



Global status of genetic resources for food and agriculture: challenges and research needs

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Abstract: Plant, animal, forest, aquatic, micro-organism and invertebrate genetic resources are vital to food security, nutrition, livelihoods and the resilience and adaptability of global agricultural production systems. Despite increasing efforts in recent years, much remains to be done to improve the management of these resources. Many are at risk of extinction or erosion and many have been overlooked in terms of use and development. There is an urgent need to address these deficiencies, both within the individual sectors of food and agriculture and in terms of how genetic resources management can be better integrated across sectors. These efforts will need to include action to address the multiple knowledge gaps that constrain improvements to management. They will also need to include the creation of policy and institutional frameworks that promote collaboration and stakeholder participation and allow sustainable management strategies to be implemented effectively at appropriate scales.

Keywords: genetic resources, food and agriculture, Sustainable Development Goals, global assessments, knowledge gaps

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Genetic resources — the foundation of food and agriculture

Genetic resources for food and agriculture (GRFA) are vital to food security, nutrition, livelihoods and the productivity, resilience and adaptability of production systems in the crop, livestock, forest, fisheries and aquaculture sectors. They are key resources in efforts to achieve the Sustainable Development Goals (SDGs). This paper presents an overview of the state of GRFA and their management, drawing largely on the findings of the monitoring activities overseen by the Commission on Genetic Resources for Food and Agriculture (Commission) of the Food and Agriculture Organization of the United Nations (FAO) (Boxes 1 and 2) and highlighting future management challenges, with an emphasis on knowledge gaps.

Status and trends uneven, with worrying declines

Knowledge of the status and trends of GRFA varies across sectors. The following subsections present short overviews. Selected key facts and figures on the status and trends of genetic resources and their management, at global level, are presented in [Table 1](#).

Plant genetic resources for food and agriculture (PGRFA)

More than 6,000 plant species have been cultivated for food ([Leibniz Institute of Plant Genetics and Crop Plant Research \(IPK\), 2020](#)), but today nine species (sugarcane, maize, rice, wheat, potatoes, oil palm, soybean, cassava and sugar beet) provide 67 percent of crop production by weight ([FAO, 2020b](#)). The precise status and trends of within-species genetic diversity is difficult to assess.

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Table 1. Selected facts and figures on the state and trends of genetic resources and their management at global level

| Categories | Plant genetic resources for food and agriculture | Animal genetic resources for food and agriculture | Forest genetic resources ¹ | Aquatic genetic resources for food and agriculture ² | Micro-organism and invertebrate genetic resources for food and agriculture ³ |
|---|---|---|---|--|---|
| Total number of known species | Estimated 391,000 plant species ⁴ | More than 17,000 avian and mammalian species ⁵ | More than 60,000 tree species ⁶ | More than 160,000 aquatic species | Unknown |
| Number of species and subspecies groups (i.e. varieties, breeds, etc.) used for food and agriculture | 6,000 species ⁷ Unknown number of varieties ⁸ | Around 40 species ⁹ Over 8,700 breeds ¹⁰ | 8,000 species of trees, shrubs, palms and bamboo reported by countries | 1,800 species targeted by capture fisheries 694 commercially farmed species items Few well-established improved farmed types | Unknown |
| Species concentration in food and agricultural production | 9 species provide 67% of global crop production ¹¹ | 8 species provide 97% of global meat production ¹¹ | 2,400 species reported as actively managed for products and services | 10 species provide 50% of global aquaculture production ¹² | Not applicable |
| Status and trends of species and within-species genetic diversity | Reported decreases in crop diversity in farmers' fields, but situation variable and complex ⁸ Many species of crop wild relatives under threat ^{8,13,14} | 28% of local breeds at risk, 10% not at risk, 62% unknown risk status ¹⁰ | 57% of species (34,204) have a conservation assessment: 38% of these are threatened globally ¹⁵ No systematic global monitoring system for within-species diversity Loss of genetic diversity in commercially important species a concern. | Limited information below species level Increase of species diversity in aquaculture, but increased emphasis on production of a few species | Limited information Available evidence indicates widespread declines |

