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# European genetic resources conservation in a rapidly changing world: three existential challenges for the crop, forest and animal domains in the 21st century

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**Abstract:** Even though genetic resources represent a fundamental reservoir of options to achieve sustainable development goals in a changing world, they are overlooked in the policy agenda and severely threatened. The conservation of genetic resources relies on complementary *in situ* and *ex situ* approaches appropriately designed for each type of organism. Environmental and socioeconomic changes raise new challenges and opportunities for sustainable use and conservation of genetic resources.

Aiming at a more integrated and adaptive approach, European scientists and genetic resources managers with long experience in the agricultural crop, animal and forestry domains joined their expertise to address three critical challenges: (1) how to adapt genetic resources conservation strategies to climate change, (2) how to promote *in situ* conservation strategies and (3) how can genetic resources conservation contribute to and benefit from agroecological systems. We present here 31 evidence-based statements and 88 key recommendations elaborated around these questions for policymakers, conservation actors and the scientific community.

We anticipate that stakeholders in other genetic resources domains and biodiversity conservation actors across the globe will have interest in these crosscutting and multi-actor recommendations, which support several biodiversity conservation policies and practices.

**Keywords:** Agroecology, climate change, *in situ* conservation, multi-actor engagement, policy

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## Introduction

Genetic resources are at the crossroads of multiple policy agendas, in particular biodiversity conservation and sustainable development goals (FAO (2019), e.g. p. 3 about diversity loss in production systems; IPBES (2019), e.g. SPM-A6 and p. 247 about erosion of genetic resources diversity; IPCC (2019), e.g. SPMB6.2; CBD (2020), e.g. Aichi Targets 13, 14 and 16; CBD (2022), e.g. Targets 4 and 13). In the Common International Classification of Ecosystem Services (Haines-Young and Potschin, 2018), the term 'genetic resources' is not used but genetic resources explicitly appear both as provisioning services under the term 'genetic material', as regulation and maintenance services under the term 'gene pool', and could also be considered as cultural services in the class of "characteristics or features of living systems that have an option or bequest value". This classification reveals the multiple values of genetic resources: direct use value of well-characterized genetic material, option value of the genetic diversity, bequest value of biodiversity components. However, the threat to and the erosion of genetic resources diversity, both in wild populations and in production systems, is now widely documented (FAO, 2019; IPBES, 2019; CBD, 2020) and the related Aichi target of safeguarding genetic diversity has not yet been achieved (CBD, 2020). The Kunming-Montreal Global Biodiversity Framework calls for "Target 4: Ensure urgent management actions [. . . ] for the recovery and conservation of species [. . . ] to significantly reduce extinction risk, as well as to maintain and restore the genetic diversity within and between populations of native, wild and domesticated species to maintain their adaptive potential including through *in situ* and *ex situ* conservation" (CBD, 2022). Despite their critical importance for sustainable development, on the one hand, and the ongoing erosion of their diversity, on the other hand, genetic resources are largely overlooked by policymakers. Three reasons may explain this paradox. First, the role of within-species genetic diversity remains poorly understood and appreciated in biodiversity conservation (Hoban *et al*, 2020). Second, few recognize the existential importance of within-species genetic diversity in sustaining continued crop, forest and animal production. Third, the term 'resources' does not explicitly refer to the notions of diversity, which in a changing world is valued over quantity, and rather focuses on the use aspects.

The important role of diversity between and within crop[1], animal and forest genetic resources for maintaining production has been recognized for centuries, but the actual term 'genetic resources' was only coined in 1967 at the International Conference on Crop Plant Exploration and Conservation (Frankel and Bennett, 1970). It received a common definition a nd global consideration in the Convention on Biological Diversity (CBD (1992), Article 2): "genetic resources means genetic material of actual or potential value". Thus, genetic resources refer to genetic diversity of actual or potential use value between and within species, with a continuum from domestic gene pools (varieties, breeds, isolates) to wild populations. The evolutionary processes during domestication are mainly driven by targeted human interventions such as selection, migration and hybridization. In the case of partially anthropized systems where populations are exploited and managed through natural regeneration systems (e.g. many forests, fisheries and grazed areas), management practices indirectly shape genetic resources by interfering with natural evolutionary and ecological processes. The domestic and wild gene pools are often connected in the landscape where they develop three types of interactions: (1) competition for land (Grau *et al*, 2013), (2) ecological interactions (Pozo *et al*, 2021) and (3) possible gene flow between domestic gene pools and their wild relatives (Ellstrand and Rieseberg, 2016). Thus, genetic resources conservation has to be considered in the context of social-ecological systems, where humans directly or indirectly sustain genetic resources and humankind benefits substantially from their genetic diversity maintenance and utilization.

The communities working on genetic resources have historically tended to be defined by the scope of their taxonomic coverage, each specializing in crop, forestry, domesticated animal, fish, microbe or pollinator genetic diversity conservation and use, the linking of conservation with use of the conserved resource setting them apart from the broader biodiversity conservation community. The crop, forestry and domesticated animal domains have worked largely independently to develop conservation and use actions specifically designed within their respective contexts, without sharing experience and benefiting from mutually advantageous collaboration. To fill this gap, the European Union's Horizon 2020 'GenRes Bridge' project brought together for the first time the European crop, forestry and domesticated animal genetic resources networks (http://www.genresbridge.eu/).

