own non-PGR based utilization. To this end, EURISCO could be better designed to meet additional user communities.
- It is widely agreed that national *in situ* and on-farm conservation should be managed in a network structure rather than each site being managed independently. The likely benefits include systematic conservation coordination and reporting, stronger partnerships and mutual support, integration of global, regional, national and local actions, truly *in situ*– *ex situ* conservation integration with improved data interoperability and coordinated policy development, facilitation of ABS for protected areas and farmers/farming communities, and tools and methodologies to aid safeguarding *in situ* PGR populations. With so many potential benefits and many different potential governance structures possible, it would be wise to start planning now to maximize national PGR *in situ*

networking that links *in situ*, *ex situ*, user access and impact.
- It would also be useful to define what data will be included and excluded from EURISCO. What data might be better maintained at individual CWR, WFP or LR population site level and or at national network level, and where there is no benefit in collating at the regional level. One example that could be considered such data is currently provided by genebank holding curatorial data (e.g. size of seed collection, germination percentages, location of sample in genebank). Similar curatorial data exists for *in situ* populations (e.g. monitoring data for *in situ* populations over time, levels and timings of management interventions, or age of LR maintainer cultivating a LR). Some such data might appropriately be recorded in National Inventories and some at site level, but boundaries need to be established to maximize overall efficiency.

## Future challenges and opportunities for *in situ– ex situ* integration

With agrobiodiversity conservation budgets limited and becoming tighter, it is imperative to maximize the efficiency of conservation expenditure. Horizon scanning, a participatory approach to the establishment of future priorities, is getting increasingly recognized as a useful tool to help prioritize and plan conservation action, inform resource allocation and provide an evidence base for conservation implementation (for its PGR application see Maxted *et al* (2012a)). This exercise is carried out here in the context of *in situ–ex situ* integration for CWR and LR conservation over the next ten years and the results are summarized in Supplemental Tables 2 and 3, respectively. Those involved in the 2025 assessment were partners in the EU-funded project PRO-GRACE[7] (23 experts from 11 countries + ECPGR Secretariat), members of the ECPGR On-farm Conservation and Management (85 experts from 43 countries) and CWR Working Groups (87 experts from 38 countries). These experts were also asked to identify emerging PGR-related issues with implications for *ex situ* and *in situ* conservation that they felt were of European importance to CWR, WFP and LR diversity in Europe, and required resolution by 2035.

The experts identified a set of 23 issues related to CWR and WFP, and 24 issues related to LR. It is anticipated that the issues detailed in Supplemental Tables 2 and 3 will be used in three primary ways. Firstly, that policymakers will critically examine the issues identified, assessing their potential impact on policy development and considering appropriate implementation timelines. Secondly, it is expected that this exercise will help the integrated *ex situ* and *in situ* PGR community better target their activities for the immediate and longer-term future, considering the relative success of the previous PGR Horizon scanning initiative. It is hoped that researchers, funders, and those working on PGR policy and regulation will use the outcome of this exercise when considering the future direction of strategic CWR, WFP and LR research. Finally, this exercise may encourage further consideration and debate about the issues that are on the horizon and the ways in which scientists and decision-makers can best communicate about them.

[7] https://www.grace-ri.eu/pro-grace, Grant n. 101094738

## Discussion

This paper discusses the largely unexplored challenges and opportunities associated with integrating *ex situ* and *in situ* plant genetic resources (PGR) communities. Historically, these communities have worked semi-independently, but there are now significant mutual benefits for humanity in their integration, transforming and enhancing the paradigm of PGR conservation and use. Traditionally, formal PGR conservation has relied almost exclusively on *ex situ* storage of seed samples in genebanks, providing users with easy access to meet evolving needs. Conversely, *in situ* and on-farm applications for PGR conservation have been extensively discussed (Jain, 1975; Maxted *et al*, 1997b, 2002, 2020; Safriel *et al*, 1997; Brush, 2000; Eyzaguirre and Linares, 2004; Heywood and Dulloo, 2005; Jarvis *et al*, 2007, 2016; Iriondo *et al*, 2008, 2021; Veteläinen *et al*, 2009; Hunter and Heywood, 2011; FAO, 2013; Hunter *et al*, 2017), particularly post-CBD established prioritized *in situ* techniques (CBD, 1992), but rarely practically applied except for farmer-based maintenance of LR. The strength of integrating both conservation strategies, *ex situ* and *in situ*, lies in maximizing the long-term and sustainable maintenance of a more comprehensive representation of PGR diversity.