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Table 1 continued

| Categories | Plant genetic resources for food and agriculture | Animal genetic resources for food and agriculture | Forest genetic resources ¹ | Aquatic genetic resources for food and agriculture ² | Micro-organism and invertebrate genetic resources for food and agriculture ³ |
|------------------------------------|---|--|--|--|---|
| Breeding | 443 crop species reported by 28 countries with active public pre-breeding and breeding programmes (81 species reported as being used in private programmes) ¹⁶ | Well-organized breeding programmes and use of advanced techniques largely restricted to developed regions and focused on a limited range of mostly temperate breeds ⁹ | 700 species reported to be included in breeding programmes | 55% of farmed species reported to be subject to some kind of genetic management | Few invertebrate and micro-organism species are subject to genetic improvement activities |
| <i>In situ</i> conservation | Among 30,000 <i>in situ</i> conservation sites reported in 39 countries, 9% had management plans for crop wild relatives and wild food plants ¹⁶ | <i>In situ</i> conservation activities widely reported, but many gaps in coverage ⁹ | Of 8,000 species used for various purposes, about 1,000 are included in <i>in situ</i> conservation programmes | Aquatic protected areas and effectively managed fisheries contribute to <i>in situ</i> conservation of aquatic genetic resources | Limited action specifically targeting these groups |
| <i>Ex situ</i> conservation | 5.4 million accessions from more than 50,000 species conserved in over 700 genebanks in 103 countries and 17 regional and international research centres ¹⁷ | Of 7,760 local breeds (including extinct ones), 258 reported to have genetic material stored in genebanks, 79 of these with sufficient material stored to allow them to be reconstituted ¹⁰ | 1,800 species reported as being conserved <i>ex situ</i> 159,579 accessions reported globally | 290 species, almost 200 of which considered threatened at national or international levels, are maintained in 690 <i>ex situ</i> collections | 791 culture collections, containing over 3 million microbial cultures of 50,875 species and subspecies, in 78 countries and regions, are registered with the WFCC ¹⁸ |

Sources: ¹ FAO (2014b), unless noted otherwise; ² FAO (2019c), unless noted otherwise; ³ FAO (2019d), unless noted otherwise; ⁴ Royal Botanic Gardens Kew (2016); ⁵ BirdLife-International (2018) Burgin et al (2018); ⁶ Beech et al (2017); ⁷ Leibniz Institute of Plant Genetics and Crop Plant Research (IPK) (2020); ⁸ FAO (2010); ⁹ FAO (2015); ¹⁰ FAO (2020a); ¹¹ FAO (2020b); ¹² FAO (2020c); ¹³ Magos-Brehm et al (2017); ¹⁴ Bilz et al (2011); ¹⁵ Global Tree Assessment (GTA) (2020); ¹⁶ FAO (2020e), data refer to reporting period 2012–2014; ¹⁷ FAO (2020e), data refer to 2019; ¹⁸ World Federation of Culture Collections (<http://www.wfcc.info/ccinfo/statistics/>).

There are no comprehensive figures available for the status of crop varieties across the world's production systems and there is as yet no standardized way of assessing their risk status. However, the available evidence indicates that, overall, the crop diversity present in farmers' fields has declined (FAO, 2010). Many farmers' varieties and landraces have disappeared or become rarer. The situation is, however, complex, with new varieties sometimes being grown in addition to, rather than in replacement of, traditional ones. The state of genetic vulnerability ("the condition that results when a widely planted crop is uniformly susceptible to a pest, pathogen or environmental hazard as a result of its genetic constitution, thereby creating a potential for widespread crop losses" (FAO, 1997a)) is also difficult to assess. However, many countries have reported significant genetic vulnerability in their production systems (FAO, 2010). Crop wild relatives are key resources in plant breeding and are widely under threat (Bilz *et al.*, 2011; FAO, 2010; Magos-Brehm *et al.*, 2017).

Threats to domesticated PGRFA include changes to production systems that lead to declines in the use of traditional varieties (FAO, 2010). Crop wild relatives are affected by pressures on their habitats, including those related to climate change and to land-use changes associated, *inter alia*, with agriculture (Magos-Brehm *et al.*, 2017; Bilz *et al.*, 2011; FAO, 2010).

Animal genetic resources for food and agriculture (AnGR)

Among the more than 17,000 known avian and mammalian species, (Burgin *et al.*, 2018; BirdLife-International, 2018), only about 40 have been domesticated for use in food and agriculture (FAO, 2015). Production is very concentrated among a few species, with eight (pig, chicken, cattle, sheep, goat, turkey, duck and buffalo) providing 97 percent of global meat production in 2018; four of these (cattle, buffalo, goat and sheep) accounted for almost 100 percent of global milk production, and chickens alone accounted for 93 percent of egg production (FAO, 2020b). A total of 8,719 livestock breeds are recorded by FAO as of 2020; 26 percent of these are classified as at risk of extinction, 13 percent as not at risk, 6 percent as extinct and 55 percent as being of unknown risk status (FAO, 2020a).

SDG Indicator 2.5.2 is "Proportion of local breeds, classified as being at risk, not-at risk or unknown level of risk of extinction" ("local breeds" are breeds found in only one country). As of 2020, 62 percent of local breeds are classified as being of unknown status, 28 percent as at risk and 10 percent as not at risk (the figures exclude extinct breeds) (FAO, 2020a). In all regions other than Europe and the Caucasus and North America, more than 80 percent of local breeds are of unknown risk status. Improving reporting is thus a major challenge. AnGR are threatened by a range of factors. Immediate threats include breed substitution, poorly managed cross-breeding and the decline of livestock-

keeping livelihoods, all driven in turn by a variety of economic, social and environmental factors, exacerbated by weak policies and institutions (FAO, 2015). Acute events such as disease outbreaks can be a threat to small, geographically concentrated breed populations (*ibid.*).