Three individual networks have been coordinating and facilitating genetic resources conservation and use in Europe for more than 25 years within their respective domains: the European Cooperative Programme for Plant Genetic Resources (ECPGR, https://www.ecpgr.org/), the European Regional Focal Point for Animal Genetic Resources (ERFP, https://www.animalgeneticresources.net/), and the European Forest Genetic Resources Programme (EUFORGEN, https://www.euforgen.org/). The three networks joined forces in the GenRes Bridge project to elaborate a *Genetic Resources Strategy for Europe* speaking with a stronger policy 'voice' and

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[1] In this article, the term 'crop genetic resources' encompasses plants used for agricultural production, including crop wild relatives and wild food plants, and is used instead of the more common 'plant genetic resources' to avoid confusion with the forest domain, which deals with the genetic resources of forest trees and other woody plants.

facilitating more effective implementation. This strategy consists of a comprehensive overarching framework of appropriate coordinated actions to conserve and sustainably use genetic resources (GenRes Bridge Project Consortium, ECPGR, ERFP and EUFORGEN, 2021), and three derived domain-specific documents accounting for respective contexts (ECPGR, 2021; ERFP, 2021; EUFORGEN, 2021).

Although the biological and socioeconomic contexts of conservation and sustainable use of genetic resources differ for agricultural crop, animal farming and forestry domains, from the biological point of view, the coexistence of human-directed and natural evolutionary processes are common to all domains of genetic resources. Furthermore, from the socioeconomic point of view, sustainable development depends on continued access to a combined set of genetic resources from each domain and combined production systems (e.g. agroforestry). Finally, genetic resources conservation and sustainable use in all domains are currently facing common challenges in the context of environmental, socioeconomic and legal changes. Therefore, joining expertise from different domains, with various social-ecological contexts, will help effectively address these challenges for sustainable use and conservation of genetic resources. This paper illustrates crosscutting and integrated solutions to three existential challenges for genetic resources in the $21^{st}$ century:

1. How to adapt genetic resources conservation strategies to climate change
2. How to promote *in situ* conservation strategies (with common objectives despite diverse modalities across domains)
3. How can genetic resources conservation contribute to and benefit from agroecological systems

We here provide general arguments and recommendations reusable by different genetic resources and conservation communities.

## Methodology

The three challenges were addressed during three workshops engaging a global panel of 43 invited experts on genetic resources, i.e. scientists in conservation science and practitioners, from 16 countries and one international organization, with balanced representation of the three domains. To develop policy-relevant conservation science, we first identified **evidence-based statements** common to all genetic resources domains, beyond biological and socioeconomic specificities. These statements were based on the reports of international agencies and platforms (FAO, 2019; IPBES, 2019; IPCC, 2019; CBD, 2020, 2022) and workshop participants' expertise. Then, each evidence-based statement was deconstructed and reviewed, and **key arguments and recommendations** were derived for each of the three prime target audiences: policymakers, conservation actors and the scientific community. Final statements and recommendations were elaborated through online collaboration.

These statements and recommendations have broad general interest not only for other genetic resources domains, e.g. fisheries or industrial microbiology, but also for other biodiversity conservation programmes accounting for genetic diversity at global, regional and national levels. Here, we present a list of 31 evidence-based statements, and 88 arguments and key recommendations related to the three challenges. We then briefly analyze the targeted audiences and describe how these particular statements and recommendations were considered in the *Genetic Resources Strategy for Europe*. Finally, we propose some perspectives building on the inter-domain collaborative experience.

## Results

### How to adapt genetic resources conservation strategies in the context of climate change

Ten statements (CC1 to CC10) and 26 recommendations on this challenge are given in Table 1.

The first three statements, CC1 to CC3, raise the point that, in the context of climate change, the diversity of genetic resources is both at risk while also representing a reservoir of options to sustain agriculture and forestry in the face of multiple uncertainties (Koskela *et al*, 2007; FAO, 2015). Therefore, to better use genetic resources, we need to explore and characterize their diversity and potential benefits using both *in situ* material and *ex situ* collections. Scientists and actors on genetic resources in all domains agree on the severe level of threats of erosion and extinction currently impacting genetic resources diversity. Efforts to improve the conservation, characterization and use of genetic resources need to be actively promoted, even if there is still a lack of quantitative assessment of these threats (IPBES, 2019).

A second set of statements, CC4 to CC6, stresses the need for raising awareness on genetic resources diversity, conservation and use issues, and for better sharing science-based knowledge with multiple actors and policymakers involved. This lack of knowledge sharing was identified as a limiting factor in genetic resources conservation and use. The related recommendations aim to support the 'chain of knowledge' from science to policy decisions, on the one hand, and to facilitate exchanges of information or material among local expert communities in genetic resources, on the other hand, both needed to adapt genetic resources conservation and use strategies in the context of climate change.