Historically, commercial plant breeding has been hesitant to utilize non-domesticated or highly heterogeneous CWR and LR germplasm, likely due to a lack of economic incentive for broader diversity, limited availability of non-domesticated CWR or diverse LR germplasm, challenges in identifying germplasm with known adaptive and desirable traits, and the economic, time and complexity costs associated with pre-breeding and elimination of unwanted traits inadvertently introduce via linkage drag. However, the status quo is shifting: climate change and ecosystem instability necessitate a greater breadth of PGR diversity to sustain agricultural production, while precision techniques facilitate the identification of valuable adaptive traits and enhance the precision of trait introgression (Prohens *et al*, 2017). This knowledge highlights that *ex situ* approaches alone cannot satisfy users' demands for a comprehensive range of diversity, prompting a renewed focus on *in situ* conservation.

Despite recent progress in experimental *in situ* applications, experience over the past 30 years indicates that implementing *in situ* methods independently of *ex situ* approaches is both ineffective and counterproductive.

*In situ* conservation should be complemented by *ex situ* strategies to: (1) provide long-term backup for security and potential population reinforcement or reinstatement; (2) assist in characterization and evaluation; and (3) ensure ease of access for end users. Likewise, *ex situ* conservation should be complemented by *in situ* approaches to: (1) maximize the preservation of taxonomic and genetic diversity; (2) allow for the evolution of adaptive traits in changing environments; and (3) address the evolving demands of end users. Thus, both *ex situ* and *in situ* conservation methods are interdependent and should function in a mutually supportive manner. However, unlike *ex situ* conservation, which can be largely managed within controlled environments, *in situ* conservation necessitates the active participation of diverse actors with various skill sets (ecology, wild plant biology, field geno- and phenotyping, remote monitoring, climate change management, invasive species and pest management) to enact conservation actions, adding layers of complexity and associated challenges. Integration of these diverse actors in a distributed Research Infrastructure on Plant Genetic Resources is likely to unite these additional actors.

Moreover, a critical question arises: who will take primary responsibility for coordinating *in situ* conservation efforts? The experiences of the ECPGR CWR and On-farm Conservation and Management Working Groups have demonstrated that neither protected areas nor farming communities can effectively coordinate *in situ* PGR diversity conservation activities, and many are reluctant to engage in formal *in situ* PGR conservation. Protected area managers focus on biodiversity rather than crop diversity conservation, while farming communities are primarily engaged in commercial agricultural production rather than systematic diversity conservation. Therefore, there is a pressing need for additional training for GRC staff and/or extending collaboration with actors possessing the necessary skills and experience in ecology, pest management and field conservation to complement the existing GRC staff's expertise in genotypic, phenotypic and agronomic evaluation, sampling, viability and phytosanitary testing, documentation, data upload to EURISCO, and distribution to users, including knowledge of national and international legislative implementation. This collaboration is fundamental to enhancing the conservation of *in situ* diversity, its description and its availability to end users.

Additionally, the existential problem of user supply is often underestimated by the *in situ* PGR community. For PGR conservation to be effective, meaningful, and serve a utilitarian purpose beyond its intrinsic value in nature preservation, a link must exist between conservation and utilization. However, neither protected areas nor farming communities possess experience in germplasm supply within the context of access and benefit-sharing legislation. Consequently, it can be argued that without the involvement of the *ex situ* community in these roles, *in situ* implementation risks becoming limited to 'academia,' 'hobbyists' or short-term project support without long-term sustainability. Therefore, it is evident that the application of *ex situ* and *in situ* strategies is mutually dependent, and their complementary integration should be led by GRC. Leadership from GRC would entail adjusting their perspective to encompass both *ex situ* and *in situ* aspects, along with appropriately increased resources to fund the necessary structural and skill provisions for practical implementation. Conversely, if the *in situ* or on-farm community was able to take such a leadership role, would the genebanks welcome the competition?