Forest genetic resources (FGR)

There are over 60,000 tree species in the world (Beech *et al.*, 2017). Most of these are wild species that have not been subject to any form of domestication. The country reports submitted for *The State of the World's Forest Genetic Resources* (SoW-FGR) (FAO, 2014b) listed nearly 8,000 species of trees, shrubs, palms and bamboo, of which about 2,400 were being actively managed for the products and/or services they supply and over 700 were included in breeding programmes. Information on the status of tree species remains incomplete. The Global Tree Assessment, which aims to assess the conservation status of all known tree species by 2020, reports as of March 2020 that 34,204 species (57 percent of all tree species) have been assessed and that 12,237 (36 percent of the assessed species) are threatened globally (Global Tree Assessment (GTA), 2020). There is no systematic global monitoring system in place for intraspecific diversity in tree species, but loss of genetic diversity in commercially important species has long been a concern among forest managers (FAO, 2014b).

FGR are threatened, *inter alia*, by land-use change, particularly conversion of forests to cropland and grazing land, overexploitation, selective harvesting and climate change (*ibid.*). Forests cover 31 percent of the global land area (4,060 million hectares), but they continue to be lost at an alarming rate despite efforts to promote natural regeneration and tree planting (FAO and UNEP, 2020). Between 2015 and 2020, the rate of forest expansion was 5 million hectares per year, while the rate of deforestation was 10 million hectares per year, meaning that the net loss of forests was about 5 million hectares per year (*ibid.*).

Aquatic genetic resources for food and agriculture (AqGR)

There are more than 160,000 species of fish and aquatic crustaceans, molluscs and plants in the world (FAO, 2019c). Of these, around 1,800 species or species items (a species item is a category of aquatic animal or plant at the species, genus, family or higher taxonomic level) are targeted by capture fisheries (*ibid.*). The total number of farmed species items recorded in aquaculture production by FAO, as of 2018, was 622, corresponding to 466 individual species, 7 interspecific hybrids of finfish, 92 species groups at genus level, 32 species groups at family level and 25 species groups at order level or higher (FAO, 2020d). However, *The State of the World's Aquatic Genetic Resources for Food and Agriculture* (SoW-AqGR) (FAO, 2019c) indicated that such production figures underestimate the number of cultured species, reporting farming of 694 species or

Box 1. The work of the Commission on Genetic Resources for Food and Agriculture

The Commission, a permanent intergovernmental body currently comprising 178 countries and the European Union, was established in 1983 as the Commission on Plant Genetic Resources for Food and Agriculture. It negotiated the legally binding International Treaty on Plant Genetic Resources for Food and Agriculture, adopted in 2001 (FAO, 2009). In 1995, its mandate was extended to cover all components of biodiversity of relevance to food and agriculture. The Commission regularly oversees country-driven global assessments of particular categories of genetic resources. The first of these, *The State of the World's Plant Genetic Resources for Food and Agriculture* (FAO, 1997a), was followed by *The State of the World's Animal Genetic Resources for Food and Agriculture* (FAO, 2007a), *The State of the World's Forest Genetic Resources* (FAO, 2014b) and *The State of the World's Aquatic Genetic Resources for Food and Agriculture* (FAO, 2019c), the latter covering farmed aquatic species and their wild relatives within national jurisdiction. The Commission has also overseen a global assessment covering all components of biodiversity of relevance to food and agriculture, *The State of the World's Biodiversity for Food and Agriculture* (FAO, 2019d). The global assessments are repeated at intervals of approximately ten years, meaning that second reports on plant and animal genetic resources have been published (FAO, 2015, 2010) and that the second assessment on forest and the third on plant genetic resources are ongoing. The first global assessments for plant, animal and forest genetic resources were followed by the adoption of global plans of action for the respective sectors (FAO, 2014a, 2007b, 1997b). In the case of plants, a second global plan of action was adopted in 2011 (FAO, 2011). A global plan of action for aquatic genetic resources is currently under negotiation (FAO, 2019b). The Commission has overseen the development of a number of codes, standards and guidelines to support the implementation of the global plans of action. In 2019, the Commission adopted a Work Plan for the Sustainable Use and Conservation of Micro-organism and Invertebrate Genetic Resources for Food and Agriculture (*ibid.*).

species items. In Asia, approximately twice as many species are reported farmed as in other continents. The report also records over 200 species that are farmed in countries where they are not native.

Aquaculture is, for the most part, a relatively new activity and the sector has few well-established improved farmed types equivalent to the varieties and breeds of terrestrial crops and livestock (FAO, 2019c). Farmed aquatic organisms are often very similar to their wild counterparts, which are sometimes used as broodstock or seed. Little information is available on the status of AqGR below the species level. As noted in Box 2, FAO is currently developing a prototype registry for these “farmed types”.