**Table 1.** Statements and recommendations on how to adapt genetic resources conservation strategies in the context of climate change. Prime target audience: P, policymakers; S, scientific community; C, conservation actors (other than P and S).

| | **Statements** | | **Arguments and recommendations** |
|---|---|---|---|
| CC1 | Climate change poses a significant threat to genetic diversity. | CC1.1 | Immediate conservation action is needed now to prevent loss of genetic diversity and political commitment linked to policy action is required to support this initiative. [P, C] |
| | | CC1.2 | The diversity of climate change-related threats needs clarification, and their mitigation demands a diversity of responses. [S] |
| | | CC1.3 | Threats from climate change need to guide future genetic resources conservation and use strategy developments and prioritize mitigating action implementation. [C] |
| CC2 | Genetic diversity provides resilience in the face of unexpected change. | CC2.1 | Social and economic studies are required to evaluate how genetic resources diversity mitigates threats to food security and other contributions of agriculture and forests to people. [S] |
| | | CC2.2 | Studies are required to provide concrete examples of the benefits provided by genetic diversity in the agroecosystems and the values of such ecological, social and economic benefits. [C, S] |
| CC3 | In order to deploy sources of resilience, diversity has to be identified and characterized. | CC3.1 | Characterization of genetic resources and sharing of this information in a standardized manner are essential. [C, S] |
| | | CC3.2 | Improved availability of more standardized scientific information on genetic and phenotypic diversity is required. [S] |
| | | CC3.3 | Predictive characterization may also be used to speed up identification of desired traits. [S] |
| CC4 | Genetic resource-related policies should be based upon relevant scientific findings. | CC4.1 | Science provides evidence-based insights that are essential in defining effective policies. [P, S] |
| | | CC4.2 | Increased collaboration between scientists and policymakers could improve the uptake of scientific messages in policy decisions. [P, S] |
| CC5 | Awareness of the importance of genetic diversity for the survival of humankind should be raised. | CC5.1 | Public and political support for genetic resources conservation is essential to secure appropriate funding. [P] |
| | | CC5.2 | The general public, but also policymakers, are rarely aware of the important role of the diversity provided by genetic resources in adaptation to the changing climate and changing demands from society. [P, C, S] |
| CC6 | Cooperation between formal genetic resources conservation, breeding programmes and community-based conservation initiatives should be improved. | CC6.1 | Community-based activities can play an important role in the identification of resilient genetic resources suitable for the changing environment. [C] |
| | | CC6.2 | Link between the formal genetic resources management systems with local initiatives is often weak, and access to each other's genetic resources is often limited. [C] |

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*Table 1 continued*

| Statements | | Arguments and recommendations | |
|---|---|---|---|
| CC7 | Early signs of potential future needs and threats to genetic diversity and genetic resources use have to be detected. | CC7.1 | Foresight studies (Horizon scanning exercises) can produce scenarios to guide long-term strategies for genetic resources conservation and use. [C, S] |
| | | CC7.2 | Studies should address possible relevant socioeconomic changes and technological advances. [S] |
| | | CC7.3 | Scenarios of change should also consider biotic and abiotic hazards, as well as external contingencies. [S] |
| CC8 | Periodic monitoring of the actual impacts of climate change on genetic diversity and associated organisms is required. | CC8.1 | Given the climate crisis and associated uncertainties, regular monitoring allows tracking of changes and development of scenarios. [C] |
| | | CC8.2 | Based on the knowledge gained from monitoring, prioritization of actions can and should be made. [C] |
| | | CC8.3 | Monitoring should not only include genetic resources but also associated organisms, like pollinators. [C] |
| CC9 | Communication between all practitioners involved in genetic resources management and use (genebank managers, *in situ* network managers, breeders, farmers and foresters, protected area managers, etc.), policymakers and scientists, needs to be improved. | CC9.1 | Coordination of genetic resource-related actions will improve with better communication. [P, C, S] |
| | | CC9.2 | This will lead also to establishing and reinforcing collaboration between multiple actors involved in genetic resources conservation and sustainable use. [P, C, S] |
| | | CC9.3 | Multiple actors will contribute to awareness raising on the basis of values and trade-offs between all relevant values. [P, C, S] |
| CC10 | The traits related to adaptation of genetic resources to climate change need to be given more attention in research. | CC10.1 | Tolerance to climate-related hazards (heat, drought, etc.), and resistance to existing and emerging pests and diseases will become essential in adaptation to climate change; more knowledge about these traits will become essential to allow adaptation. [S] |
| | | CC10.2 | Genetic resources will benefit from basic research on these traits and their use as study objects should be promoted. [S] |
| | | CC10.3 | The way how these traits can support adaptation of agroecosystems, or help to diversify these systems, should be assessed. [S] |

**Table 2.** Statements and recommendations on how to promote *in situ* conservation strategies. Prime target audience: P, policymakers; S, scientific community; C, conservation actors (other than P and S).