There is also an economic argument for GRC to adopt a more proactive role in *in situ* conservation. As outlined, one justification for PGR conservation is to enhance user access and benefits, which may encompass various industries, with the most prominent being those related to economic and food security, medicinal products and material uses. The most recent estimate of the use value for CWR closely related to 29 globally important crops is US$42 billion, with a potential future value of $120 billion. The annual gross added value was $581 billion in 2010, indicating that CWR are already valued at about 7% of the annual production value of these 29 crops (PWC, 2013). This valuation is conservative, as it does not account for the potential expansion of CWR use in breeding these or other crops, nor the value of utilizing LR diversity. Therefore, the overall annual gross added value of using PGR diversity in crop improvement could approach a trillion US dollars. This significant valuation raises the question: does not the potential revenue stream justify the modest investment required now in PGR conservation to secure future substantial benefits? The rationale for integrating *ex situ* and *in situ* conservation lies in the fact that *ex situ* collections typically capture only a snapshot of the genetic diversity present in natural populations at the time of collection. It also should be acknowledged that over time, genetic drift or selection during storage and regeneration can lead to the loss of some of this genetic variation. In contrast, *in situ* conservation allows the remaining spectrum of genetic diversity to persist and evolve naturally in response to environmental changes. Without leveraging both approaches, a significant portion of the genetic diversity available in natural populations remains untapped, limiting its potential contribution to crop improvement and other industries.

While the practical establishment of CWR genetic reserves or LR on-farm diversity maintenance sites has progressed more slowly than anticipated, this may be partly attributed to the PGR community's long-standing focus on the established 'in-nature and on-farm sampling to genebank to user' paradigm (Guarino *et al*, 1995, 2012; Hawkes *et al*, 2000; Smith *et al*, 2003; FAO, 2014). This paradigm has proven resilient and successful over the last century, consistently meeting the needs of breeders and consumers. However, the very success of this established paradigm poses a significant challenge to the adoption of in situ conservation approaches. To gain wider acceptance, these approaches must articulate an equally robust and straightforward model that demonstrates long-term effectiveness – the PGR germplasm user is indifferent to the conservation source if it meets their trait needs. Promoting *in situ* application includes clearly communicating the value of the proposed *in situ to ex situ to* use paradigm and its mutual advantage in diversity breadth. Although the clarification of the Principles of PGR Conservation and Use Congruence and the derived proposals presented provide an initial foundation for a proposed *in situ to ex situ to* use paradigm led by the national GRC, further development will be necessary based on a growing evidence base.

Another related topic that has progressed more slowly than anticipated is the systematic *ex situ* and *in situ* conservation of WFP. These include fruits, leafy vegetables, woody foliage, bulbs and tubers, cereals and grains, nuts and kernels, saps and gums, mushroomsand seaweeds (Wunder, 2014). WFP have historically served as a coping strategy for many rural households, particularly during the 'hungry season' before the next season's crops ripen and as part of subsistence farming systems (Hunter *et al*, 2015; Kennedy *et al*, 2017). FAO (2019a) estimates that around one billion people globally incorporate wild foods into their diets regularly, and forests alone provide livelihoods and food for approximately 300 million people through non-timber forest products. However, WFP are rarely included in PGR conservation initiatives and are unlikely to be targeted for biodiversity conservation only if they are threatened or rare. FAO (2019a) calls for (1) active *ex situ* and *in situ* conservation and sustainable use, (2) breeding of improved varieties, and (3) raising awareness of the importance of WFP, particularly local and traditional foods that are vital for nutritionally balanced, healthy diets and food security. WFP, like CWR, are simply wild species with specific food value, although the former is associated with direct consumption rather than trait provision. Therefore, WFP planning and conservation implementation are unlikely to differ significantly from CWR-based actions, making it timely to test this assumption. Implementing WFP conservation falls within the remit of national GRC activities and should be integrated with other PGR activities. Most importantly, WFP can provide material for future domestication efforts, thereby expanding the foundation of our food production systems.

Here much has been made of expanding *in situ/ex situ* integration, but there is also significant leverage in *in situ*/on-farm working more closely with biodiversity communities. CWR and LR could be used as 'cultural ambassadors' to help promote PA-based conservation or traditional cultivation practices. The collaboration offers opportunities to marry biodiversity conservation management with food security or traditional foods associated with healthier lifestyles. While such collaboration would also help conserve the critical PGR resource more extensively and effectively – demonstrating the mutual relevance of each community contribution – PA don't only maintain birds, mammals and reptiles, they conserve the founding resource for our food. Traditional farming is not just picturesque, it sustains cultural benefits such as recreation, education, spiritual and creative enrichment, and improved mental health and wellbeing. Whilst PA management may recognize the importance of these ecosystem services, their consideration and usefulness in site management decision-making is worth closer understanding.