Micro-organism and invertebrate genetic resources for food and agriculture (MIGR)

Micro-organisms and invertebrates contribute to food and agriculture in a multitude of ways, including in pollination, pest control, nutrient cycling, food processing, and digestion in ruminant animals. The status and trends of micro-organisms and invertebrates, including those that contribute to food and agriculture, are generally less well monitored than those of plants and vertebrate animals. However, at the level of broad taxonomic and functional groups the available evidence indicates worrying declines (e.g. (FAO and ITPS, 2015; FAO, 2019d; IPBES, 2019; IPBES, 2016)). The habitats upon which useful micro-organisms and invertebrates depend are often in decline (FAO, 2019d). While the overall number of honeybee colonies worldwide has increased over recent decades, some countries have experienced substantial falls in colony numbers or have required extra efforts on the part of beekeepers to maintain production (FAO, 2019d; IPBES, 2016).

There are big knowledge gaps on the state of soil biodiversity, but there are grounds for serious concern

in all regions of the world (FAO, 2019d; FAO and ITPS, 2015). Threats to MIGR include habitat destruction, inappropriate use of pesticides and other agricultural inputs and the effects of climate change (FAO, 2019d).

Management strengthened, but progress patchy

Management of GRFA is taken here to include use and conservation. Each of the three existing global plans of action (GPAs, see Box 1) sets out priorities in each of these areas. Implementation is monitored via periodic rounds of country reporting and via the information systems mentioned in Box 2. The following subsections provide overviews based on these and other sources. It needs to be borne in mind, however, that use and conservation are multifaceted and interlinked fields of activity and that their boundaries are not clearly defined. Definitions and approaches to monitoring vary across sectors, as does the significance of specific management activities (e.g. *in situ* vs. *ex situ* conservation). Space precludes a detailed discussion of the state of the art in management or of the status of implementation of management activities around the world. Readers are directed to the “*State of the World*” reports (Box 1) for additional information.

Plant genetic resources for food and agriculture

Higher level composite indices for the implementation of the Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture (Second GPA-PGRFA) were calculated for the period 2012 to 2014 based on data provided by 69 countries (FAO, 2020e). Scores for actions related to the sustainable use of PGRFA were generally at a medium level (averaging approximately 4.3 out of a maximum possible 8). A

Box 2. FAO's information systems on genetic resources for food and agriculture

FAO operates global information systems for plant and animal genetic resources for food and agriculture, both of which are used for monitoring progress towards Sustainable Development Goal (SDG) Target 2.5.

The Domestic Animal Diversity Information System (DAD-IS)^a provides tools that can be used to monitor national breed populations and to support informed decision-making on the management of animal genetic resources for food and agriculture. It provides access to official data for monitoring progress towards the animal component of SDG Target 2.5.

The World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS)^b provides access to official data for monitoring progress towards the plant component of SDG Target 2.5 and on the implementation of the 18 priority activities of the Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture.

In 2019, the Commission on Genetic Resources for Food and Agriculture requested FAO to initiate the development of a new global information system on forest genetic resources (FAO, 2019b). Work is also underway to develop a global information system for aquatic genetic resources for food and agriculture, including a prototype registry of farmed types based on standardized terminology (Mair and Lucente, 2020). In the absence of such a system, AqGR are largely excluded from the monitoring of progress towards SDG 2.5. These new information systems will be fundamental to the implementation and monitoring of the Global Plans of Action in the respective sectors.

^a <http://www.fao.org/dad-is/en/>

^b <http://www.fao.org/wiews/en/>

preliminary study conducted on a smaller sample of country reports (FAO, 2016) indicated several positive developments in the field of characterization, evaluation and further development of specific collection subsets to facilitate use, with many genebank accessions reported as having been assessed and distributed for use. In the field of plant breeding, genetic enhancement and base-broadening, again a range of activities were reported, focused mainly on major crop species. International and regional networks of genebanks were reported to be widely involved in the supply of germplasm. About one-third of the reported activities in this field aimed to address constraints relevant to the production systems of small-scale farmers or local communities. Genetic enhancement and pre-breeding activities mainly targeted local cultivars and landraces. Actions promoting diversification of crop production and broadening crop diversity received a relatively low average score. However, several initiatives were reported, including the introduction of a number of new crops or wild species into cultivation. Countries reported a range of laws, policies, programmes and projects promoting the development and commercialization of crop varieties. Actions related to supporting seed production and distribution received the highest average scores, with vegetables and cereals being the crop groups most widely reported to be targeted¹.

The state of *ex situ* conservation for PGRFA is monitored under SDG Target 2.5 (Box 2). Over the past 24 years, the number of PGRFA accessions stored under medium or long-term conditions has steadily increased (by approximately 100,000 accessions per year) reaching 5.4 million – held in over 700 genebanks in 103 countries and 17 regional and international

centres – in 2019 (FAO, 2020e). These figures are lower than previously published estimates (e.g. FAO, 2010) as current WIEWS data comply with SDG 2.5.1 prescriptions for avoiding duplication in the reporting of collections and accessions within national inventories. Between 2000 and 2018, the number of species conserved in these collections more than doubled, increasing from about 24,000 to over 51,000 (*ibid.*). While the highest rate of increase occurred during the first 10 years, on average about 700 new species were added to *ex situ* collections worldwide annually during the period from 2014 to 2018. These increases were the result both of collecting missions and of improved taxonomic classification of already conserved materials.