| **Statements** | | **Arguments and recommendations** | |
|---|---|---|---|
| IS1 | Dynamic *in situ* conservation strategies integrate adaptation to global change into the conservation process. | IS1.1 | Genetic resources are kept in the productive environment allowing exposure to change and stress situations. [C] |
| | | IS1.2 | *In situ* conserved genetic resources stay useful in a changed environment. [C] |
| IS2 | *In situ* conservation continuously contributes to multiple ecosystem services and benefits to people. | IS2.1 | *In situ* conservation with management contributes to rural development. [P, C] |
| | | IS2.2 | *In situ* conservation provides a broad range of diversity to users. [P, C] |
| | | IS2.3 | *In situ* conservation also contributes to regulation and maintenance as well as cultural ecosystem services. [P, C] |
| | | IS2.4 | *In situ* conservation allows for better dynamic reactions to different drivers of change, including market needs and new market niche exploration. [P, C] |
| IS3 | Effective and efficient *in situ* conservation and sustainable use of genetic diversity rely on the participation of multiple actors and coordinated efforts. | IS3.1 | Key actors and potential new actors should be identified/recognized and involved in genetic resources strategies. [P, C, S] |
| | | IS3.2 | *In situ* conservation programmes should be designed based on a participatory approach involving all actors. [P, C, S] |
| | | IS3.3 | All actors need to be financially supported and incentives should rely on available scientific proofs. [P, C, S] |
| IS4 | Coordination of efforts by the various actors involved in dynamic *in situ* conservation is needed to ensure that long-term objectives are reached. | IS4.1 | Actions are needed to strengthen the links between all actors (practitioners, scientists, etc.) in *in situ* management of genetic resources. [C, S] |
| | | IS4.2 | Strategical recommendations, guidelines and directives should be tested by practitioners in collaboration with scientists and extension services before general implementation. [C,S] |
| IS5 | Coordinated and standardized national inventories of *in situ* genetic resources have to be prepared and made accessible. | IS5.1 | Inventories of *in situ* genetic resources improve our knowledge about what and where they are still maintained or cultivated, thus providing a resource from where important traits can be identified for plant and animal improvement by breeders or direct utilization by farmers. [C] |

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*Table 2 continued*

| Statements | | Arguments and recommendations | |
|---|---|---|---|
| | | IS5.2 | Inventories of *in situ* genetic resources are needed for planning more systematic crop-collecting missions addressing possible gaps and for designing on-farm conservation and management projects. [C] |
| | | IS5.3 | Data structure of the national inventories of *in situ* genetic resources should feed the appropriate European information systems. [C, S] |
| IS6 | Active genetic management including selective breeding for performance traits and evolution-oriented forest management can contribute to *in situ* conservation ‘in use’ of genetic resources. | IS6.1 | Knowledge of the qualitative and quantitative impacts of agricultural and forestry practices on evolutionary processes needs to be improved and shared with practitioners. [C, S] |
| | | IS6.2 | Information is needed on the potential role of active genetic management on performance and adaptive traits to improve self-sustainability of *in situ* genetic resources within the constraints of their typical characteristics. [C, S] |
| IS7 | New operational tools for the *in situ* conservation of genetic resources have to be developed and practically applied in all domains to increase our understanding and capacity to develop more efficient strategies for genetic resources conservation and use. | IS7.1 | There is a need for operational tools for *in situ* characterization, evaluation, management and monitoring of genetic resources. [S] |
| | | IS7.2 | The development of tools is a dynamic process, both for the update and the uptake, in which the three domains could share experiences and innovations. [S] |
| IS8 | A commitment and a concept for long-term genetic monitoring are needed to guide *in situ* conservation and sustainable use of genetic resources. | IS8.1 | Genetic monitoring is an efficient tool to characterize and detect changes in genetic diversity over time. [C, S] |
| | | IS8.2 | The standardization and/or comparability of genetic monitoring information over time must be ensured to allow proper assessment of the changes (independently of the new tools). [S] |
| | | IS8.3 | Sufficient resources should be committed to implementing long-term genetic monitoring. [P] |
| IS9 | The complementarity between *in situ* and *ex situ* techniques can contribute to increasing the systematic coverage of genetic diversity under conservation as well as the efficiency of genetic resources conservation. | IS9.1 | There is a need to investigate explicitly the multiple advantages, and risks, of combining *in situ* and *ex situ* strategies: provide insurance and backup, facilitate access to material, provide additional material for reinforcement *in situ*, etc. [S] |
| | | IS9.2 | Suitable methods and tools to integrate dynamic and static conservation approaches should be developed for all domains. [S] |
| | | IS9.3 | Such integrated approaches will allow opportunities for a wider range of stakeholders, including local communities, to participate in different networks at various levels. [C, S] |

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*Table 2 continued*

| | **Statements** | | **Arguments and recommendations** |
|---|---|---|---|
| IS10 | Opportunities for the protection with utilization and valorization of the diversity of genetic resources in various ecosystems should be promoted. | IS10.1 | Characterization of the genetic diversity of genetic resources available in cultivated areas, protected areas, rural and urban spaces, and private and public gardens, is needed. [C, S] |
| | | IS10.2 | Using these spaces for conservation of both wild and cultivated diversity should be promoted and supported. [P] |
| IS11 | Long-term conservation policies, strategies and programmes are needed to ensure dynamic *in situ* conservation of genetic resources diversity. | IS11.1 | Long-term perspective of genetic resources conservation strategies must clearly appear in the related EU policies, strategies and programmes, to support adaptive dynamics in the *in situ* conservation devices. [P] |
| | | IS11.2 | Long-term policy support for *in situ* management and monitoring is needed. [P] |
| IS12 | Cooperation within and across domains at the European scale to develop dynamic *in situ* conservation strategies of genetic resources is needed. | IS12.1 | Dynamic *in situ* conservation strategies of genetic resources can use very diverse methods and tools; sharing experiences and research efforts across domains, geographic areas or species, is needed. [C, S] |
| | | IS12.2 | Dynamic *in situ* strategies provide opportunities to combine multiple genetic resources targets in the same conservation action, including trans-domain actions. [C, S] |
| | | IS12.3 | Following an adaptive management framework, permanent upgrading should be incorporated into the strategies, including complementarity of *in situ* and *ex situ* conservation. [C, S] |