There exists an opportunity and a central role for the proposed GRACE research infrastructure (see https://www.grace-ri.eu/pro-grace), which builds on 55 years of ECPGR collaborative networking aimed at ensuring long-term conservation and facilitating utilization of PGR to implement the necessary transition from genebanks to GRC and enact more effective *in situ* PGR conservation. This role may prove existentially important for humanity in the future. Without appropriate financing, skills and capacity provision, and cooperation with the broader biodiversity community, establishing and maintaining *in situ* and on-farm networks would be unsustainable in the medium to long term, even under GRC direction. The core mission of the PGR community remains unchanged, as summarized in the Principles of PGR Conservation and Use Congruence, and it is essential to reassess and reconfigure this mission to ensure it is fit for purpose today and in the future.

## Conclusions

The dual challenges of human population growth and climate change's negative impact on crop production have resulted in increased demand from germplasm users and consumers for greater breadth of diversity. *Ex situ* genebanking alone is unable to secure such breadth of diversity, as are *in situ* or on-farm conservation activities; the urgency of the situation is such that the much-discussed but rarely applied implementation of complementary PGR conservation offers the only practical and expedient solution. The Principles of PGR Conservation and Use Congruence describe the fundamental principles of PGR conservation (long-term, sustainable conservation, application of complementary conservation techniques, and documentation and availability of the conserved resource for utilization) and provide a framework for indicating success. Evidence and experience have shown that neither *ex situ*, *in situ* nor on-farm conservation functions adequately in isolation, but further that systematic *in situ* and on-farm genetic conservation is not a priority for practitioners of either biodiversity-focused conservationists or production-based farmers. The comprehensive integration of *ex situ*, *in situ* and on-farm conservation communities and their activities, with the local communities where the bulk of the genetic resources exist, led by national GRC and CGIAR institutes, is now critical for global, regional, national and local food security; failure to address this issue could have devastating consequences for humankind in the 21st century. Specific recommendations are outlined for collaborative resource management, user access to *in* *situ* and on-farm conserved PGR, improving user selection of *in situ* conserved populations and what the future challenges and opportunities there might be for future *in situ*– *ex situ* integration. Other recommendations will undoubtedly come from further steps toward PGR community integration. Although realistically this initiative is doomed to failure unless national GRC step up to take the lead, skill gaps are filled, and they are adequately resourced.

## Supplemental data

Supplemental Table 1. Genetic conservation strategies and techniques (Maxted *et al*, 2020).

Supplemental Table 2. Horizon scanning issues associated with CWR *in situ*– *ex situ* conservation in 2025 that require resolution by 2035.

Supplemental Table 3. Horizon scanning issues associated with LR *in situ*– *ex situ* conservation in 2025 that require resolution by 2035.

## Acronyms used

- ABS – Access and Benefit Sharing
- AEGIS – A European Genebank Integrated System
- C & E – Characterization and evaluation
- CBD – Convention on Biological Diversity
- CWR – Crop wild relatives
- CWR-NI – CWR-National Inventory
- ECPGR – European Cooperative Programme for Plant Genetic Resources
- EURISCO – European Search Catalogue for Plant Genetic Resources
- FAO – Food and Agriculture Organization of the United Nations
- GPA – Global Plan of Action
- GR – Genetic reserve
- GRC – Genetic resource centre
- IRCC – Internationally Recognized Certificate of Compliance
- ITPGRFA – International Treaty on Plant Genetic Resources for Food and Agriculture
- LR – Crop landrace
- NGO – Non-governmental organization
- OECM – Other effective area-based conservation measures
- PA – Protected area
- PGR – Plant genetic resources
- SMTA – Standard material transfer agreement
- TAGS – Tools to Aid Germplasm Selection
- WFP – Wild food plant

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## Conflict of interest statement

The authors declare no conflict of interest.

## Author contributions

NM drafted the first iteration of the text and coordinated production of the final text, all authors contributed to the conception, discussion, and text of the paper.

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