As of December 2019, 290 genebanks around the world held almost 96,000 samples from over 1,700 species listed in the International Union for Conservation of Nature's categories of major global concern² (FAO, 2020e), including relatives of crops particularly important for global and local food security. Despite the progress made, the global response in terms of preserving crop diversity in *ex situ* facilities compliant with genebank standards is likely to be insufficient to respond to the alarming pace of the growth of the threats posed by climate change, particularly of the case for crop wild relatives, wild food plants and neglected and underutilized crop species. Species in these groups continue either to be absent from genebank collections or have their intraspecific diversity poorly represented.

Reporting on the implementation of the Second GPA-PGRFA between 2012 and 2014 indicated that increased attention was being given to the *in situ* conservation of crop wild relatives. Among the 30,000 *in situ* conservation sites reported in 39 countries, 9 percent had management plans addressing crop wild

¹ All the findings presented here from the preliminary study were confirmed by the analysis of the larger sample of countries (FAO, 2020e).

² Extinct in the Wild, Critically Endangered, Endangered, Vulnerable, Near Threatened and Data Deficient (IUCN, 2020).

relatives and wild food plants (FAO, 2020e). However, indicator scores for this area of management were low. Overall, *in situ* conservation and on-farm management (comprising priority activities in the fields of surveying and monitoring, supporting on-farm management and improvement, assisting farmers in disaster situations to restore crop systems, and promoting *in situ* conservation and management of crop wild relatives and wild food plants) underperformed as compared to *ex situ* conservation and other areas of PGRFA management (*ibid.*).

Animal genetic resources for food and agriculture

The third round of country reporting on the implementation of the Global Plan of Action for Animal Genetic Resources (GPA-AnGR) took place in 2019. Analysis of the 104 country progress reports submitted is ongoing at the time of writing, but broadly speaking they reveal that many countries have continued to strengthen their activities related to sustainable use and development. However, the level of implementation and the extent to which progress has been made since the adoption of the GPA vary greatly both across regions and across countries within regions, with higher levels reported in Europe and the Caucasus and North America than elsewhere. In 2014, when the previous round of country reporting took place, strategic priorities targeting sustainable use and development were at low to medium levels of implementation, with global average scores of between 0.5 and 1 out of a maximum of 2 (FAO, 2014c). Actions related to breeding programmes scored slightly better than those related to ecosystem approaches and support for local and traditional production systems. Sustainable use policies scored lowest, with averages dragged down by the underdeveloped state of access and benefit-sharing policies in many countries (*ibid.*).

As with PGRFA, the state of *ex situ* conservation of AnGR is monitored under SDG Target 2.5 (Box 2). Out of 7,760 local breeds (including extinct ones), 258 are reported to have some genetic material stored, and 79 are reported with sufficient material stored to allow them to be reconstituted (FAO, 2020a). The 2019 progress reports on the implementation of the GPA-AnGR indicate that conservation actions have continued to be strengthened over recent years in many countries. The previous round of country reporting again indicated low to medium levels of implementation of strategic priorities in this field (FAO, 2014c). *In situ* conservation scored relatively well compared to *ex situ* conservation (*ibid.*), although it needs to be borne in mind that *in situ* activities and their impacts are difficult to monitor because of a lack of detailed data and differences in the way the term is used in different countries. Country reporting for The Second Report on the State of the World's Animal Genetic Resources for Food and Agriculture (FAO, 2015) indicated that at least some *in situ* conservation activities were being implemented in most countries, with a wide variety of different

approaches reported, including those related to breeding programmes, to market development and to other forms of support for farmers and herders raising rarer breeds. However, it also clearly indicated that levels of implementation were far below those that countries considered necessary to provide an adequate degree of protection for their AnGR (*ibid.*). As of May 2020, 223 (11 percent) of the 1,808 local breeds recorded in DAD-IS (Box 2) as “critical” or “endangered” were listed as “maintained”, meaning that “active conservation programmes are in place or populations are maintained by commercial companies or research institutions” (FAO, 2020a).

Forest genetic resources

The first round of country reporting on the implementation of the Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources (GPA-FGR) took place in 2018 (FAO, 2019a). The response rate was quite low (44 countries) and hence it is not possible to draw comprehensive conclusions. Across the GPA-FGR as a whole, reporting countries had on average achieved 67 percent of action points and had initiated efforts to achieve a further 10 percent. Only four had achieved all 15 action points. A total of 1,145 tree and other woody plant species (including hybrids) were included in the 44 country progress reports. With regard to the state of use, a total of 531 tree species were reported to be included in national tree seed programmes. The numbers reported by individual countries varied greatly, from zero in several cases up to 114. A total of 288 species were reported to be included in tree-breeding programmes, with the numbers reported per country ranging from zero to 55. However, many more species are used in forestry; for the SoW-FGR, countries reported about 2,400 species as being actively managed for products or services in forestry and more than 700 as being included in tree improvement programmes (FAO, 2014b).