Finally, statements CC7 to CC10 illustrate the fact that climate change is forcing us to revise our vision, tools and methods for sustainable genetic resources management particularly as genetic resources are evolving in an unpredictable and dynamic context. More than on current diversity per se, the focus should be put on its trajectory and the drivers of this trajectory. Putting genetic resources management in such a dynamic perspective also requires monitoring strategies. To support innovative approaches, the recommendations provide a list of actions to develop governance and decision support tools like indicators or scenarios and new target traits of interest for research.

## How to promote *in situ* conservation strategies

Twelve statements (IS1 to IS12) and 31 arguments and recommendations on this challenge are given in Table 2.

The first two statements emphasize key characteristics of *in situ* conservation: framed in a dynamic perspective as mentioned above, genetic diversity continuously evolves in diverse and changing biotic and abiotic environments, and it combines conservation with sustained local use benefits. This integrative conservation approach illustrates the socioecological dimension of genetic resources: ecological adaptation interlaces with contributions to people. Based on these statements, the European experts from the different domains derived some general 'arguments' to explain and promote the integrative *in situ* approach in various contexts, rather than specific recommendations for each domain.

Combining conservation and use, *in situ* conservation strategies systematically rely on multiple and diverse actors, either directly managing genetic resources or indirectly controlling the environment in which they are left evolving. To ensure effective and efficient *in situ* conservation, multiple actors must be coordinated not only locally, but also at national level to establish networks of local initiatives. These points are raised in statements IS3 to IS5. The related recommendations aim to create and support multi-actor engagement, coordinate their actions with appropriate science-based guiding tools and monitor jointly the development of actions and the diversity of genetic resources that result from these actions.

Statements IS6 to IS8 identify three specific aspects of *in situ* conservation on which knowledge, i.e. both scientific knowledge and practitioners' expertise, must urgently be expanded. The first aspect is a quantitative assessment of the potential role that ecosystem management (agriculture or forestry practices) can play as evolutionary drivers of genetic resources diversity. The second aspect is the need to develop operational tools specifically dedicated to *in situ* genetic resources and actors involved. The third aspect is the need for standardized, long-term monitoring programmes applicable to all three domains, in the framework of international initiatives towards global genetic diversity monitoring (Hoban *et al*, 2022). The related recommendations represent priority actions in these fields.

Statements IS9 and IS10 reveal other actions which *in situ* conservation could easily complement with great benefits: association with other genetic resources conservation approaches (i.e. *ex situ* conservation) or other compatible land uses (e.g. protected, cultivated or even urban areas). The related recommendations aim to support this integrative approach of *in situ* genetic resources conservation in a broader framework.

Finally, the last two statements and related recommendations raise the fact that benefiting from all integrative dimensions of *in situ* conservation requires long-term programmes and support, as well as large-scale cooperation.

## How can genetic resources conservation contribute to and benefit from agroecological systems

Nine statements (AE1 to AE9) and 31 recommendations on this challenge are given in Table 3. The challenge here is to search for mutual opportunities between the emerging interest to apply agroecological principles in the development of agricultural and forestry systems and genetic resources conservation.

During the discussions, European experts highlighted the potential benefit of genetically diverse resources in the agroecology framework (Chable *et al*, 2020). To reach this benefit, the recommendations related to the first statement AE1 focus on the identification and contextualization of genetic resources in agroecological systems, and on sharing this information. The second statement AE2 highlights the key role of genetic resources managers in agroecology. Five recommendations explain how to support these actors.

The next five statements, AE3 to AE7, underline the specific relevance of the local scale (landscape, territory) to develop synergies between genetic resources conservation, agroecology, and resilience/sustainability of agriculture and forestry systems. Indeed, local actors involved in agroecology have the capacity to implement integrative *in situ* conservation within-sites as proposed in the previous sections, while the diversity of social-ecological contexts among localities contributes to maintaining between-sites diversity. This idealistic view relies on the engagement of multiple actors in multiple sites, which cannot be achieved without searching for win-win solutions: altogether, 16 recommendations related to the above statements were proposed.

Finally, statement AE8 stresses the need for a holistic and social-ecological approach to consider all levels of diversity together, and statement AE9 raises the particular importance of data management for this challenge. Indeed, various types of data should be handled jointly: different kinds of genetic resources, multiple uses and related genetic resources characteristics, biological to socioeconomic data or regulation information, georeferencing, etc.

**Table 3.** Statements and recommendations on how genetic resources conservation can contribute to and benefit from the agroecology transition. Prime target audience: P, policymakers; S, scientific community; C, conservation actors (other than P and S).

| | Statements | | Arguments and recommendations |
|---|---|---|---|
| AE1 | Diverse genetic resources are key elements in the agroecology framework. | AE1.1 | All component species and their role in each agroforestry system need to be identified. [C] |
| | | AE1.2 | Long-term study cases should be established in different geographical and socioeconomical contexts to analyze and demonstrate the impact of genetic resources on agroecology systems across different time scales. [C, S] |
| | | AE1.3 | The use of a broad diversity of genetic resources, and the exchange of genetic resources and related information should be promoted. [P] |
| | | AE1.4 | Increased knowledge of the (epi)genetic variability of genetic resources will favour their integration into agroecological systems. [S] |
| AE2 | Genetic resources managers have a key role to play in the agroecological transition. | AE2.1 | Policy support must be implemented with a long-term view and connected with public support. [P] |
| | | AE2.2 | Ecological performance (multi-criteria performance evaluation) must be integrated into the value chain labelling process. [P] |
| | | AE2.3 | Further research is needed on how to manage genetic resources for a transition from an intensive (standard) production system to a more ecologically oriented mode of production. [S] |
| | | AE2.4 | The long-term benefits of ecological performance/sustainability when all three domains are considered should be further investigated and knowledge communicated to the end-users. [C, S] |
| | | AE2.5 | Scientists and genetic resources managers together should propose decision-making tools, identify actors and consider geographical information supporting sustainable use of genetic resources in the agroecological transition. [C, S] |
| AE3 | Research, policy, managers and users' communities on genetic resources must be connected. | AE3.1 | Demonstrations of how useful genetic resources are for farmers, forest managers, and their respective systems, are needed. [C, S] |
| | | AE3.2 | The views of the users must be taken into account in the design and the analysis of study cases and in the implementation of the strategy. [C] |
| | | AE3.3 | Research has to produce a synthesis of results and knowledge for stakeholders. [S] |
| | | AE3.4 | Common terminology must be shared across the different communities involved. [C, S] |

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*Table 3 continued*

| | Statements | | Arguments and recommendations |
|---|---|---|---|
| AE4 | The agroecology framework provides an opportunity to look at landscape/territory scale which is also relevant for genetic resources management | AE4.1 | Management and research activities must consider landscape/territory scale as the way to associate genetic resources with ecosystem services and identify multiple values of genetic resources. [C, S] |
| | | AE4.2 | Maintenance of diversity rather than specific unicity of genetic resources must be supported to avoid negative side effects of decreased diversity. [P] |
| | | AE4.3 | Conservation of diversity at local scale can be costly, so there is a need to involve multiple actors to share costs and to work on social organizations. [P] |
| | | AE4.4 | Actions that connect across territories should be supported: locally appropriate genetic resources may be non-local, may need to be imported (incl. from *ex situ* genebanks); reciprocally each territory may handle genetic resources of poor local value but high value for elsewhere. [P] |
| AE5 | Human dimension and local knowledge are important for sustainable use of genetic resources and cultural heritage | AE5.1 | Consideration and characterization of local knowledge and traditional use have to be accounted for in the characterization of genetic resources. [C, S] |
| | | AE5.2 | Participatory approaches must be supported and developed. [P, C, S] |
| AE6 | Integrated genetic resources management contributes to increasing biodiversity as a factor of resilience of production systems in the agroecology framework | AE6.1 | Case studies can be used to improve knowledge of the respective roles of the different levels of diversity in agroecological systems: from the within-crop/breed/population/species diversity to the between-crop/breed/population/species diversity. [C, S] |
| | | AE6.2 | Traceability of genetic resources uses is needed to analyze crisis situations and document the role of diversity in buffering changes and unexpected disturbances. [C, S] |
| | | AE6.3 | Research should further investigate the conditions where diversity can be beneficial or detrimental to productivity. [S] |
| | | AE6.4 | The agroecology framework should be implemented with the aim to optimize both the production and the management of diversity, either for conservation or for preserving variability for future selection. [C, S] |
| | | AE6.5 | Scenarios of complementarity between agroecology and genetic resources conservation must be evidenced. [C, S] |
| AE7 | The agroecology framework takes advantage of local context specificities. | AE7.1 | There is no single solution to be applied everywhere: it is important to find a way to share experience/methods/tools from local to global level. [P, C, S] |
| AE8 | A holistic approach is needed to consider all levels of diversity and time scale from an agroecological perspective. | AE8.1 | Implementation of management should be based on ecological considerations with an emphasis on the links between the three domains (forest, crops, animals), natural diversity (wildlife, micro-organisms, soils, etc) and human dimension. [C] |

*Continued on next page*

*Table 3 continued*

| **Statements** | | **Arguments and recommendations** | |
|---|---|---|---|
| | | AE8.2 | Implementation of an indicators system based on multicriteria including the assessment of diversity, including genetic resources, at different levels (e.g. FAO grid) is recommended. [C, S] |
| AE9 | Reliable and abundant data are needed to support a better valorization of the genetic resources into an agroecological framework. | AE9.1 | The abundant data present in individual databases should be made broadly accessible through global portals respecting FAIR principles. [C, S] |
| | | AE9.2 | Data georeferencing can be implemented to favour making links among databases and information systems. [C, S] |
| | | AE9.3 | Genetic resources managers and researchers together have to identify all relevant data related to genetic resources that can be useful for sustainable deployment and conservation of genetic resources for the agroecology transition (from biological to socioeconomic data or regulation information). [C, S] |
| | | AE9.4 | Data about the societal impact of genetic resources need to be measured and metrics have to be defined. [C, S] |

All these data need to be standardized and broadly accessible by applying the FAIR principles (Findable, Accessible, Interoperable, Reusable https://www.go-fair.org/fair-principles/).