Information on the status and trends of *in situ* conservation activities – the main approach to FGR conservation – is limited. In 2018, only 568 species were reportedly included in *in situ* conservation programmes and 647 in *ex situ* programmes. However, the country reports submitted for the SoW-FGR listed nearly 8,000 species of which about 1,000 were reportedly conserved *in situ* and 1,800 *ex situ* (FAO, 2014b). Only 625 out of 2,260 priority species listed were reported to be subject to any kind of *ex situ* conservation, with maintenance in field collections, including clone banks and provenance trials, much more frequently reported than storage in seed or *in vitro* collections (*ibid.*).

Aquatic genetic resources for food and agriculture

As a GPA for the sector has yet to be adopted, AqGR management has no global monitoring system equivalent to those existing in other sectors. However,

some relevant data are available. For example, [Metian et al \(2020\)](#) report the use of a large and increasing range of species in aquaculture, particularly in Asia, and argue that this enhances the resilience of the sector by improving capacity to adapt to change. While new species are being developed for aquaculture and the list of cultured species continues to expand, global aquaculture production is increasingly dominated by a few key species, with the top ten species accounting for 50 percent of global production ([FAO, 2020c](#)), a trend which, if it continues, may erode resilience to challenges such as disease and climate change.

As noted above, genetic improvement activities are relatively underdeveloped in the aquaculture sector. Among the species listed as being farmed in the country reports submitted for the SoW-AqGR only 55 percent were reported to be subject to any kind of genetic management ([FAO, 2019c](#)). While studies indicate that there is potential for major gains in productivity via selective breeding of farmed aquatic species ([ibid.](#)), 45 percent of countries reported that genetic improvement was yet to have any significant impact on their aquaculture production, and the report identified an important need to increase the adoption of genetic programmes, especially for lower-value species important to food security. The report highlights the need to set an appropriate balance between investment in the diversification of species used in aquaculture and the application of genetic technologies to better adapt existing cultured species to diverse culture environments.

In situ conservation of AqGR relates mainly to the protection of wild species, for example via the establishment of protected areas, management and regulation of fishing and other habitat-protection measures, although “on-farm” conservation to prevent the loss of farmed-type genetic resources is also required. Both aquaculture and capture fisheries have an important role to play and conservation objectives need to be integrated into aquaculture development and fisheries management strategies.

Countries that contributed to the SoW-AqGR generally considered protected areas to be an effective means of conserving the genetic resources of wild relatives of farmed aquatic species ([FAO, 2019c](#)). Seventy-five percent of the 92 reporting countries indicated the implementation of *ex situ* conservation activities for aquatic organisms of national relevance falling within the scope of the report. Approximately 290 different species, almost 200 of which were considered to be threatened at national or international levels, were being maintained in a total of 690 *ex situ* collections. Finfish accounted for 90 percent of the species concerned, with the other 10 percent accounted for by macro-invertebrates and aquatic micro-organisms such as rotifers and microalgae. Most *ex situ* conservation is *in vivo*. About 38 percent of reporting countries indicated the existence of *in vitro* conservation of AqGR (farmed species and wild relatives), involving a total of 133 different species.

Because of the difficulty of preserving the eggs and embryos of aquatic organisms, most *in vitro* conservation involves cryopreservation of sperm.

Micro-organism and invertebrate genetic resources for food and agriculture

Many micro-organisms and invertebrates of importance to food and agriculture are not actively managed in any way by producers. However, many approaches that involve introducing them into production systems or managing habitats to encourage their presence, for example in the context of integrated pest management, pollination management or integrated plant nutrition management, are becoming more widely implemented globally ([FAO, 2019d](#)). Few species are subject to genetic improvement. However, there are a substantial number of commercial honey-bee breeding companies around the world that implement genetic improvement programmes, with the main goals being higher honey production, greater docility, reduced swarming and, particularly in recent years, better disease tolerance ([ibid.](#)). Micro-organisms used in food processing and in agro-industrial processes are subject to a variety of genetic-improvement strategies ([Alexandraki et al, 2013](#); [Chatzispavlidis et al, 2013](#)). Some genetic improvement is also being conducted in micro-organisms used in plant nutrition, biological control and food preservation ([FAO, 2019d](#)).