## Synthetic overview: targeted audiences and action plan

Each of the 88 (altogether) arguments and recommendations has one or multiple target audiences drawn from policymakers, conservation actors and scientists. In the consensus reached by the international experts of the different genetic resources domains, policymakers are called to be highly concerned by one-third of the arguments and recommendations, with a slightly higher proportion for climate change and *in situ* issues, while more than half of them concern practitioners and scientists (Table 4). The proportion of arguments and recommendations addressed to conservation actors is higher for the *in situ* and the agroecology issues because addressing both issues requires engaging a broad range of local actors, not only genetic resources specialists. Overall, more than two-thirds of the arguments and recommendations addressed to scientists are jointly addressed to other audiences, reflecting the need to reinforce participatory approaches, co-development and policy support activities in research.

All of these arguments and recommendations are picked up by the *Genetic Resources Strategy for Europe*, which defines a comprehensive action plan at national and European levels with three main objectives: (1) strengthening and widening actions for genetic resources conservation and sustainable use, (2) enabling transformative change and (3) reinforcing international cooperation. Each objective of the action plan is subdivided into several sections. Figure 1 shows that the action plan of the Strategy addresses most of the arguments and recommendations at multiple levels, and it also shows that all aspects of the action plan are needed to respond to the three new challenges reviewed for genetic resources.

## Perspectives

Despite contextual differences between crop, forest and animal genetic resources, the international panel of experts drawn from these domains recognized the emergence of a new era for genetic resources conservation and sustainable use in a context of potentially existential environmental and socioeconomic changes. Such changes that trigger multiple uncertainties require adaptive responses. In this era, the broad diversity of genetic resources can provide solutions to multiple issues, but only if the threats to diversity are effectively mitigated. Multiple conservation actions and sustainable uses must be considered in an integrated way.

For each of the three challenges under discussion, sharing expert views across domains resulted in a comprehensive list of general recommendations that are equally strategic for each genetic resources community in Europe. Beyond personal scientific expertise within the panel, the general arguments and recommendations made here also feed on the scientific evidence provided by the international conventions (the Convention on Biological Diversity CBD), platforms (the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES) and organizations (the UN Food and Agriculture Organization, FAO) addressing genetic resources and biodiversity conservation issues. Other genetic resources communities around the world could benefit from this work and reuse these evidence-based arguments and recommendations in two ways. Firstly, other communities can use them as a benchmark for the review of their own internal work plan. Secondly, these tables provide an opportunity to identify possible collaborative actions involving multiple genetic resources and conservation communities together rather than each one independently. Furthermore, all genetic resources activities have value through methodological application in the broader genetic and biodiversity conservation context. For instance, the crop wild relative population management guidelines (Iriondo *et al*, 2021) and conservation planning toolkits (Maxted *et al*, 2015; Brehm *et al*, 2017) are equally applicable for genetic or taxon-based biodiversity wild plant or animal conservation planning and *in situ* implementation. Therefore, these arguments and recommendations can feed the implementation and update of the FAO Global Plan of Action on genetic resources in the different domains, the International Treaty on Plant Genetic Resources for Food and Agriculture, and the CBD.

To address the three challenges, the experts agreed on the need for innovative solutions requiring cross-cutting collaborations, multi-actor engagement and policy support for effective implementation. Actions addressing genetic resources should engage conservation managers and users of genetic resources together with scientists from life sciences and social sciences addressing new research questions related to genetic resources, and decision-makers at multiple policy levels possibly benefiting from or influencing genetic resources conservation and sustainable use. Key are local actors concerned with *in situ* genetic resources management in production systems and conservation programmes.

With these recommendations, the panel of experts urges scientists to collaborate proactively with policymakers and a broad range of actors at local, national and international levels. Engaging new actors will depend on the capacity of the genetic resources communities to raise awareness of genetic resources values, share academic and non-academic knowledge and expertise on threats and solutions, co-develop efficient tools and advocate for supportive regulations. The *Genetic Resources Strategy for Europe* and the related action plan can help address the three challenges mentioned here and many more. In turn, disseminating the recommendations to their respective audiences will help support the uptake of the strategy. The panel of experts hopes that the statements and recommendations jointly

**Table 4.** Number of arguments and recommendations addressed to different target audiences for each challenge. CC, climate change challenge; IS, *in situ* challenge; AE, agroecology context. *, for each challenge, the sum of percentages is more than 100% because each recommendation may have multiple target audiences. **, out of the 59 recommendations to scientists, 41 (69%) are jointly addressed to other audiences.

| | Target audience | | | |
|---|---|---|---|---|
| **Challenge** | **Policymakers** | **Conservation actors** | **Scientific community** | **Total** |
| **CC** | 8 (31%)* | 14 (54%) | 18 (69%) | 26 |
| **IS** | 11 (35%) | 22 (71%) | 19 (61%) | 31 |
| **AE** | 8 (26%) | 21 (68%) | 22 (71%) | 31 |
| **Total** | 27 | 57 | 59** | 88 |

formulated by genetic resources experts in the three domains will be sufficiently integrated into future agricultural, food security, ecological, social and political policy across Europe and broader global fora to influence these sectors' policies. The implementation of the recommendations and follow-up with policymakers will require a tailored approach taking into account the specificities of each domain: this is achieved in the sectorial *Plant, Animal and Forest Genetic Resources Strategies for Europe* (respectively, ECPGR (2021); ERFP (2021); EUFORGEN (2021)).

This was the first time the three genetic resources communities (agricultural crop, animal and forestry domains) have come together at a continental level to investigate the similarities and dissimilarities between the three domains and to investigate if closer linkages could produce beneficial synergies. There is wide agreement within the panel of experts that the process itself has proven beneficial: it has shown that similarities outweigh differences, and that speaking with one unified voice is more effective in the policy context. The challenges posed by climate change, the benefit in this context of *in situ* conservation combined with sustainable use, and the need for locally adapted diversity have become so predominant, that the genetic resources communities should strive for continuous collaboration with mutual benefits.

## Authors' contributions

FL, DB, MBDK, MB, ECL, SJH, HK, DL, GR, SS, ES, TVH, MW and NM organized and chaired the three GenRes Bridge Expert Panel workshops and wrote the text of the manuscript; the Expert Panel elaborated the

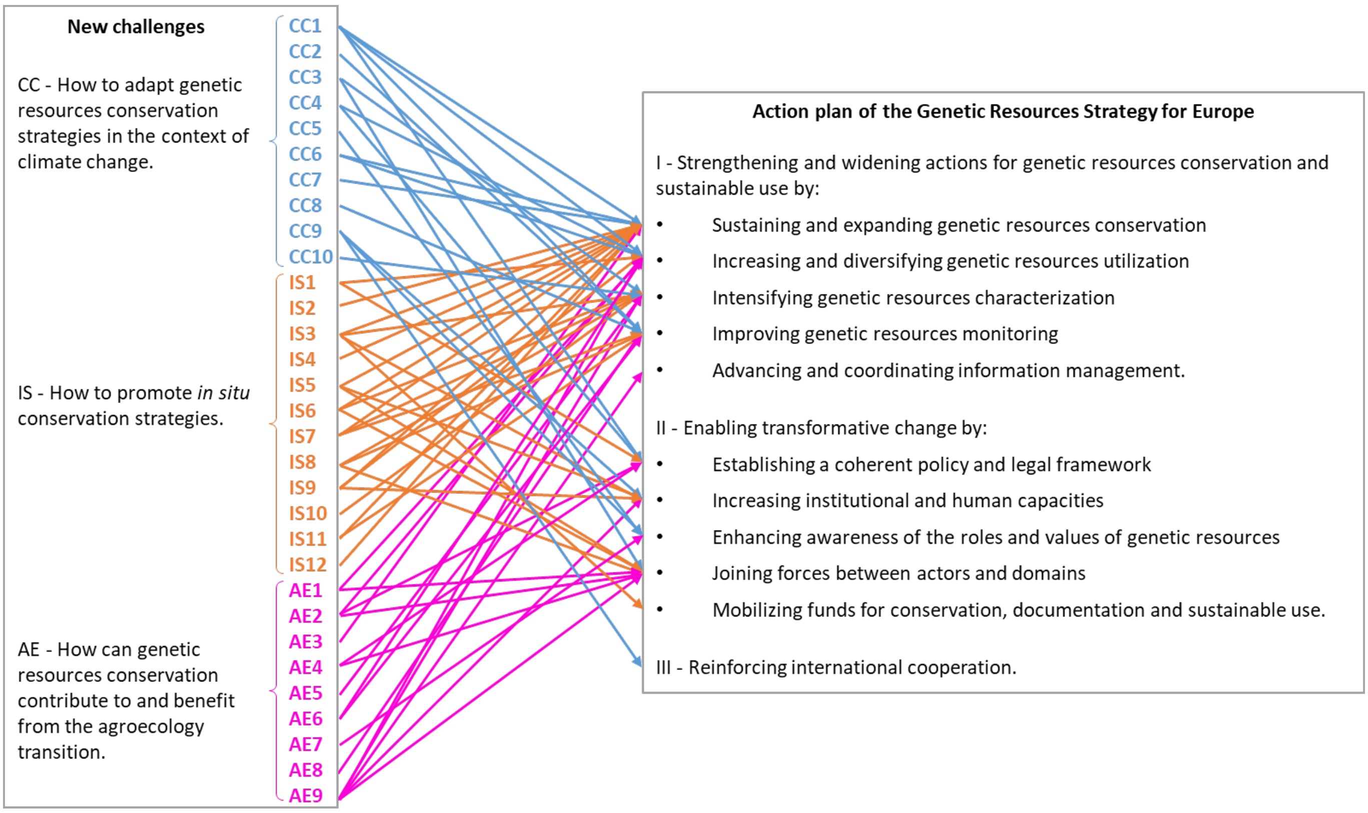


**Figure 1.** Main sections of the action plan of the *Genetic Resources Strategy for Europe* where the recommendations for the three new challenges are considered, here grouped by statement.

statements and recommendations (Tables 1-3) during the workshops and reviewed the manuscript.

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## Conflict of interest

The authors declare no conflict of interest.

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