Micro-organisms and invertebrates are conserved *in situ* along with other components of biodiversity in protected areas. They also benefit from the adoption of biodiversity-friendly management practices in the food and agriculture sector and elsewhere. However, the number of species specifically targeted is limited, as is information on the coverage and effectiveness of conservation measures ([ibid.](#)). Micro-organisms can be stored under laboratory conditions in a range of different ways. Existing culture collections are, however, far from representing the full range of micro-organisms of relevance to food and agriculture ([ibid.](#)). Various invertebrates of importance to food and agriculture are raised in captivity by commercial companies or by research institutes. However, there are few systematic *ex situ* conservation programmes, even for high-profile groups of invertebrates such as pollinators. Some work has been done on the cryoconservation of bee semen, although the technique has not become widely used ([ibid.](#)).

Knowledge gaps a key constraint

Knowledge gaps are a major constraint to the effective management of GRFA. As discussed above, population status and trends are inadequately monitored across most categories, hindering the planning of conservation efforts. The following subsections briefly outline key knowledge gaps by sector and related to cross-sectoral integration.

Plant genetic resources for food and agriculture

Monitoring PGRFA diversity *in situ* and on-farm to predict and minimize loss of inter- and intra-specific genetic variation is a major challenge, particularly in vulnerable groups such as crop wild relatives, wild food plants and underutilized crops. National conservation planning would greatly benefit from the development of indicators that could be widely used to quantify genetic erosion and monitor changes in the extent and distribution of individual species and populations at various scales. Research on the characteristics of the above-mentioned vulnerable groups, including on their reproductive biology, agronomic and nutritional properties, traditional and potential uses, and contributions to the health of agro-ecosystems, is vital to efforts to improve their conservation and sustainable use. Knowledge of their geographical distribution also needs to be improved.

Efforts to integrate *in situ* and on-farm management and conservation of PGRFA with the work of national, regional and international genebanks and research institutes need to be documented and widely publicized. Knowledge gaps on recalcitrant seed physiology and behaviour in neglected species, along with a lack of standardized protocols for their *in vitro* conservation and cryopreservation – and a lack of alternative low-cost conservation methods – is often a severe constraint to national *ex situ* conservation programmes. Other key knowledge gaps relate to breeding systems, reproductive biology, dormancy mechanisms and technical problems associated with regeneration practices for “unconventional” species. The use of molecular methods, biochemical assays and high-throughput phenotyping in germplasm characterization and evaluation to identify useful genes, understand their expression and variation, and in particular understand their roles in adapting to climate change, increasing nutritional values and strengthening ecosystem services, has been limited to a few major crops in developed countries. Further work is also needed on development and harmonization of standards for the exchange of data on *in situ* germplasm and the documentation of ethnobotanical information on farmers’ varieties, landraces and underutilized species.

Animal genetic resources for food and agriculture

The genomic revolution has led to impressive progress both in terms of improving knowledge of AnGR and in terms of genetic improvement. However, it has also widened gaps between developed and developing countries and between the relatively few international transboundary breeds that increasingly dominate high-input production systems globally and the mass of breeds adapted to more extensive systems. There are clear knowledge gaps in terms of the characterization of phenotypes (especially functional and adaptive traits) and their relations to production environments. As characterization is a prerequisite

for effective implementation of genetic improvement programmes (Leroy et al, 2016), these knowledge gaps are to some extent hindering the realization of the opportunities offered by genomics.

One of the most important challenges in AnGR management relates to the difficulty of developing governance systems that fully integrate livestock keepers from developing regions (Leroy et al, 2017). Systems of this kind are vital to the implementation of characterization studies, breeding programmes and market development (Gowane et al, 2019). Experiences in this field need to be documented and publicized, although success will also depend on the provision of adequate institutional, technical and financial support over the long term (Mueller et al, 2015).

Forest genetic resources

Priorities in the field of FGR management include improving knowledge of the amount and distribution of genetic diversity in forest trees and of how well current efforts to conserve FGR *in situ* are maintaining this diversity in the long term (FAO, 2014b). There is also a need to enhance the production of seed and other forest reproductive material, especially for many native tropical and subtropical tree species, to meet demand for restoration and for establishing new forests and tree-based production systems (FAO, 2014b; FAO and UNEP, 2020). Furthermore, recent advances in forest genomics need to be translated into practical applications for conserving and using FGR and for increasing our understanding of the adaptation of forest trees to climate change (e.g. Holliday et al, 2017).

Aquatic genetic resources for food and agriculture

Characterization and monitoring of AqGR suffers from a lack of knowledge of genetic resources below the level of species and a lack of standardization and harmonization of terminology and nomenclature. The prototype registry being developed by FAO for farmed types (Box 2) will help address this issue by promoting the collection and sharing of key information on the availability and properties of AqGR. A variety of genetic technologies can be used to develop and improve farmed types for use in aquaculture. However, a clear understanding of the risks and benefits of these technologies is often lacking. Aquaculture stands to benefit greatly from effective implementation and uptake of well-managed breeding programmes, with a focus on selective breeding. Many governments consider this a role for the public sector, but such programmes often fail to deliver tangible and long-term increases in production. There is a need to identify mechanisms for effective engagement of the private sector in such programmes, for example through public–private partnerships. Finally, cryopreservation clearly has a role to play in *ex situ* conservation of AqGR, but further

research is needed into methods for cryopreservation of eggs and embryos.

Micro-organism and invertebrate genetic resources for food and agriculture

There are enormous knowledge gaps related to MIGR. In every taxonomic and functional group, many species remain to be identified and characterized. The roles of MIGR in the supply of ecosystem services, how they are affected by environmental changes and how they can be managed to support food and agricultural production need to be much better understood. Knowledge of the significance of micro-organism and invertebrate diversity at within-species level to food and agriculture is very limited.

Integrated management

Integrated use of the various “sectoral” categories of genetic resources can give rise to a range of synergies and complementarities that can help increase productivity in a sustainable way and make production systems more resilient (Dawson *et al*, 2018; Duval *et al*, 2018; FAO, 2019d). There is a need for research into how integrated management can be made more effective at a range of scales, from the individual plot to the landscape. This needs to include research into how genetic resources management can contribute, for example via appropriate choice of combinations of species, varieties, breeds, etc. for use in particular integrated systems and via appropriate genetic improvement strategies.

Time to step up action

Despite some positive developments in various aspects of GRFA management, much remains to be improved. Progress towards SDG 2.5 has been minimal overall. Action clearly needs to be urgently stepped up across all sectors. However, there is also a vital need to improve cross-sectoral cooperation. For example, many drivers of loss of GRFA affect more than one sector of food and agriculture and in many cases also affect species and ecosystems that are priorities for the nature conservation sector. Habitat destruction is a major driver of loss of forest, aquatic, invertebrate and micro-organism genetic resources, as well as of wild relatives of crops and livestock and of biodiversity in general. Climate change is a severe threat across all categories of GRFA. Threats of this kind need to be addressed in a comprehensive and cross-sectoral way, with the food and agriculture sector recognizing its role as a major contributor to biodiversity loss.

For domesticated plants and animals, changes in consumption patterns and production systems that lead to declines in the use of diverse GRFA are a major threat. This threat can to some extent be addressed by ensuring that diversity is utilized as fully as possible in the interests of livelihoods and food security, for example via the production benefits of raising species, breeds,

varieties and farmed types that are well adapted to local conditions, the nutritional significance of diversity in the food supply and the marketing opportunities associated with unique products provided by specific GRFA. However, there is a need to recognize that the maintenance of genetic resources for the long term is a public good and that interventions specifically aimed at supporting producers in this role will, in some cases, be necessary. The challenge is to maximize synergies and manage trade-offs among the various demands placed on production systems in terms of supporting and improving local livelihoods and in terms of the reliable supply of a broad range of ecosystem services, including genetic resources conservation. Within a given landscape or seascape, this may require cooperation among stakeholders from the crop, livestock, forest, aquaculture, fisheries and nature-conservation sectors (among others).

Approaches that effectively combine *ex situ* conservation with *in situ* conservation, and conservation with sustainable use, need to be promoted. These activities need to ensure that they target a sufficiently wide range of genetic resources to meet the needs of producers and other stakeholders across a range of diverse and changing production systems and, in the longer term, the needs of future generations. In this regard, there is a need to increase efforts to raise awareness among policy-makers (and other stakeholders, including consumers) of the importance of neglected and underutilized GRFA. More generally, awareness raising with respect to the significance of all types of GRFA and the need to manage them sustainably remains a key priority.

Across all sectors (including in the context of integrated management), the numerous knowledge gaps that constrain effective management of GRFA need to be urgently addressed. Where research is concerned, there is again a need to ensure that activities are sufficiently broad based in terms of the genetic resources and production systems targeted. Attention needs to be given to how new technologies and existing good practices can be scaled up and adapted for implementation in different contexts.

Enabling policy, legal and institutional frameworks for sustainable management need to be put in place at all levels, including mechanisms for ensuring active and equitable stakeholder participation and collaboration. Stakeholder organizations and networks of various kinds have important roles to play, and their establishment or strengthening should be promoted where necessary. Although not a topic focused on in this paper, problems with the implementation of access and benefit-sharing mechanisms also remain to be addressed in many countries.

At global scale, the existing GPAs have provided a valuable framework for planning and monitoring actions across the various fields of GRFA management, helped to raise awareness and promoted international cooperation. Over the coming period, the Commission will be working to finalize a global plan of action

for AqGR and a global plan of action or other policy response for biodiversity for food and agriculture as a whole. The Convention on Biological Diversity is in the process of developing a global framework for all biodiversity for the post 2020 period (Convention on Biological Diversity, 2018). There is an urgent need for the international community to engage fully in these processes and in the implementation of their outcomes and those of the existing GPAs. Research has an essential role to play in informing both policy development and the implementation of agreed actions.

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Author contributions

D.P. and J.B. contributed to the conception and design of the submitted manuscript. D.P. drafted the manuscript. All authors contributed to data gathering and analysis and to the drafting, revision and final approval of the submitted manuscript.

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